

Easy to use power electronics converter

by

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FOREWORD

This work presents the research and development performed over many years to produce an electric power converter suitable for industrial applications: more precisely, the development of Imalog's Universal Family™ of power electronics converters. This family of converters is intended for applications ranging from fifty kilowatts to five megawatts. These converters are mostly operated from low voltage (208V to 660V) three phase supplies. A short list of applications includes AC and DC power supplies for ozone generators, plasma torches, fast battery chargers, and micro-grid interfaces. While the basic design for these power converters is not new, the efforts were oriented towards making them relatively easy to use by general product designers. The initial case made is that the use of power electronics converters needs to be simplified to reach its full market potential. Aside from a few exceptions, such as solar panel inverters and simple DC power supplies, it has been too complex to gain wide acceptance in the equipment designer community. This is a deplorable situation as the gain in efficiency and performance brought by power electronics to machinery should be a cornerstone of many CO₂ reduction strategies. The example of vehicle electrification needs to be followed by other industries to help reduce global warming.

This work focuses on the high-level design. The architecture and the design philosophy used to make this power converter suitable for general use is presented with some precisions regarding the electronic circuits, the digital controllers, or the control algorithms that have already been covered in detail in numerous publications and textbooks. The subject is treated using multi-disciplinary notions from education, communication, and marketing science. Important ideas from various authors are presented to support the development of this design philosophy. Contribution from these “non-engineering” fields was needed to understand the human aspect governing the diffusion of technologies. The reader is welcome to consult the references for more details.

The power converter design method presented below relies heavily on the software tools available from manufacturers instead of pages of mathematical derivations and computer

simulations found in a typical power electronics thesis. This may surprise some researchers, but it is justified by the need to inform new engineers about the availability of efficient design tools optimized for the specific components they consider using. The tools provided by component manufacturers are based on the science developed over the years by hundreds of experts and have usually been validated on real component operations. This helps attain the important requirement of producing a reliable power converter.

Examples of decisions made to enhance the reliability and safety of the product are presented in Sections 3.14 and 3.15. The reader will see how hardware and software are combined to produce multiple levels of protection. The importance of safe work procedures is emphasized, and tips on how to implement them are given. Some of the mishaps experienced during the development are presented to warn designers about the dangers associated to the conversion of large amounts of energy. These events were used to improve the overall safety of the product.

Since the reliability of a product cannot be completely evaluated on paper (as one cannot imagine all the issues that complex equipment will present), the converter designs have been verified by producing full size prototypes followed later by production units. CHAPTER 6 is dedicated to the presentation of the application for this power converter as an ozone generator power supply. It illustrates the flexibility of the new converter design by presenting the field-specific challenges and how they used to be solved with previous thyristor technologies.

ACKNOWLEDGMENTS

This work was supported by my employer, Imalog Inc. I am grateful to work for an organization where scientific research is part of product development. I would like to thank all of my colleagues who have contributed to the design of the power converter described herein. This has been a multi-year team effort. I have the pleasure of directing a team of professional designers with a passion for high quality work. Major contributors are Mr. Sylvain Tremblay, Dr. Smain Medar P.Eng. and Imalog's president, Mr. Tony Di Schiavi. To this core team, we must add half a dozen engineers and technicians who also made valuable contributions.

I would like to extend my appreciation and admiration to my research director Dr. Handy Fortin Blanchette, whose skills as a teacher have been an inspiration. His patience and dedication are making a difference in the transfer of advanced power electronics technology knowledge. He makes this complex subject easier to understand for many beginners, and even for more experienced engineers like myself.

Finally, I have been supported through this work and in the writing of this paper by my wife, Sheila, and my daughter Stephanie who patiently reviewed the manuscript.

CONVERTISSEUR DE PUISSANCE ELECTRONIQUE FACILE A UTILISER

Marco TREMBLAY

RÉSUMÉ

Ce document présente une philosophie de conception de convertisseurs de puissance adaptés aux besoins des fabricants industriels désireux de les utiliser pour améliorer leurs procédés et leurs équipements. Une prémisse de base de ce travail est que les convertisseurs électroniques de puissance peuvent être utiles pour améliorer l'efficacité des procédés et des équipements. Les succès obtenus par l'électronique de puissance dans les transports et l'énergie supportent bien cette prémisse.

Malheureusement, l'électronique de puissance est une technologie pointue qui requiert plusieurs années d'études spécialisées pour être adaptée aux besoins spécifiques des applications. Ce fait a grandement limité sa diffusion et elle demeure peu connue et incomprise par ses utilisateurs potentiels.

L'objectif de ce projet est donc de développer un convertisseur électronique de puissance dont l'usage est aussi facile que celle des automates programmables, si populaires dans l'industrie. Le convertisseur est conçu pour permettre au personnel des fabricants de l'adapter à leur procédé sans pour autant avoir à devenir des experts en électronique de puissance. Cette philosophie a été au cœur de la conception de ce nouveau convertisseur. Dans ce document, l'emphasis n'est pas mise sur les performances électriques mais plutôt sur la flexibilité et la facilité d'utilisation qu'on ne retrouve pas sur le marché. La fiabilité et la sécurité de ces équipements sont aussi traitées. Ces sujets sont abordés dans le chapitre portant sur les méthodes de conception. Ces sujets souvent négligés sont très importants pour tous les concepteurs de convertisseurs de puissance. Ils le sont d'autant plus lorsque des gens moins informés utilisent les convertisseurs dans leurs applications.

L'utilité de ce convertisseur est démontrée dans le dernier chapitre par la présentation d'une application industrielle en production d'ozone avec des exemples d'équipements allant jusqu'à 1.2MW.

Mots-clés : Convertisseur de puissance, onduleur, prototypage rapide, générateur d'ozone, alimentation, qualité de l'onde, électronique de puissance, IGBT, Simulink.

EASY TO USE POWER ELECTRONICS CONVERTER

Marco TREMBLAY

ABSTRACT

This work presents a power electronics converter design philosophy adapted to the needs of Original Equipment Manufacturers (OEMs) wanting to integrate them into their products and processes. A basic premise of this research is that the use of power electronics can help advance various processes and equipment. Noteworthy successes in transportation and energy are convincing examples supporting the validity of this premise.

Unfortunately, power electronics is an abstract field that takes many years of advanced studies to master. It is unthinkable for most users to modify their power electronics equipment themselves. This has greatly limited its diffusion, remaining unknown and misunderstood by potential industrial users.

Our objective is therefore to develop a power electronics converter that is as easy to use as the Programmable Logic Controllers (PLCs) that are so often used in industrial equipment. The converter is designed so that OEM staff can adapt it to improve their process, without the need to become power electronics experts. This philosophy was central to the design of this new power converter. The focus of this work is not on the electrical performance of this converter but on its functionalities designed to simplify its usage by the OEMs.

The chapter dedicated to design methodology also covers some reliability and safety aspects of this type of equipment. This subject is often neglected but is crucial to power converter designers. This is especially important when the converter is intended to be used by people less who are less aware of the dangers.

The usefulness of the design is presented in the last chapter, with a real industrial application in ozone production reaching up to 1.2MW.

Keywords: Power converter, inverter, rapid prototyping, ozone generator, power supply, power quality, power electronics, IGBT, Simulink.

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LIST OF ABBREVIATIONS AND ACRONYMS

A	Ampere
AI	Artificial Intelligence
AHF	Active Harmonic Filter
BIOS	Basic Input Output Software
CSA	Canadian Standard Association
DE	Distributed Energy
FACTS	Flexible AC Transmission Systems
FFT	Fast Fourier Transforms
HIL	Hardware-In-the-Loop
IAS	Industry Applications Society
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical Engineering Engineers
IGBT	Insulated Gate Bipolar Transistor
IoT	Internet of Things
IPEM	Integrated Power Electronics Module
M2M	Machine to Machine
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PEBBs	Power Electronics Building Blocks
PF	Power Factor

PLC	Programmable Logic Controller
PLL	Phase-Locked Loop
PSU	Power Supply Unit
PV	PhotoVoltaic source
PWM	Pulse Width Modulation
RMS	Root Mean Square
RoHS	Restriction of Hazardous Substances
STATCOM	STATic COMpensator
THD	Total Harmonic Distortion
UL	Underwriters' Laboratory
V	Volt
VA	Volt-Ampere
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
<i>w.r.t.</i>	with respect to

Note: I-PSU™ and I-Pack™ are trademarks of Imalog Inc.


INTRODUCTION

Our economy is based on technologies that make life more comfortable and that facilitate our work. A large portion of this technology is implemented in machinery and processes developed and produced by Original Equipment Manufacturers (OEMs). Their objectives are to reduce various costs and improve the desirability of their products to increase their share of the various markets they are involved in. A basic premise of this work is that power electronics converters can contribute greatly to the products and processes that the OEMs are developing. Unfortunately, their adoption has been slowed down by their complexity and the general lack of awareness of their potential contribution.

This work begins by showing how the use of power electronics is helping improve the efficiency and the performance of various processes and equipment. Variable speed drives and DC power supplies are the original applications for which power electronics technology has been developed, but it can contribute to several others. An example of these applications is the hybridization or replacement of internal combustion engines with electric motors in some models of cars. While electric cars have been available for more than a hundred years, the low performance level obtained with early electro-mechanical technology limited their popularity. Suitable power electronics converters only became available near the turn of the millennia. This finally brought electric cars to a level of performance attractive to a wider market.

This success story is likely to be reproduced when power electronics converters will be used in other applications. The following table illustrates a few potential candidates.

Table 0.1 Examples of successful applications for power electronics

<p>Battery chargers and conditioners for vehicles or renewable energy</p> 	<p>Photovoltaic solar panel inverters</p> 
<p>Frequency converters to connect windmills or solar panels to a utility network</p> 	<p>Motor drives: the work-horses of the industry</p> 

Pictures taken from indicated web sites in early 2006

Based on previous success in fields such as transportation and energy, researchers and industry commenters (Admin, 2013) are convinced that many other processes and products can benefit from power electronics converters.

One factor that is slowing down the diffusion of power electronics is that developing a new process or equipment requires skills and know-how specific to the field of application. For example, to develop a new chemical process, one must be at least an expert in industrial chemistry. It is not likely that an electrical engineer will develop advanced chemical processes.

Therefore, new processes development is usually conducted by a small team of experts (OEMs) that rarely include power electronics engineers. Therefore, the benefits that power electronics could bring to the process or equipment are not always recognized. When they are, the OEMs must either set up a power electronics engineering section with their own lab or sub-contract the power electronics converters' design to another firm. Both choices are time-consuming and expensive; not what a fast-paced application development team is looking for.

A possible avenue of simplification is to develop a power electronics converter architecture that could be used by any OEM team with a minimal amount of power electronics know-how. This would be the equivalent to the Programmable Logic Controllers (PLCs) so widely used to automate machines and processes. When using a PLC, one doesn't need to be a microprocessor expert and develop printed circuit boards to automate a machine, but simply must respect the voltage and current levels of the inputs and outputs. Even the programming is simplified by using graphical ladder language that resembles the electrical schematics that electricians are familiar with.

The objective of this work is therefore to develop a power electronics converter that will be as easy to use as a PLC, so that OEM staff can configure and program it to improve their process, without needing expertise in power electronics. It is very likely that this will open the door to a wider range of applications that are not yet taking advantage of power electronics technology. The other advantage of simpler power electronics is that it will allow a greater number of teams, even those with limited resources, to develop their own solutions to machinery or process problems. This is likely to increase the quantity of innovative products designed to solve the technical challenges our society faces.

The solution proposed in this document is the I-Stack™ power converter shown in Figure 0.1. I have conducted the development of this power converter for my employer. This section gives an overview of some of the application needs that led to its design. It presents the motivation behind the design philosophy. Chapter 1 concentrates on identification of the problem and what others have done about it. The following chapters show how a solution can be implemented

in the form of an industrial power converter. The objective of this document is not to provide all of the design details, but to trigger a reflection in the power electronics community on the subject of usability of power converters and the simplification of their design. Finally, an example of an application in the water treatment industry is presented to validate this work. The product line covers the 100kW to 2.4MW range.

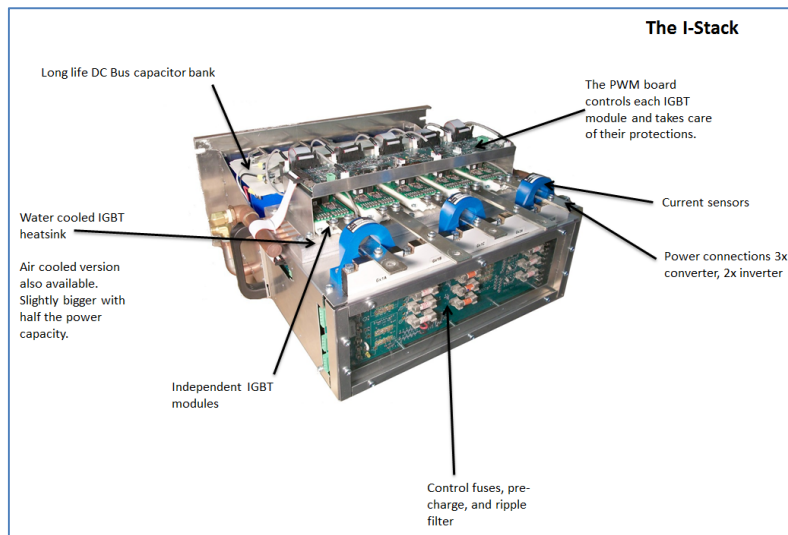


Figure 0.1 Imalog's I-Stack power converter

Potential applications for power electronics converters





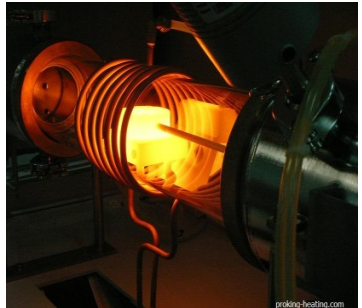

There are dozens of applications where power electronics can be used to improve a product or process performance. A simplified list of the applications is provided in 0. The scientific literature is filled with research detailing how various forms of electrical power can be used to achieve useful results. This list is a good starting point for those looking for challenges. In these applications, the electrical power needs to be controlled in specific ways. The electricity supplied by the utility company is rarely provided in a form suitable for these applications. Power electronics converters are one of the possible solutions to transform this electricity into a suitable form.

Table 0.2 A and B, illustrate some of the well-known applications where power converters are presently used or will be used in the near future.

Table 0.2A Examples of applications

<p>Large battery chargers and conditioners for vehicles or renewable energy</p>  <p>fuelgreener.com</p>	<p>M2G (Motion to Generation) converter, shock absorbers with energy recovery, stability control, hybrid motors</p>  <p>cat.com</p>	<p>Electric services and propulsion for airplanes</p>  <p>SOLARWORLD</p>
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Table 0.2B Examples of applications (continued)

<p>Electro-magnets for frictionless bearings, load handling, and linear motors</p>  <p>maglev.net</p>	<p>Chlorine generator (Sodium hypochlorite) to transform chemical products from one form to another</p>  <p>EST's K-series generator Cheminfo.com</p>	<p>Electro-separation of liquids for petroleum extraction and oil removal from other substances</p>  <p>killminat2012.wordpress.com</p>
<p>Frequency converters to connect windmills or solar panels to a utility network</p>  <p>vestas.com</p>	<p>Induction heating and metal processing with even and precise temperature control</p>  <p>priking-heating.com</p>	<p>Plasma torch power supplies</p>  <p>http://advancedpowders.com/</p>

Pictures taken from indicated web sites in early 2006

Solutions analyzed in this document

This section presents the development effort and the philosophy behind a new line of power electronics converters specially designed to be used by the product and process developer community (OEMs). Figure 0.2 is a simplified illustration of the power electronics converter design process from idea to application.

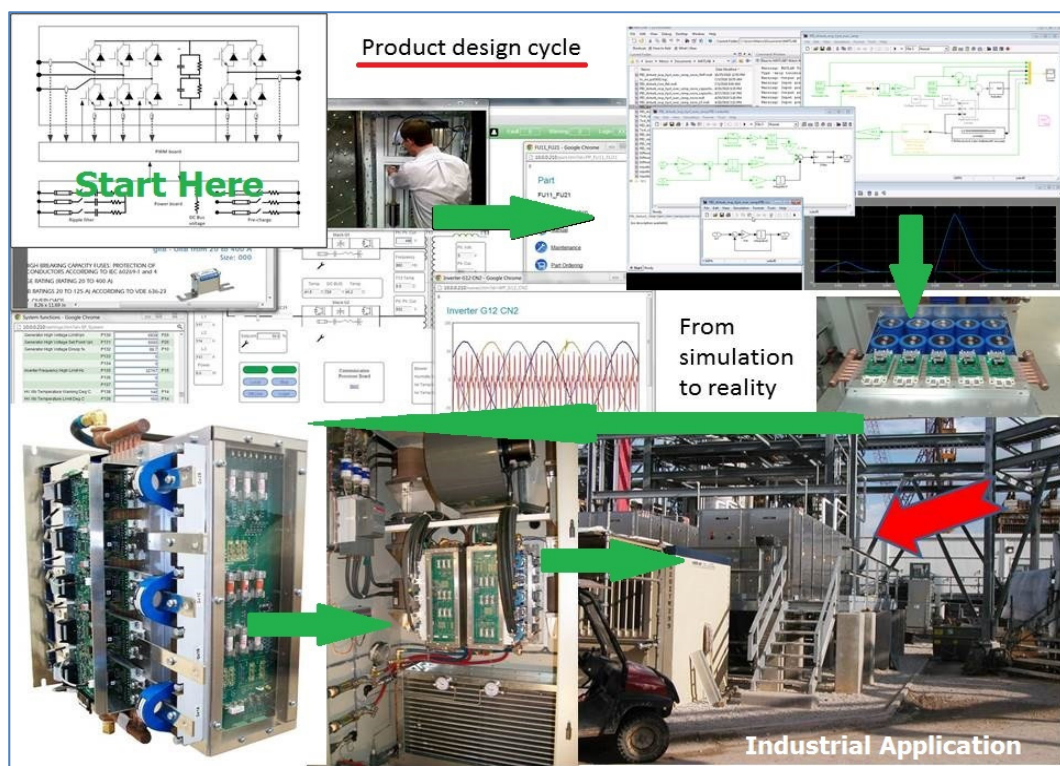


Figure 0.2 Simplified product design cycle from conceptual design, simulation, programming, fabrication, tests, to installation at an industrial end-users site

This simplified illustration of the design process from the idea to the industrial usage is based on a real application. It skips over millions of details but gives a roadmap to young designers venturing in the field of power electronics. It starts in the top left corner where the initial research for a solution has led to an electronic circuit. The designer then uses various computer tools and measurements on test prototypes to come up with a working design (top section). After many months of work, the electrical design is then implemented on a physical unit

(middle right). Suitable component selection is a crucial part of this process, as even the best components are unreliable when used improperly. Iterations are common, and returning to the beginning of the process (when the results don't meet the expectations) is a real possibility. The mechanical and electrical designs are then integrated into a finished power converter (bottom left corner). The work to fulfill a complete application doesn't stop there as months of testing are still needed and a suitable cabinet with auxiliary components must be provided (bottom center). Finally, the system engineering team can integrate the power converter into a complete solution to satisfy the needs of an industrial customer. Months later, the complete system can be installed at the industrial site, followed by weeks of commissioning work (bottom right). In the case of the I-PSU™ presented in the last chapter, this process took a few years.

CHAPTER 1

WHAT SLOWS DOWN POWER ELECTRONICS ACCEPTANCE

1.1 The broken connection with potential users

Power electronics is different from the technologies used by mechanical or chemical process engineers. What could be done to help Original Equipment Manufacturers (OEMs) and process developers succeed in using power electronics converters? This lack of familiarity creates a barrier that is very difficult to cross for many product development teams. A way to reduce this barrier must be found to help them recognize, understand, and use power converter technologies as a solution to their problems. This is crucial as OEMs will not use this technology if they are not aware of its benefits.

We can divide the problem of making the power converters technology more popular into two parts:

Finding a way to design and present a power electronics converter to facilitate its acceptance and its use by OEM staff;

Finding topologies and accessories needed to cover as many applications as possible.

To solve the first part of this problem, one must gain a better understanding of OEMs' product development process. A basic review of the literature on the subject of technology innovation and communication between different technical groups shows that people choose what they are familiar with or what excites their curiosity. In their paper, (Barham et al. 2013) cover the ambiguity aversion that affects the adoption of new technologies. Basically, people don't like what they don't understand. Also, (Chen et Granitz, 2012) showed us that the perception of the usefulness of a high technology product is key to its adoption. The trick is to convince customers that the product is useful. (Lanzolla et Suarez, 2012, p836) explain how "the information diffusion mechanism can help explain the time to technology use". They also

support the case that customers need to know about a technology before electing to use it. These authors' work and our own 25 years of experience working with OEMs, was used to formulate what are, in our opinion, three important guidelines for new product acceptance:

To accept a new technology, one must first learn of its existence. This seems trivial, but it is a major problem for power electronics converters as this technology is not visible. It is almost always hidden inside the product and its function is not publicized. Most people use some power electronics without knowing it. Here are some suggestions to promote the use of power electronics converters to OEMs:

- a) Organize events to inform people about converters, either in related technical publications, at "their" conventions, through publicity, or through word of mouth;
- b) Have presentations in a language that mechanical or process-trained designers understand. This includes the language itself as well as the technical jargon used. Documents should not be written by electrical engineers for electrical engineers as they often are;
- c) Overcome the cultural barriers and bypass their "interest filters" since people prefer to use technologies from their own field of expertise to solve problems: turn power electronics converters into one of their tools.

To be motivated, the designers must realize the usefulness of the technology from examples or descriptions of its use in their field of interest. They must perceive an advantage to compensate for the effort needed to learn how to use it. The designer's motivation can be increased by providing instant gratification. The product must reward them immediately, showing quick results instead of having to work on it for months before running the first tests. Supplying working demonstrators is a way to achieve this.

The technology must be available to the OEMs in a form that they can use. Most people shy away from technologies that are too difficult to use. The difficulty can come from its

complexity but also from having to justify a high development cost or a long lead time for the project.

These guidelines are seldom followed by power electronics (PE) manufacturers. Their presentations of power converters capabilities are usually tailored to the electrical engineering community. This is because most of the PE manufacturers are still operating under the belief that their equipment must be customized by their own power electronics engineers for each application. This is likely to be true once a solution has been tested and needs to be optimized, but the PE manufacturers never get to this point if the potential user doesn't buy it. The result is that power electronics converters application knowledge is not transferred to the people that are often specialized in mechanical technology or chemical processes. They do not see how power electronics technology can be used in their application to solve their problems.

1.2 Communicating with people of different technical backgrounds

The following section presents more details on ways to simplify the concepts of power electronics and to make them accessible to most designers. This process begins with learning how to communicate the general concepts, and is followed by methods to simplify the use of this technology to make it accessible to the intended audience.

1.2.1 The technical language barrier

Education professionals have confronted the technical language barrier for centuries. They found that education of individuals is more than just telling them about something. In their book "Telling Ain't Training", (Stolovitch et al., 2002) tell us that the information that we acquire is rarely turned into knowledge unless we already have similar concepts to relate to in our mind. In the most common learning process in adults, the links formed by new concepts in our memory need to be anchored to already-existing memories in order to be processed.

This makes it very difficult for people with different backgrounds to educate each other as they are lacking common memories or ideas. The words and concepts used by the communicator (teacher) must be carefully chosen to trigger connections with the learner's memories. This implies that to educate and motivate people to use power electronics converters in their work, the converters must be described using terms and examples commonly used by mechanical and chemical engineers instead of the typical electronics jargon that we use every day.

As scientists, we take comfort in believing that since mathematics is a universal language, we can use it to communicate effectively with all our peers. Unfortunately, effective communication, even amongst technical people, requires more than exchanging equations and numerical results. Even when we agree on a specific communication language (such as English), every specialty has its own lexicon to express concepts that use the same mathematics. An example of this is a sinusoidal oscillation. The mechanical engineer will call it a vibration and use terms like inertia, spring constant, viscous dampener and Newton's second law of motion, as shown in Equation 1.1.

$$m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + kx = F_o \cos(\omega t + \phi_d) \quad (1.1)$$

To represent a similar concept, electrical engineers use inductance, capacitance, and resistance, that may be expressed as shown in Equation 1.2.

$$\frac{d^2I}{dt^2} + \frac{R}{L} \frac{dI}{dt} + \frac{I}{LC} = \omega V_o \frac{I}{L} \cos(\omega t + \phi) \quad (1.2)$$

When the two engineers talk about oscillation, they have difficulty understanding each other simply because they use different mental images and terms to express the same basic concepts. This means that some education about the other's "language" is needed to bridge the gap and to facilitate the understanding of power electronics converters by more people.

1.2.2 Generating interest

Another important education concept is given in “Building EXPERTISE, cognitive methods for training and performance improvement” (Clark, 2008). The author provides many techniques to facilitate the transfer of knowledge from one party to the other. Chapter 16 is particularly useful to this work. It contains valuable tips on how to motivate the learner. The main task is to find ways to make the abstract concepts of power electronics attractive to those who are passionate about challenges from other fields. In other words, our subject must be adapted to the target audience.

1.3 The technical innovation

The innovation presented here is not as much a way to educate the community of product and process designers (OEMs) but a way of developing power electronics that can be used by the OEMs’ staff, and presenting it to them. It is easier to train a few power electronics engineers to use terms and concepts familiar to an OEM designer than it is to train tens of thousands of OEM designers to understand the details of power electronics. It is especially true that in this case, the power electronics engineers (us) are the ones trying to convince the OEM designers that our technology is beneficial to their work.

The innovation is therefore making power electronics accessible to “the others”. While it is new to our field, a similar revolution has already taken place in the computer industry. In the early years (1940-60’s), someone basically needed a PhD in electronics or computer science in order to use a computer. Today, five-year-old (and even younger children) can do amazing things on a tablet. This wasn’t achieved by providing advanced training to toddlers, but by making computers simpler to use. Can this be repeated? Let’s see what our power electronics experts are doing to make our field more accessible to the masses.

The IEEE Industry Applications Society (IAS) had a whole conference on this subject in 2004 in Italy (reference?). As always, many papers were presented and expert wisdom was shared. Blaabjerg et al. in their paper “The Future of Electronic Power Processing and Conversion” (2005) described how the field evolved over the years and where it was expected to go. One of their points was that the demand was not so much for basic products and components but for whole systems solving complete problems. People didn’t want IGBT modules, inductors, and drivers; they wanted a whole battery charger that only needed to be plugged in the wall. This expert panel also foresaw a large demand for energy related applications and expected that many practical applications would develop over the next 25-30 years. Since the conference was held ten years ago, we can confirm that they were right and we are just at the beginning of the revolution. Many real applications are presently operating in solar, wind energy and electric vehicles. They also predicted a proliferation of standardized power supplies. This is yet to be seen on a general level, but it is true for the computer industry. You can now re-charge your telephone or tablet with any USB charger found lying around the house. It looks like the world is waiting for something similar in other applications. Finally, they predicted the use of intelligent controls to facilitate energy management. This too is not yet widely available for real life applications, but it is being worked on.

Our own industrial experience corroborates the opinion of these researchers, motivating our effort to develop a power electronics solution as complete as possible, using a familiar interface for its operation.

1.4 The standard route

Once the designers’ interface and needs are understood, the next step is to define what solution can solve as many problems as possible. A few researchers have published high level analyses of power converter topologies applicable to the most popular applications. Chakraborty and his colleagues (2009) provided an interesting analysis. They tell us that “[t]he integrated power electronics module (IPEM) based back-to-back converter topologies are found to be the most

suitable interfaces that can operate with different DE [Distributed Energy] systems with small or no modifications” (page reference). This is important as they identified a flexible architecture that reinforces the IPEM concepts developed by many other researchers over the years. Like others before them, they also point out that a standardized interface, not only between the building blocks but with the users, is needed and challenges the IEEE to continue to work on it. They point out that “The concept of power electronics building blocks (PEBBs) provides a way to hardware standardization of power electronics systems” (page reference). Finally, they confirm that the standardisation of the interface between the different modules, both hardware and software, is a real challenge.

Their conclusion is valid but not likely to be implemented anytime soon. This opinion is based on my own understanding of the power electronics manufacturers’ mentality. This may not apply to all of them, but working for a few different manufacturers and having done business with many others over the years helped develop this opinion. While some manufacturers have tried standardizing their interfaces, it has not been a widespread commercial success. The reason is found in the laws of the market. Manufacturers need to differentiate their products from the competition. In our field, the main product differentiators are price and functionalities, as aesthetics rarely influence our customer’s decisions. Once the IPEMs are perfectly standardized, product manufacturers can only compete on price, since they all perform the same function. This pressure on price reduction limits innovation because an easy way to reduce the cost of an item is to stop investing in improvements. An argument can be made that they could innovate by implementing module technologies with reduced cost. That is true, but it is very limited if a strict standard is kept. Let’s take as an example different manufacturers building DC-DC converter to meet a standard specification for electric vehicles. It needs to convert 400VDC to 24VDC for accessories. If manufacturer “A” uses IGBT switching at 50kHz while manufacturer “B” uses SIC MOSFETs switching at 5MHz, are the two converters meeting the same standard? They perform the same function but their size or weight may be different because of the smaller magnetics from manufacturer “B”. The two converters are not likely to have the same power losses and their EMI emissions are likely to

be different. Therefore, to switch between “A” and “B”, the car manufacturer may need to adapt the mounting of the module, its cooling requirements, and re-do the EMI testing.

This example is an over-simplification as to why many have tried to define a standard but few have succeeded commercially. A noteworthy exception is the case size for some DC-DC converters such as “half brick, quarter brick”, but even in this case, the electrical specifications can vary from one manufacturer to another. Technology advances so fast that standards are often obsolete by the time they come out. In the past, when standardizations took hold, it usually resulted in the elimination of many players as the price goes down. This was then followed by the virtual abandonment of the standard as higher performances were established by products not restricted by the old standard.

A major disadvantage of using standards is that they are based on compromises. This means that you don’t get the best performance but an average product. In his paper on standardisation, (Uusitalo, 2011) tells us that standards are difficult and risky. They cannot be applied to all subjects and standard failures are costly. Successful standards tend to be applied at higher application levels, leaving flexibility for the manufacturers to differentiate themselves with functionalities and performance. The USB port on computers is a good example where the interface is standardized but the implementation of the device connecting to it is extremely flexible. While their operation and functions are similar, many different sizes and types of memory sticks and accessories can use the USB port.

1.5 The manufacturers’ building block route

The trend we are witnessing in the industry is that more and more component manufacturers are offering their products in building blocks instead of in basic component form. This is seen for sensors, controllers, and power semiconductors. While the interface between these building blocks is not standardized at the industry level, each component manufacturer tries to simplify its own interface and keep it consistent over their product range, and often across generations.

This greatly facilitates the task for their customers (the end-product designers) who don't need to completely re-design their product each time the component manufacturer makes an improvement.

Using this building block technique, each end-product designer must choose a group of blocks that are best suited to their product needs. This usually "lock them up" to specific manufacturers as alternate sources are seldom available. This disadvantage is compensated by the relative ease of integration of the blocks, freeing more time to concentrate on the end-product and its application. Here are a few examples of these blocks:

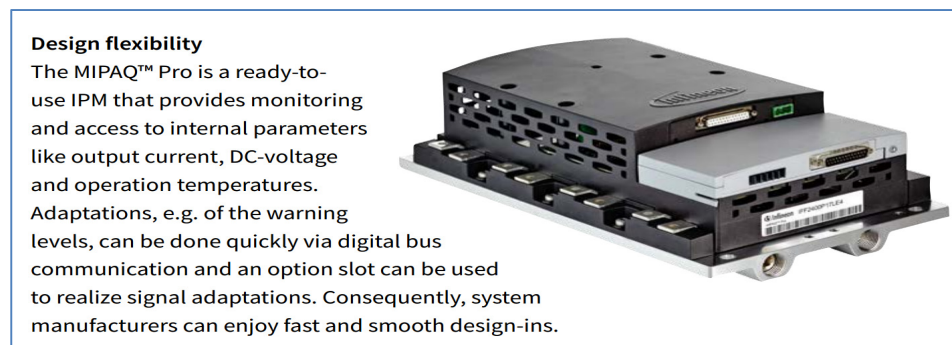


Figure 1.1 Infineon's complete IGBT bridge simply needs a capacitor bank, a controller, some inductors, and auxiliary components

Taken from <https://www.infineon.com/cms/en/product/power/igbt/igbt-stack/channel.html?channel=ff80808112ab681d0112ab6a454b047c>

(December 2016)

Figure 1.2 is another example of building block intended to facilitate the design process. Simply add the power semiconductors, the magnetics, auxiliary components, and the software.

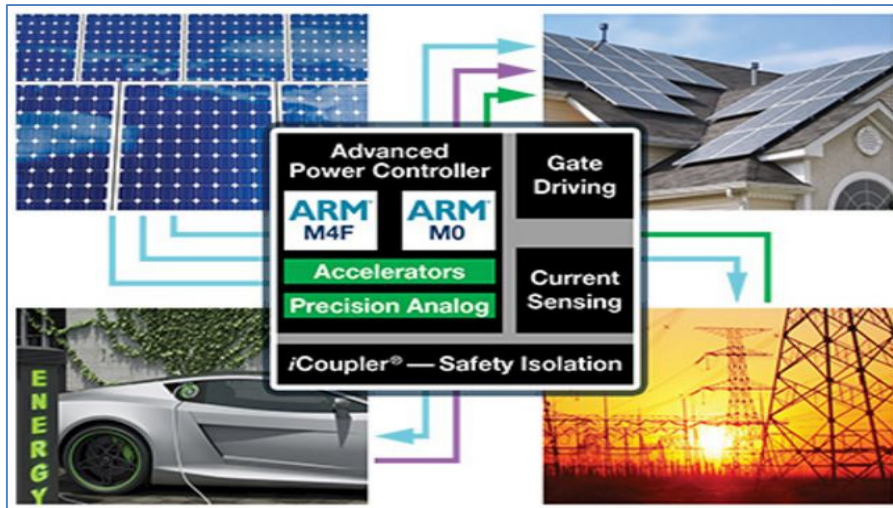


Figure 1.2 Analog Devices' ADSP-CM41x Mixed-Signal Control Processors
 Taken from www.analog.com/en/products/landing-pages/001/adsp-cm41x-product-family.html (December 2016)

One can conclude that the partial standardisation of building blocks has facilitated the task of the end-product designer. Unfortunately, we are still far from a complete power converter solution that can be purchased by an OEM to be used in a new machine design. To use these blocks, one needs specific power electronics know-how. The OEM must still rely on a power electronics converter manufacturer to integrate the building blocks, magnetics, and controls, in an enclosure suitable for their application.

CHAPTER 2

IDENTIFYING THE NEEDS

2.1 Hypothesis for product development

Researchers have explored the power electronics design complexity issues and developed partial solutions based on standard modules such as the PEEBs and its commercial analog, the intelligent power module (IPM). These modules greatly facilitate the design of power electronics converters but are far from being a complete solution that could be used by an OEM. One must still be a power electronics expert to produce a complete system. One must add special inductors, capacitor banks, heatsinks, current and voltage sensors, EMI filters, some form of digital controller with an interface, and program the whole thing with specialized control techniques. In short, a power electronics expert is needed to complete it.

Most power converter manufacturers offer semi-completed converters and promote them to the OEM community. They usually have moderate success with the concept, which indicates that they aren't completely meeting the market requirements. Their advertisements show that they are still geared toward an intense customization of their design before an OEM can use it. This means that the OEMs must disclose a fair amount of details about the application's intellectual property (IP), pay for prototype development, and wait months before trying it in their process. Additionally, the OEMs take on the high technical risks of using newly developed equipment that come with their own set of bugs, hampering the development of their application.

As presented in the previous sections, OEMs need a complete power electronics converter that can easily be scaled to various application sizes and meet different applications. To maximize flexibility, most of the functionalities should be implemented in the software. The reference software provided with the product should be easily adaptable by the OEMs to meet their

specific needs. A few software examples are needed to help the OEMs' staff to progress rapidly and get the early success needed as discussed in detail in Section 2.4, item C.

While a general power converter may not be optimal for the specific application, it is meant to be easy to use by a professional concerned about evaluating how power electronics can solve their immediate mechanical or chemical process issue. Once the OEM's developer is satisfied with the results, they will be motivated to invest in the optimization of the power converter for their specific needs.

Based on the OEM's needs and the above discussion, we have narrowed our development down to five high level design objectives. They will be discussed in more detail in the following sections.

- A. The products must be complete systems fulfilling all the power conversion needs of the OEM;
- B. The power electronics solution must be accessible, presented with terms and concepts understood by the OEM's staff who are not trained in electronics;
- C. The products must provide instant gratification: use the "plug and play" philosophy;
- D. The converter topologies should be suitable for the applications;
- E. The product must be reliable with protection against misuse.

These points are discussed in more detail in the following page.

2.2 What does a complete power converter solution include? (Item A)

A complete power converter solution should include at least the following:

- The application software or at least some examples that can be modified;
- A processor board that interfaces with the power electronics;
- Some means of user interface, such as keypad and display;
- An auxiliary power source as needed to operate the system;
- A cooling system, or at least a simple interconnection;
- The power electronics converter;
- Protection for the personnel and the equipment;
- All the fuses, contactors, inductors, transformers;
- An enclosure.

2.3 How to produce an accessible presentation of the product? (Item B)

For the power electronics solution to be accessible, it must be presented using terms and concepts understood by an OEM's designer that is not trained in electronics. The application documentation needs to be written by somebody who understands those fields to use terms of that trade. Similarly, the user manual needs to be understood by a non-expert in power electronics. Jargon relating to electronics is to be avoided or at least minimized. A separate maintenance manual or a section of the user manual can be produced with more electronic jargon intended for people trained in electronics. A good example of this is the user manual produced by car manufacturers. It simplifies the operation of an extremely complex machine to make it accessible to most people. The computer industry is an extreme example of this as the user manual has been simplified to a few pages, informing the user mostly about safety and how to start the equipment. The rest of the operation is arguably "intuitive" or learned using the built-in help pointers.

2.4 How to provide instant gratification? (Item C)

Use the “plug and play” philosophy. One should only need to provide power to the equipment to see it come to life. Built-in protections should ensure a safe operation even in an incomplete system. This means that the operator interface comes to life but the power is not applied to the output until a valid load is detected. This way, the user is encouraged to continue its effort and can get familiarized with the product even if the whole application is not yet ready.

2.5 Which converter topology is suitable for many applications? (Item D)

While many power converter topologies exist, our initial market is for large applications in the tens to hundreds of kW. These are mostly operated from three phase supplies. In agreement with many researchers as presented by (Chakraborty, Kramer et Kroposki, 2009), we have also found the back-to-back converter topology to be suitable for the applications we intend to service. The decoupling provided by the DC bus gives more flexibility by allowing a semi-independent operation between the input and output. This leads to simpler control strategies than seen on tightly coupled topologies, such as single stage matrix converters. In a back-to-back converter topology, the active rectifier section is controlled independently from the inverter section. When properly sized, the DC bus absorbs most of the line or load imbalances, harmonics, and transients experienced by most converters. Of course, the power balance needs to be controlled to maintain the DC bus voltage but this can be achieved using a PI controller.

Another problem of the single stage matrix converter is that the filtering of the load ripple is done on the AC side where the filter is exposed to the line AC. It is therefore difficult to have a large filter because it will affect the line and will be subject to resonance. While one can design this filter to be stable with the controller, nobody can guarantee its operation in a real application. This is because many plants have multiple harmonic sources that inter-modulate and include variable parallel resonances that are outside the control of our converter. The *IEEE-519-2014 Recommended Practices and Requirements for Harmonic Control in*

Electrical Power Systems is a comprehensive document guiding engineers and setting acceptable harmonic levels. One look at this document gives a good idea of the complexity of the task.

Finally, the double stage AC/DC/AC converter isolated by a large capacitor bank is better suited when the load ripple is large, such as for a single-phase load or a high turn-down chopper. The DC bus filters out most of the ripple and helps maintain the feeding line power quality.

2.6 How to implement a reliable product with suitable protections? (Item E)

Designing a reliable product is not a question of chance. One must start with a good circuit and select the right components. If ample safety margins are built-in, one should expect a reliable operation as discussed in Section 3.10. At least, that is how it used to be. Today's products rely heavily on software that comes from libraries maintained by other entities. It becomes very important to re-test the product after each compilation as "updated" libraries may produce unwanted behaviors.

Protections are extremely important aspects for power converters. One must think about personal protection as much as equipment protection. The level of energy handled by power electronics make them potentially dangerous. One must therefore follow the applicable safety regulations during prototype work, as well as during final product development, as discussed in Sections 3.14 and 3.15.

In conclusion, developing a new power converter begins with an identification of the users' and applications' needs, otherwise the converter is not likely to have commercial success. This chapter supported the case that power electronics is complex and its usage must be simplified to gain market acceptance. One way the manufacturers implement this simplification is

through the development of pre-designed modules containing ever-increasing functionalities. The other way is through standardisation. We argued that the modular approach facilitates the task of the power electronic designers but is still too complex for the end users. Similarly, some standardisation is useful but may limit innovation. This led us to formulate five high level design objectives for the power electronics engineer intending to design converters adapted to the end users.

CHAPTER 3

ONE STEP CLOSER TO THE COMPLETE SOLUTION

As described previously, power electronics applications are usually associated with improving energy efficiency of machinery and industrial processes as well as enabling cleaner processes than those traditionally used in industrial applications. Major examples are hybrid and electric cars reducing CO₂ emissions, and electro-chemistry eliminating or replacing carcinogenic chemicals with less toxic ones. Given this performance, one would expect that potential users would rush to find ways to include power electronics into their technologies but it is rarely the case. I observed this lack of interest during our thirty years of work in the industry. A possible explanation is that power electronics is misunderstood by those in the branches of science and engineering who develop machines and processes. Unfortunately, electrical engineers seem to reinforce this by using specialized lingo whenever possible.

To circumvent these difficulties, this work proposes that electrical engineers should use ideas and concepts in their communication that relate to the language of people from other fields. Another facilitator is to design complete power converter packages that can be used with minimal knowledge of how it is made as opposed to the modules commonly available on the market. These converter packages should be made as user friendly as possible by including an easy to use interface and be self-protecting against most misuse. This chapter presents some solutions to the above problems. It will be followed by a discussion of the software and hardware functionalities in the next two chapters. Later, chapter 5 will briefly cover the I-Pack™ that gets close to the optimal complete solution and chapter 6 will present a large application for our power electronics converters as power supplies for ozone generators.

3.1.1 Designing for industrial applications

At Imalog, the main applications were for large power supply units (PSUs) used in the ozone generation industry. Reliability and ease of maintenance are paramount for an equipment that has a useful life of twenty years. We had to come up with a proven topology that meets the requirements of high power quality on the line side. Simultaneously, performant control of the power to the ozone generator is needed. The generator is a non-linear load that requires specific control strategies and protections. All of this is needed while meeting industrial safety requirements at a competitive price.

Based on these considerations, we chose to begin our work with an AC/DC active rectifier followed by a DC/AC inverter. This configuration is often called a back-to-back converter. The voltage DC bus is fitted with a generous capacitor bank to filter the high ripple current produced by the single-phase load. This also decouples the two IGBT bridges, preventing the inverter's harmonics from reaching the supply line. We could have chosen an AC/DC buck rectifier or an exotic matrix converter, but the back-to-back converter topology is well understood in the industry and has been shown to be reliable for the hundreds of N-PSUs that Imalog has produced since 2001. Past references are very important for an industrial equipment manufacturer. Therefore, the chosen topology is conservative. The innovation is in the implementation and added functionalities.

The active rectifier is a typical three phase, six IGBT bridge and the inverter uses a single phase, four IGBT, H-bridge configuration. Both bridges are two levels, four quadrants hard commutated, from a voltage controlled DC bus as shown on figure 3.1.

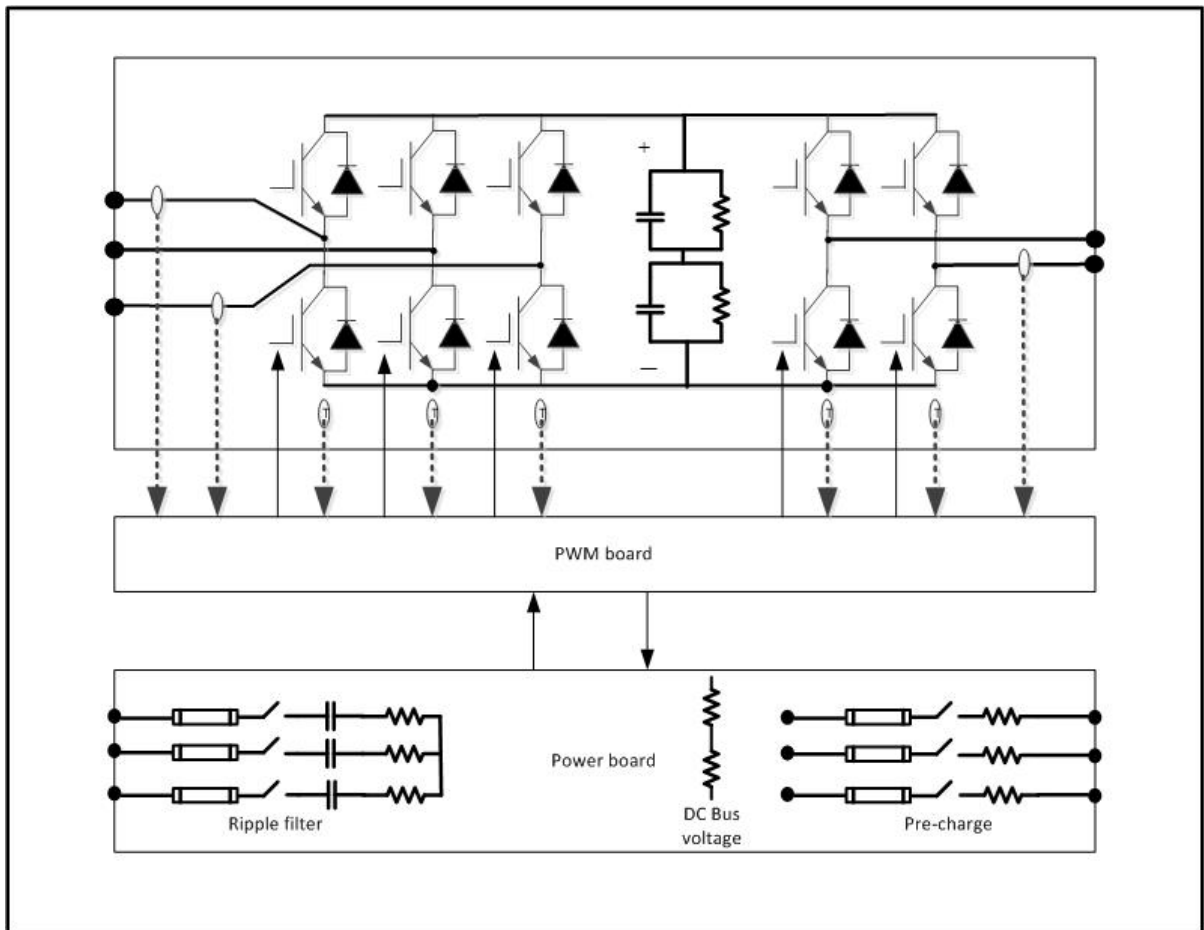


Figure 3.1 AC/DC/AC power converter schematic. (Top half) The six pulses IGBT rectifier (left) is followed by a capacitor bank (middle) and then a single-phase H bridge inverter (right). The control electronics and auxiliary functions are shown in the bottom section.

We decided to integrate the active rectifier and the inverter on the same converter assembly for cost reduction reasons. In the main applications we are targeting, the two IGBT bridges are needed. A convenient way to reduce the cost was to minimize the redundancy of components we would have had with two independent assemblies. The savings are:

The heatsink does not double in cost even when we increase its length by 60% to accommodate more IGBTs. It also cuts the water piping connections in half;

There are savings on the electronic boards as common sections such as the power supplies can be shared.

The interconnection of the two DC buses is also simplified by using continuous busbars. It minimizes the parasitic inductance introduced between the IGBT bridges;

One enclosure is also less expensive than two smaller ones.

3.2 Converter capacity consideration

The following section explains why Imalog chose to design a 200kW power converter. Other designers working on different applications are likely to come up with other power capacity, but here are a few of the reasons for this choice:

Most importantly, we had an application for it. The ozone generator power supply unit application will be discussed in chapter 6. This converter size allowed us to cover a range between 100 kW and 2.4 MW using repeats of the same components and magnetic design. To go above 200 kW, we simply placed multiple complete converters in parallel;

A 200kW design is in the range of many of the other industrial applications that are being investigated by process researchers as discussed at the beginning of this document. This converter needs to prove the viability of the design in the intended power range of the applications;

A small prototype is not usually representative of the larger version. Power electronics doesn't scale up very well. Many of the parasitic elements such as leakage inductance grow rapidly with power. Control strategies are also affected by the equipment size. With today's components, one can easily design a 10 kW hard-switched converter switching at 50 kHz but it is almost impossible, or at least very expensive, to switch at this frequency for 200 kW or

more. The reduced frequency possible at high power greatly reduces the speed of response of the control loops and affects the performance that can be obtained with a given controller. The common industrial strategy of starting with a small prototype and up-sizing it later is riskier as design parameters that were negligible or easy to solve in a small system can lead to technological impasses on larger systems. This means that the scaled-up controller is not likely to respond the same way as the smaller experimental unit. This may become a problem when the OEM that tested their processes on the small converters wants to use the same control strategy in a full-scale plant. The large converters are likely to be too slow, leading to control issues and delays, and even to a failure of the project;

While scaling up is risky, scaling down is relatively easy. If a 200kW unit is too large for product evaluation by OEMs, one can easily downsize the transistors, current sensors, capacitors, and inductors to produce smaller test units. It may not be optimized for size or cost but it will work in a manner that is representative of the large converter. That non-ideal converter would probably be acceptable for a test unit. Once a pre-production converter is needed, the OEM can invest in the packaging and reducing the unit cost;

This power level is in the comfortable range for an active front-end converter application. Semiconductor manufacturers perform extensive studies to define the size that fits most industrial needs. It is easy to consult their product line for the semiconductors available. The same consultation can be done for major components such as line inductors. We searched for the largest components that would perform properly when hard-switching between ten to twenty kHz. As of 2011, when this project was started, the components became difficult to procure and the switching losses increased rapidly when going above 200 kW. Doing the same evaluation in 2016, we would probably double, if not triple, the comfortable power range. We had anticipated this progression but needed to work on a product in 2011, versus waiting until better components were available. Time to market is very important in the industrial world.

3.3 Converter physical size consideration

Industrial equipment is usually relatively bulky compared to their consumer or aerospace equivalent. This section will explain why. Even if some researchers obtained 12kW/l (Kolar et al., 2007) for their compact converter, these extreme designs rely on specialized components and extensive design efforts more suited to aerospace applications. Compact designs also go against the ease of maintenance philosophy that we are upholding for industrial applications. When components are buried under multiple layers of circuitry, it becomes very difficult to troubleshoot them.

While Imalog's new converter design uses forty percent less space than the preceding generation of N-PSU, it still features a low power density of 0.2 kW/l (figure 3.2). This is relatively compact for industrial users accustomed to much more weight and bulk. Industrial users generally do not like equipment so compact that they are difficult to maintain. A good example of this is that in an industrial control panel, the compact PLC electrical connections are wired to larger terminals resulting in an electrical panel ten to 20 times the size of the PLC where the signals come from (figure 3.3). This spreading of the connections is mainly to make it easier for the plant personnel to connect to the equipment and troubleshoot the system. In these applications, compactness is not appreciated. An industrial plant is usually a rough place with large machinery manned by strong guys (and women) used to handling big tools. They don't like the flimsy electronic stuff; it is too fragile. Industrial product designers must face this reality if they want their product to last.

The ergonomics of producing the power converter was also considered. The largest component is kept under 36 kg. This weight can be handled with a simple lifting aid (Liberty Mutual, 2016). Even with the limited component sizes, this power converter is not intended for portable applications. Typically, it is installed in a plant and is expected to operate for at least twenty years with minimal maintenance. The I-Pack™ is shown in Figure 3.2.

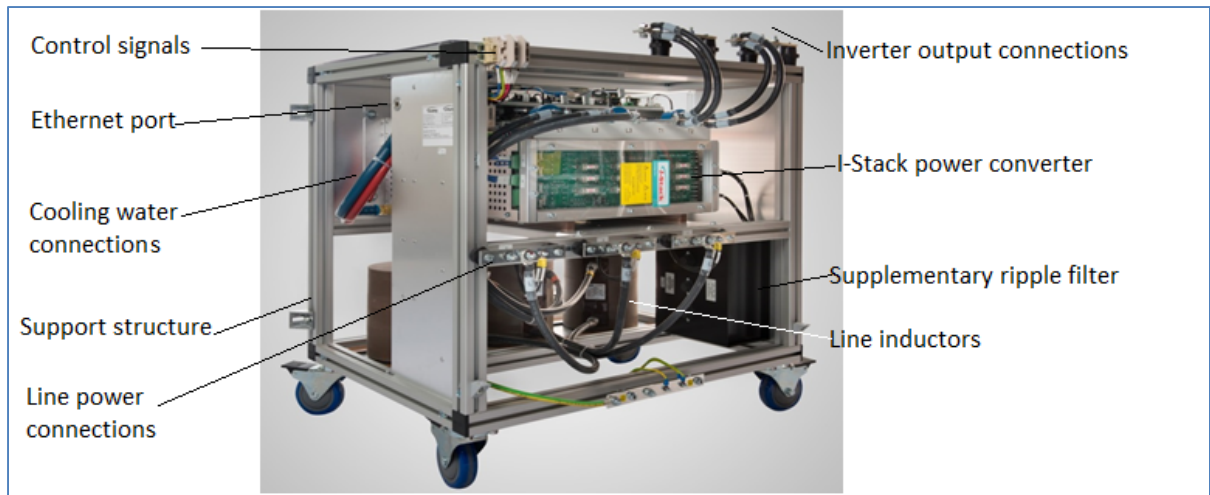


Figure 3.2 Power converter used as an upgrade module for legacy thyristor PSU

Figure 3.3 shows how the electrical connections of a compact PLC are brought out to larger terminals for convenient field wiring and diagnostic.

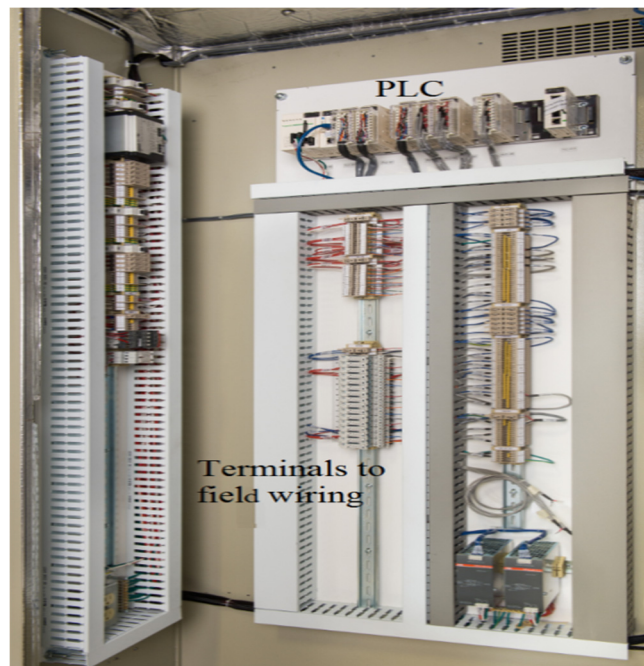


Figure 3.3 Industrial control panel with PLC and field terminals

3.3.1 The active rectifier operation

The three phase AC/DC rectifier is IGBT-based and operates in an AC current controlled mode. The rectifier function is to keep the DC bus charged to about 750V by drawing power from the three-phase line. The PWM processor synchronizes the rectifier to the in-coming line to draw a sinusoidal current. This is done by switching the six IGBTs on/off at around 10kHz. This frequency was chosen to minimize the size of the line inductor while maintaining the switching losses in the range of the conduction losses. Its choice is a design trade-off specific to Imalog's product line. During the switching, the PWM processor constantly recalculates the required duty cycle to track the sinusoidal reference waveform.

Figure 3.4 shows a simulation of the active front-end rectifier, drawing a sinusoidal current from the line when switching at 1 kHz. This lower switching frequency example has been chosen to make the pulses easily visible when explaining the rectifier's operation. We see the line voltage in purple, the rectifier switching in green and the resulting line current in black.

The ripple on the current waveform is the result of the IGBT switching across the line inductors. Higher switching frequency produces lower ripple amplitude but increases the switching losses (Figure 3.5). A higher inductor value can be used to reduce the ripple but its size and cost increase rapidly.

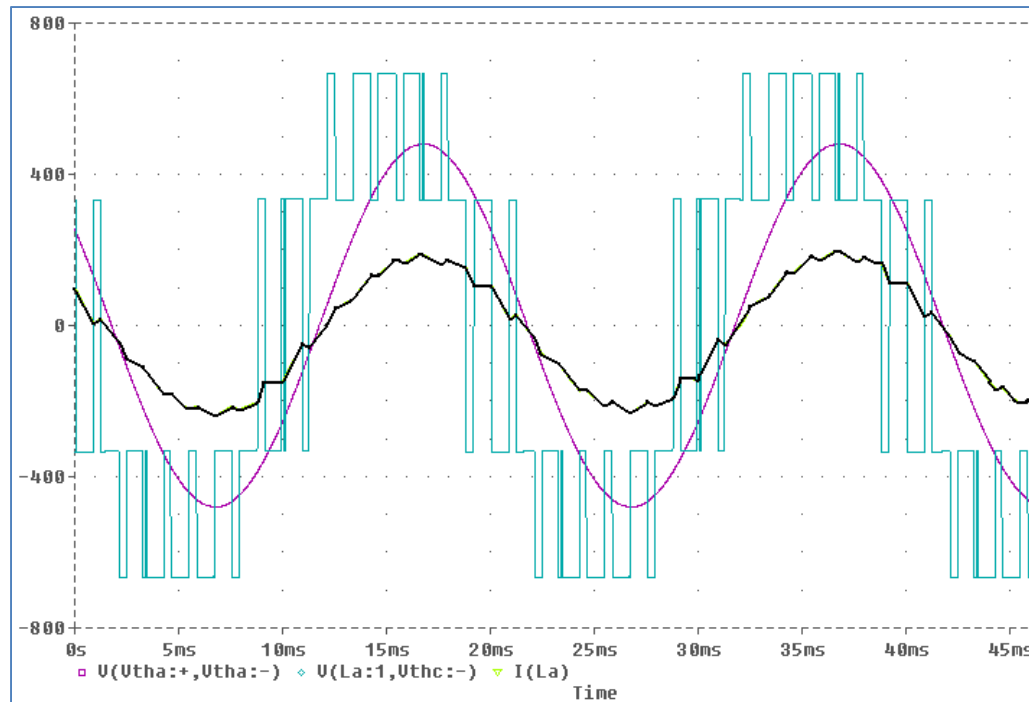


Figure 3.4 Simulation of a rectifier PWM waveforms operating at 1 kHz for illustration purpose

In reality, the rectifier switches at 10 kHz and the actual waveforms captured at the IGBT are shown in Figure 3.5. The line voltage is in blue and the line inductor current is in green. The thickness of the current line is caused by the switching ripple. Most of this ripple current is then absorbed by the ripple LCL filter preventing it from reaching the plant supply. At a switching frequency of 10kHz, the audio noise is mostly outside the audible range. It is rare that the rectifier's audio noise is noticed by the industrial users accustomed to louder equipment.

Figure 3.5 corresponds to the current drawn by the rectifier at a nominal load. The rectifier can operate from 0% to 100% of its capacity. At a lower load (less than 20%), the input current contains a noticeable amount of distortion and the power factor is not as good as one could expect. This is because of the precision limits of the controls. Multiple parameters such as the digitizing resolution errors, a small amount of aliasing from the sampling and controller rate, and some chaotic responses of the closed loop system produce this dance-like response. This

is not a problem since at low power, the harmonic currents generated are very small with respect to the plant feeder capacity keeping the Total Demand Distortion (TDD) well below IEEE limits.

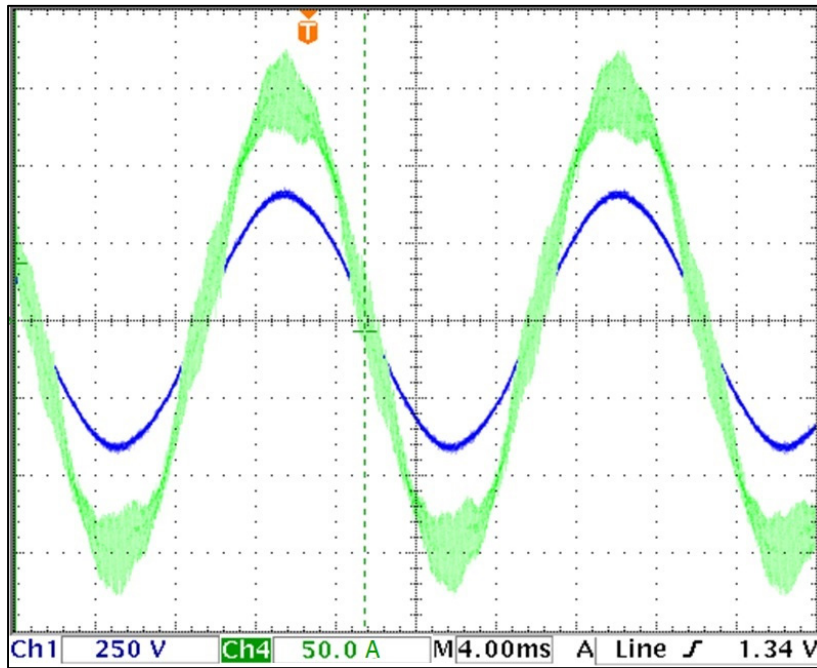


Figure 3.5 Real Rectifier current and voltage waveforms

3.3.2 The inverter operation

The operation mode of the H-bridge inverter depends on the application. It is normally used to supply power to a load or get power from a DC source such as solar panels. A detailed example of applications such as a single phase, AC power supply will be given in the last section of this document. Other examples of its use are:

- As a variable frequency, variable voltage inverter when connected to an AC load;

- It can also be connected to extract power from an AC source such as a windmill or flywheel generator, as it can operate in all four quadrants. The H-Bridge is generally connected to a single phase load but a supplementary connection from the DC bus common can be used to provide the third leg for a three phase application presented by Dzung (Phan Quoc Dzung, 2007);
- The H-bridge can also be used as a pair of independent DC to DC chopper legs to operate in buck or boost mode. This is useful to interface with DC loads such as a plasma torch or a source such as a solar panel. In those applications, each leg can be used to control the current in the corresponding load inductor to meet the objectives.
- Various control strategies can be programmed into its independent controller as will be addressed further in this work. This allows the product designers to load pre-defined examples of control strategies and even adapt them to their specific needs. Chapter 6 will present the details regarding the ozone generator power supply application.

3.3.3 Integrating the rectifier and the inverter in a module, the I-Stack™

The I-Stack™ is the name we gave to this power electronics converter. It holds the two back to back IGBT bridges for the rectifier and the inverter, the heatsink, the DC capacitor bank, the PWM processor board, the power board, and auxiliary control circuits with sensors.

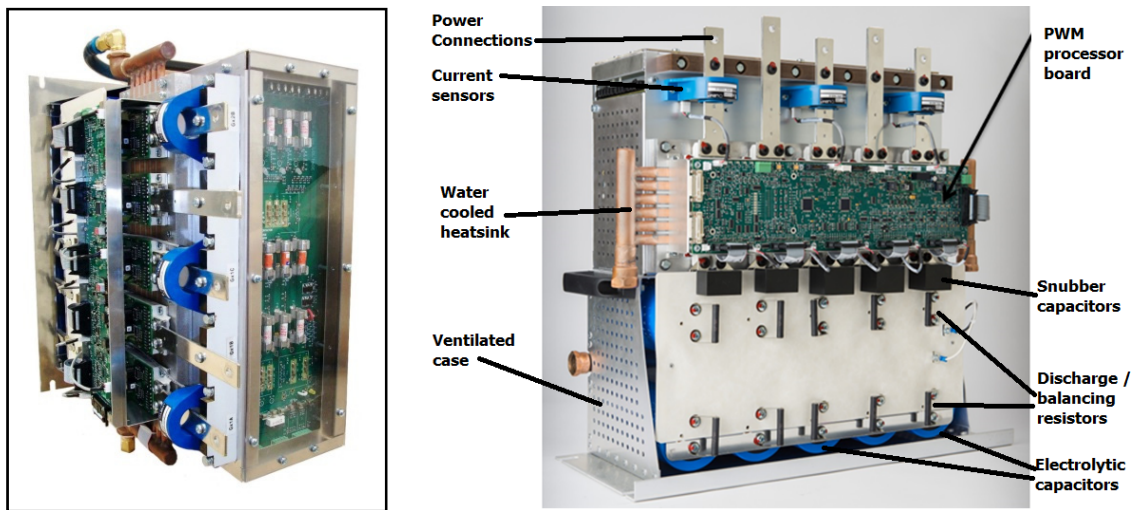


Figure 3.6 Water cooled I-Stack™

The converter assembly uses a grouping of components that minimizes the parasitic elements such as the stray inductance and resistance between the capacitor bank and the IGBTs. This is an important design parameter for the fast switching of large currents with acceptable over-voltages. Minimizing the stray inductances is particularly difficult in larger power converters as the components become large and electrical distances increase. Draining the heat losses away from the semiconductors also adds difficulties. The design of the heatsink also affects the electrical parameters. Placing the IGBTs far apart on a large heatsink would have simplified its thermal design at the expense of increasing the parasitic inductances. This would have raised the over-voltages seen by the IGBTs when switching off. These over-voltages are an important design limit. The heatsink design is presented in detail in the Section 3.5.

In a fast switching converter, it is important to place the gate drivers and PWM processor boards near the IGBTs to reduce the wiring length and noise pickup. This configuration also minimizes the wiring to the current and temperature sensors, which simplifies the assembly. We used a microcontroller for each IGBT bridge to provide enough computing power to run control algorithms implemented in a high-level language. The microcontrollers made by ST Microelectronics (STM32F4 family) are based on an ARM™ core integrated with a wealth of powerful peripherals such as PWM timers, A/D converters with DMA, memory, communication servers and even a DSP core. We wrote a BIOS (basic input output software) in C language to interface the hardware with the application firmware. The microcontrollers generate the switching patterns for the IGBT and implement the feedbacks and protections using the information from multiple current, voltage and temperature sensors per IGBT bridge. The microcontrollers also sequence the DC bus charging and control the cooling blowers using the power relays integrated on the power board mounted inside the I-Stack assembly.

A simplified schematic for the power circuit was presented in Figure 3.1 and its physical implementation shown in Figure 3.6. The power board (behind the Plexiglas™ (Dupont) window) takes care of the DC bus charging, the ripple filtering, the voltage sensing, and the auxiliary supplies protection. The integration of the control fuses on the PCB allows monitoring each fuse to detect and report a failure. This supplementary effort is part of our strategy of self-diagnostic of the product. It motivated us to add many intermediate voltage measurement points to extract information about the status of the assembly. We also integrated a ripple filter in the I-Stack to help reduce the commutation noise emitted in the plant electrical supply. It is not intended to cover the MHz range of an EMI filter but it greatly reduces the noise emitted in the tens to hundreds of kHz that may affect other equipment in the plant. It was not desirable to have a built-in EMI filter as each country has its own limits, forcing the use of different filter designs. The type of installation receiving the power converter also influences the EMI limits. This subject has been treated by many researchers (Colotti, 2006; R. Burkart, 2012) and will not be covered here. Following these limits is important to avoid affecting other equipment sharing the same power feeder as the active front-end power converter.

3.3.4 Component selection for the I-Stack:

Selecting the perfect components for the application is never an easy task. There are dozens of parameters that can be optimized to find the “perfect match” for the application. The amount of time a designer can spend on this task depends on the volume of sales expected for the product. The designers working on a high-volume product will spend countless hours optimizing the cost of each component selected. It is important as every dollar saved will be multiplied by millions of units sold. On the other hand, for low volume industrial products, as is often the case for specialized power electronics converters, components are usually optimized for parameters such as; reliability, ease of assembly, and availability. In low volume production, one can rarely influence the component manufacturers into producing custom components or using highly automated production techniques. Specialized power electronics converter manufacturers use what is available. The engineering effort must be limited as it must be amortized on few units and it affects the final cost drastically. It is often advantageous to select an oversized component instead of spending days optimizing it. This choice is even easier to justify when it improves the product reliability.

3.4 IGBT selection

After defining the power range for the product, we begin the task of selecting the IGBTs. This involves more than the electrical and thermal sizing of the device itself. One must choose the manufacturer of a critical component that has historically been one of the least reliable of the power converter. We chose Infineon’s Econopack™ IGBT module shown in figure 3.7, for its ease of use, especially when combined with the off-the-shelf gate driver board from Power Integrations™. These two manufacturers have proven track records and the devices can also be procured from a second source which is important in case of disturbances in the supply chain.

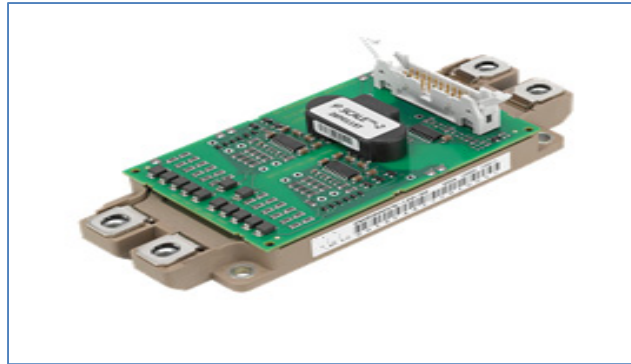


Figure 3.7 IGBT module
Taken from www.infineon.com (December 2016)

The manufacturer's dimensioning tool is available on their web site to aid in selecting the appropriate IGBT capacity. The main criteria for our selection were the low losses, ease of assembly, availability, and price. As presented earlier, our target was to design a three phase, 200kW converter bridge switching at ten kHz. At this power level, the plant supply line is usually between 400V and 480V RMS. This means that the DC bus of the active front-end converter needs to be around 750V to obtain enough margins to control the current effectively. Using a higher DC bus voltage increases the switching losses and reduces the IGBT safety margins needed to resist over-voltage spikes when switching off.

We know from experience that most industrial water cooling sources are available below 30°C. Since the temperature rise commonly accepted¹ for a suitable cold plate is about 20°C (see heatsink design in the next section), one can use 50 °C (30 °C + 20 °C) to evaluate the maximum load and power losses from different IGBT modules. The real-life variation of operating conditions will have some effect on the losses that are evaluated in the manufacturer's IGBT dimensioning tool. This tool can quickly evaluate the losses and the temperature rise for different IGBT module current ratings as shown in figures 3.8 and 3.9. This makes for a rapid selection of an acceptable device.

¹ Rule of thumb based on reasonable heatsink size for an industrial application. Other applications where weight and performances are weighted differently use different values.

IGBT Parameters				IGBT Parameters				IGBT Parameters			
FF600R12ME4C				FF600R12ME4				FF450R12ME4			
$E_{on}+E_{off,125^{\circ}C}$	128.30	mWs		$E_{on}+E_{off,125^{\circ}C}$	155.00	mWs		$E_{on}+E_{off,125^{\circ}C}$	81.30	mWs	
$R_{G,on}$	0.51	Ω		$R_{G,on}$	1.5	Ω		$R_{G,on}$	1.3	Ω	
$R_{G,off}$	0.51	Ω		$R_{G,off}$	1.5	Ω		$R_{G,off}$	1.3	Ω	
R_{thJC}	0.0370	K/W		R_{thJC}	0.0371	K/W		R_{thJC}	0.0660	K/W	
R_{thCH}	0.0350	K/W		R_{thCH}	0.0350	K/W		R_{thCH}	0.0300	K/W	
T_{vjmax}	150	$^{\circ}C$		T_{vjmax}	150	$^{\circ}C$		T_{vjmax}	150	$^{\circ}C$	
Diode Parameters				Diode Parameters				Diode Parameters			
$E_{rec,125^{\circ}C}$	50.50	mWs		$E_{rec,125^{\circ}C}$	44.00	mWs		$E_{rec,125^{\circ}C}$	48.50	mWs	
R_{thJC}	0.0710	K/W		R_{thJC}	0.0650	K/W		R_{thJC}	0.100	K/W	
R_{thCH}	0.0393	K/W		R_{thCH}	0.0390	K/W		R_{thCH}	0.0450	K/W	
T_{vjmax}	150	$^{\circ}C$		T_{vjmax}	150	$^{\circ}C$		T_{vjmax}	150	$^{\circ}C$	
Heatsink Parameters				Heatsink Parameters				Heatsink Parameters			
$T_{Heatsink}$	50	$^{\circ}C$		$T_{Heatsink}$	50	$^{\circ}C$		$T_{Heatsink}$	50	$^{\circ}C$	
Fixed Heatsink Temperature				Fixed Heatsink Temperature				Fixed Heatsink Temperature			
Simulation Results				Simulation Results				Simulation Results			
Junction Temperature				Junction Temperature				Junction Temperature			
IGBT	86	$^{\circ}C$	✓	IGBT	88	$^{\circ}C$	✓	IGBT	103	$^{\circ}C$	✓
FWD	58	$^{\circ}C$	✓	FWD	57	$^{\circ}C$	✓	FWD	60	$^{\circ}C$	✓
Switching Losses				Switching Losses				Switching Losses			
IGBT	63.55	W		IGBT	77.97	W		IGBT	60.13	W	
Diode	22.69	W		Diode	17.99	W		Diode	25.29	W	
Conduction Losses				Conduction Losses				Conduction Losses			
IGBT	372	W		IGBT	373	W		IGBT	447	W	
Diode	38.44	W		Diode	33.91	W		Diode	37.33	W	
Total Losses				Total Losses				Total Losses			
IGBT	436	W		IGBT	451	W		IGBT	507	W	
Diode	61.14	W		Diode	51.90	W		Diode	62.61	W	

Figure 3.8 IPOSIM™ Results for different IGBT modules with a 200kW load

Based on this data, we decided that the IGBTs need is a 1200V, 450A device such as the Infineon FF450R12ME4 to provide enough safety margins for our application. During an over-current event, the over-capacity helps in keeping the IGBT within its safe operating area. Under normal full load operating conditions, its junction temperature will reach 103°C which

leaves enough of a margin for the extreme conditions that are sometimes experienced in the field. These extreme conditions can be:

- Low cooling water flow;
- Mineral deposit accumulation in the heatsink;
- Electrical overloads;
- Higher cooling water temperature.

The oversized IGBT has lower operating losses than the smaller version which also eases the heatsink design. Up to a certain point, a larger IGBT can often reduce the size of the heatsink, compensating for the increase cost of the silicon. This designer trick produces a gain in reliability at little overall cost, and possibly even produces a saving. The literature also directly links the equipment reliability to the thermal cycles and peak operating temperature as described by Huai (Huai, Ke et Blaabjerg, 2012). A smaller IGBT module could have been chosen, but this would have increased the amplitude of the temperature cycle seen by the module each time the load changes, reducing the life span of the product.

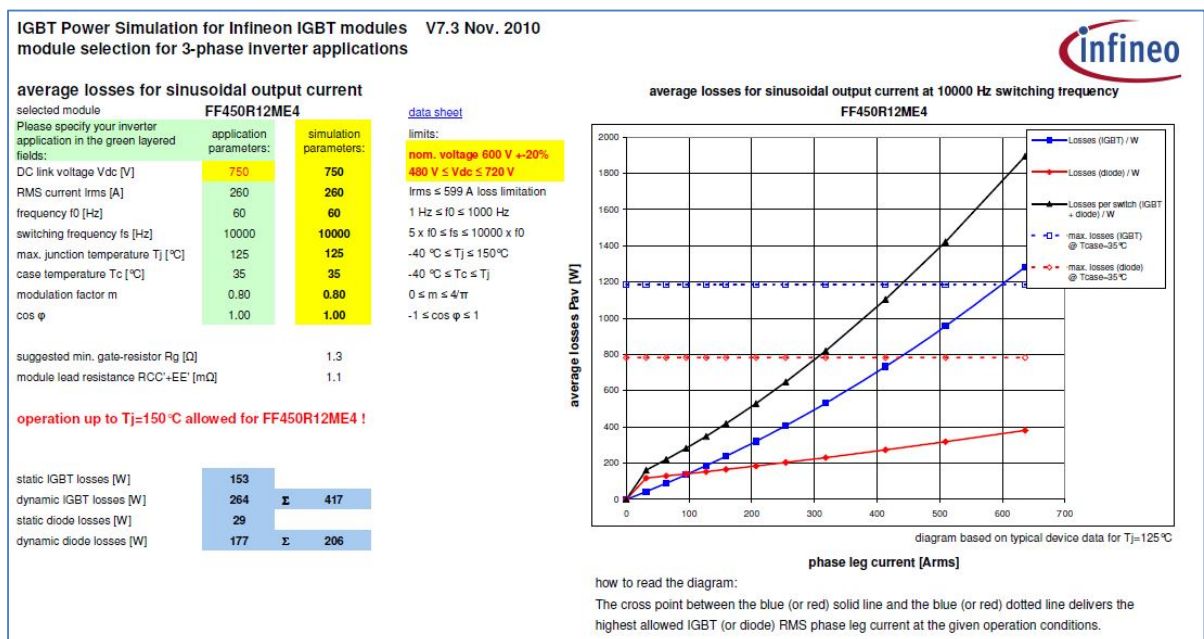


Figure 3.9 IPOSIM™ IGBT losses evaluation sheet

3.5 Heatsink design

Using the power losses and the physical dimensions from the IGBT selection tool, we can look for a suitable heatsink. One of the first questions for most industrial applications is air or water-cooled? The second one is what material should we use? A third is custom or special fabrication? All of these questions become easier to answer when the application is considered, but in case of the I-Stack this is complicated by the fact that it is intended for various applications. It may need the convenience of an air-cooled heatsink when a cooling water source is not available or when the ambient temperature can go below freezing. There are other applications where the cooling water is available and the operating temperature is always above freezing. A water treatment plant is a good example where water is plentiful and freezing temperatures are avoided at all costs. In this case the higher power density resulting from using a water-cooled heatsink is an advantage. The difference is significant as a water-cooled heatsink usually occupies about ten percent of the volume of the equivalent air-cooled heatsink.

This means that the I-Stack needed both cooling media. This constituted an interesting challenge. How can we have similar IGBT assemblies to reduce fabrication costs while using the two cooling methods? The solution was to produce both heatsinks with identically positioned top surfaces so that the IGBTs are always positioned the same way. To fit the available space in the I-Stack, the air-cooled heatsink had to be restricted in size. This meant that the 200kW water-cooled I-Stack had to be de-rated to 80kW when air-cooled. Note that this is with the use of a high performance bounded-fins air-cooled heatsink, the de-rating would have been even more severe with an extrusion. As for the material selection, a quick survey of the manufacturers showed that aluminum was the most cost effective material to use in these large applications. Its machinability and strength allows use of the heatsink as part of the structure of the I-Stack to hold other components. The main problem with aluminium in water-cooled applications is its vulnerability to the water chemistry. Since we cannot easily control

this factor in the applications, we decided to use a hybrid copper-aluminum heatsink for the water-cooled version. The water flows in copper tubing embedded in an aluminum plate. The embedded copper tubing also improves the thermal conduction over the all-aluminum equivalent. See figure 3.19 for a picture of the heatsink assembly. The heatsink manufacturer conducted a simulation of the water-cooled heatsink operating at 200kW presented in figure 3.10. This simulation predicted that the water-cooled heatsink would keep the IGBTs at an acceptable temperature at full load of 200kW. Later prototype testing showed that this simulation was over optimistic. Anti-freeze and anti-corrosion additives used in closed loop cooling water systems degrade the cooling capacity of the heatsink, increasing the IGBT operating temperature. The effect is caused by an increase of the skin effect in the pipes and a lowering of the thermal capacity of the cooling fluid. This is where the conservative design and generous safety margins pay off. Those interested in the effect of cooling additive on the equipment can review this excellent presentation by the Dow chemical company (Connor, 2016).

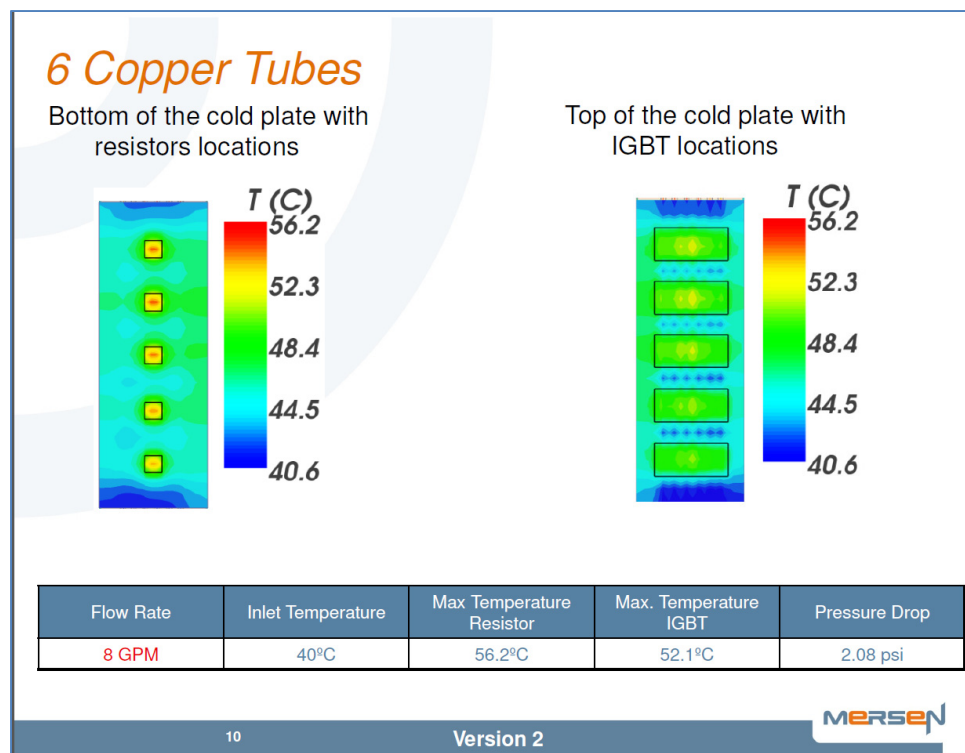


Figure 3.10 Water-cooled heatsink temperature profile simulation at 200kW by Mersen

Water-cooling is not always suitable. An air-cooled version was developed to deliver about half the power in nearly the same converter size by re-arranging the assembly as shown in figure 3.11. The heatsink manufacturer also conducted a simulation of the air-cooled heatsink operating at half the power (100kW) presented in figure 3.12. This simulation predicted that the air-cooled heatsink would keep the IGBTs at an acceptable temperature at full load. The IGBT baseplate is much warmer than for the water-cooled heatsink. This is acceptable as both use the same IGBT package but the air-cooled application operates at half the power and therefore half the losses. This results in a lower ΔT between the IGBT junction and its baseplate temperature. The ΔT was verified using the de same IGBT manufacturer design program.

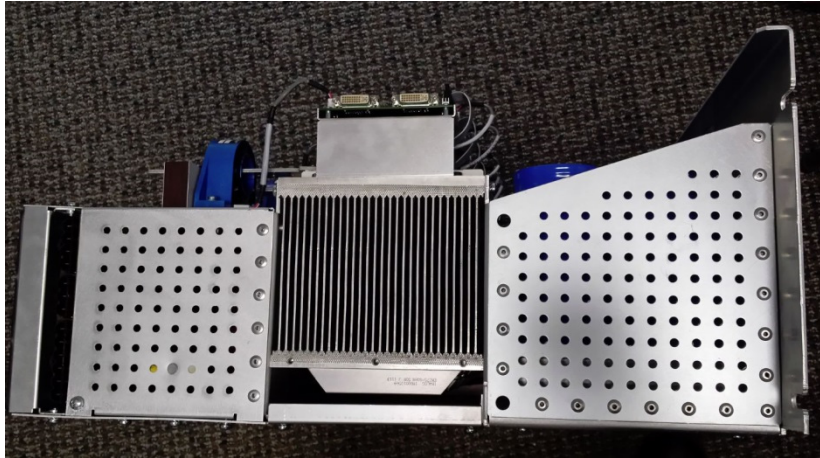


Figure 3.11 I-Stack with air-cooled heatsinks

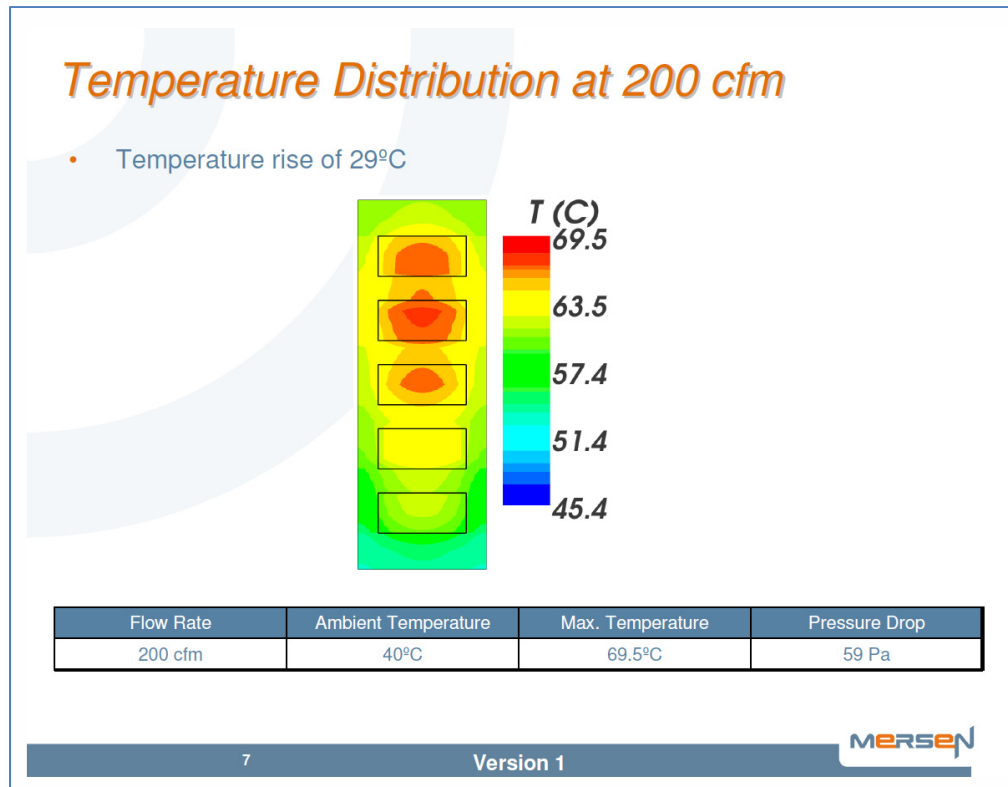


Figure 3.12 Air-cooled heatsink temperature profile simulation by Mersen

3.6 Capacitor bank with DC busbars design

When designing a power converter using a voltage DC bus, one must ensure that enough capacitance is available to maintain the stability. There are many interesting papers describing the evaluation method. A few methods are presented by these authors (Anwar et Teimor, 2002; Kolar, Wolbank et Schrod, 1999; Sam G. Parler). Another factor setting a low limit for the capacitor bank is its capacity to filter the ripple current. Capacitors do fail when they are subjected to ripple currents above their capacity. In the I-Stack, there are two sources for the ripple current, the first one is the three-phase converter and the second one is the single-phase inverter. The maximum ripple current is the sum of these two independent sources.

Once the worst-case ripple current has been calculated for the application, the capacitor technology can be selected. In our case, the conversion of power from one phase to three phases requires a lot of storage capacity since the single-phase power is pulsating. This pulsating power produces a relatively high ripple current in the DC bus. This current is absorbed and released by the capacitors each half cycle. This produces a ripple voltage inversely proportional to the size of the capacitor bank. The ripple voltage of the DC bus should be kept to a low level to prevent inter-modulation between the two IGBT bridges. This is when a large voltage ripple produced by one of the IGBT bridges is applied to the other bridge resulting in unwanted distortion.

The ozone generator application operates at a full load of 1500Hz, 600Apk, 740VDC, $\text{pf} \approx 0.8$ drawing 340A RMS at 200kW from the single-phase inverter. The DC bus average current is $I_{\text{DCave}} = 200\text{kW} / 740\text{VDC} = 270\text{A}$. This current is a “full wave rectified” version of the load current due to the action of the transistors. We can neglect the distortion introduced by the small phase shift of the power factor of 0.8 because it results in high frequency ripple that, according to the manufacturer (Dubilier, 2016), has much less effect on the capacitors’ temperature since the ESR decreases with a frequency up to $\sim 10\text{kHz}$ and increases afterward as shown in figure 3.13.

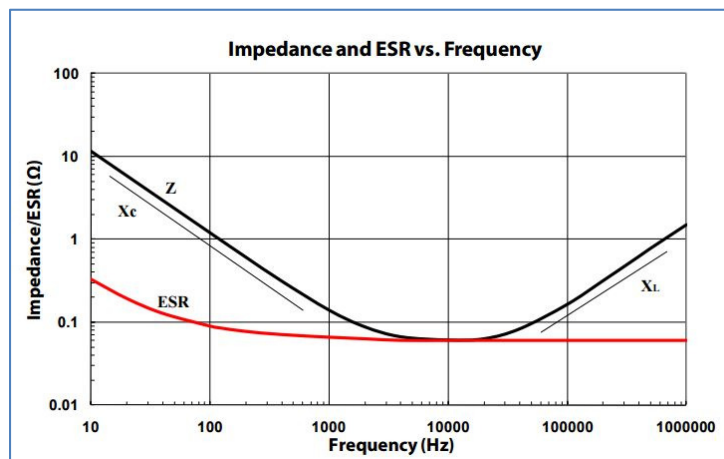


Figure 3.13 Electrolytic capacitor ESR vs frequency

From: <http://www.cde.com/resources/catalogs/AEappGUIDE.pdf>
page 8 (December 2016)

The peak ripple current in the DC bus is 600A at twice the inverter frequency and approximated to a rectified sinewave. Figure 3,16 shows a real waveform for a smaller generator operating at 70kW. The inverter wasn't at its maximum frequency either so the half cycles are not completely merged. At the maximum frequency, the current would be even closer to a sinewave as the load acts as a low-pass filter. To simplify the mathematics, the current waveform can be approximated with a sinewave even if the crest factor is a little higher (1,75 vs 1,41). The DC bus ripple current from the inverter is evaluated from the first few components of the Fourier series for a fully rectified sinewave adapted from Illing(2008):

$$|\sin \omega t| = \frac{2}{\pi} - \frac{4}{\pi} \sum_{n=2,4,6}^{\infty} \frac{\cos(n\omega t)}{n^2 - 1} \quad (3.1)$$

1. The DC component of this equation is $I_{\text{Fourier}} \times 2/\pi = I_{\text{DCave}} = 270\text{A} \Rightarrow I_{\text{Fourier}} = 424\text{A}$;
2. The first ripple component amplitude is: $I_{\text{Fourier}} \times 4/\pi \times 1/3 = 180\text{A}$ pk at 3000Hz;
3. The second and third ripple component amplitudes are 34A at 6000Hz, and 15A at 9000Hz;
4. We don't need more components as their contribution becomes negligible;
5. The RMS value for these sinewaves is then $I_{\text{RMS}} = 1/\sqrt{2} \times \sqrt{(180^2 + 34^2 + 15^2)} = 183\text{A RMS}$;
6. The high frequency ripple current components can all be assigned to 3 kHz to simplify the next calculations since capacitors are more affected by the lower frequencies as can be seen on the datasheet snip shown in figure 3.14. This "error" buys some safety margins to compensate for the components we didn't include.

In the ozone application, the inverter operates at variable frequency by inserting dead time between the pulses. The net result is that the RMS current decreases at lower frequencies. This means that the full power at 1500Hz is the worst-case scenario. Using the capacitor manufacturer's datasheet, a ripple current multiplier of 1.56 can be interpolated at 3 kHz. (The capacitors used in this bank are 450V, 3 1/2" diameter)

Ripple Current Multipliers	Ambient Temperature						
	45 °C	55 °C	65 °C	75 °C	85 °C	95 °C	105 °C
	1.66	1.52	1.37	1.20	1.00	0.75	0.36
	Frequency						
		50 Hz	60 Hz	120 Hz	360 Hz	1 kHz	5 kHz & up

1 3/8" & 2 1/2" Diameters							
200 to 350 V	0.77	0.82	1.00	1.21	1.32	1.37	1.38
400 to 500 V	0.73	0.78	1.00	1.33	1.53	1.66	1.68

3" & 3 1/2" Diameters							
200 to 350 V	0.80	0.85	1.00	1.17	1.24	1.28	1.29
400 to 500 V	0.73	0.79	1.00	1.31	1.51	1.63	1.65

Figure 3.14 Ripple current multiplier for electrolytic capacitors
Taken from Cornell Dublier 550C series datasheet (December 2016)

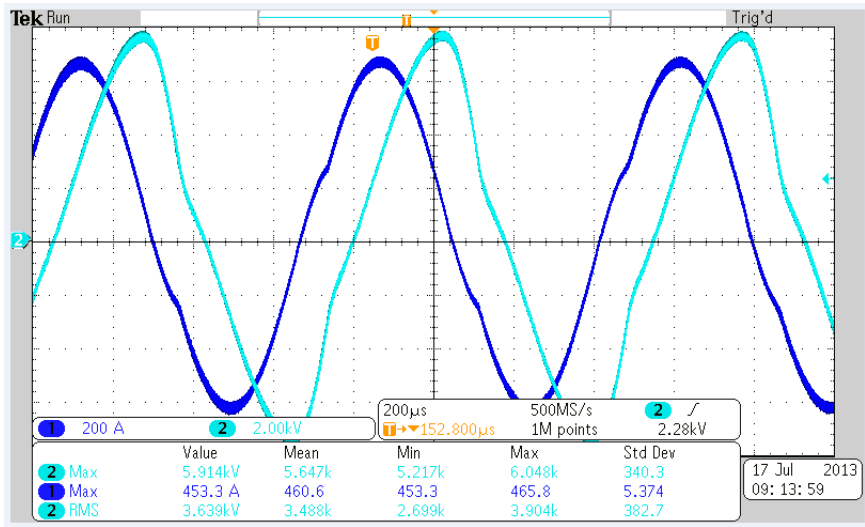


Figure 3.15 Inverter current and voltage waveforms for an ozone application operating at full load.
Trace #1 = Inverter current, trace #2 = load voltage

To keep the voltage ripple within an acceptable 1% of the nominal value (arbitrarily chosen to 1/5 of the IEEE 519 recommendation to be a small contributor to the plant distortion), we need to calculate the capacitive impedance producing less than $740\text{V} * 1\% = 7,5\text{V}$ from the inverter current ripple. The DC bus AC impedance at 3000Hz must be less than $7,5\text{V} / 183\text{A} = 0.04$ Ohms. For a first approximation, we neglect the resistive losses from the ESR for the moment

as we don't know how many capacitors will be used in series and in parallel. For this preliminary calculation, all the impedance amplitude is assigned to the capacitance X_c .

The bank needs at least: $C = 1/(2 \pi * X_c * 3000\text{Hz}) = 1,3\text{e-}3 \text{ F}$ or $1300 \mu\text{F}$.

The implementation of this DC capacitor bank using film capacitors was possible. It would have yielded better ripple current capacity than with electrolytic capacitors but would have been expensive and bulky. This led us to choose a suitable bank of electrolytic capacitors. Since the electrolytic capacitors available from different manufacturers rarely exceed 550V DC, two capacitors are connected in series to meet the voltage rating and ballast resistors are added to balance any difference in their leakage current. These resistors are also necessary for safety reasons. It is common practice to discharge a capacitor bank to a safe level within ten minutes to protect the maintenance technicians. Two 400V capacitors in series could have been used to meet the 740V DC needed for this application, but a better safety margin is obtained by using 450V units. According to the capacitor manufacturer, the higher voltage rating also increases the useful life. It is also a protection if one of the discharge resistors is damaged or if one of the capacitors leaks more than expected, unbalancing the voltage seen by the two capacitors in series.

This capacitor bank is therefore composed of many pairs of capacitors connected in series. All these pairs are then connected in parallel to obtain the desired capacitance value. We also need to take into consideration that the capacitance is reduced with age. Since we aim for a useful life of 20 years, we must add more capacitance as per the manufacturer's evaluation of a loss of 20% over that period (Dublier, 2016).

The switching ripple current generated by the three-phase converter also needs to be considered. While the amplitude depends on the value of the inductor, it is common practice to aim for less than 20% of the maximum line current. Using the 480V line voltage as nominal, the line current is $200\text{kW}/480\text{V}/\text{Sqrt}(3) = 240\text{A RMS}$. The high frequency ripple current is

usually less than $240\text{A} \times 20\% = 48\text{A RMS}$. The ripple current multiplier for the 550C series at 10 kHz is 1.65, which gives us the equivalent heating of 30A at 120Hz.

The converter can also be subject to a current imbalance of up to 10%, producing a 120Hz ripple in the DC bank. Using the same single phase ripple calculations used for the inverter above the first ripple component amplitude is: $240\text{A RMS} \times 10\% \times 4/\pi \times 1/3 = 10\text{A RMS}$ at 120Hz.

To recap, in the worst case, our bank sees the following ripple currents: 30A RMS equivalent at 120 Hz from the converter ripple plus 10A RMS from imbalance plus 183A RMS from the inverter. The vector sum gives $(30^2 + 10^2 + 183^2)^{1/2} = 186\text{A}$. We also need to have more than 1300uF to keep the (capacitive) ripple voltage to an acceptable level. Finally, 20% must be added to compensate for the capacitance losses during the bank's life.

The active front-end converter stability has not been covered in this document but the result from simulations is that at least 10 000uF are needed to ensure a stable operation under extreme conditions. This far exceeds the worst case electrical requirements stated previously and becomes our new minimum value.

From the capacitor datasheet (figure 3.17), we see that the largest capacitor that fits mechanically in our application is a 7100uF unit taken from the Cornell Dublier's robust 550C series. It can handle a RMS current of 34A at 120Hz at 85°C on the case. This is much warmer than experienced in our application, meaning that a higher current is acceptable. The factor of 1,65x is obtained from the manufacturer's datasheet for operation below 45°C. Up to $34\text{A} \times 1,65 = 56\text{A}$ of ripple current is acceptable for each capacitor.

The number of parallel capacitor strings for 186A total ripple at 56A per capacitor = 3,2 parallel capacitors sharing the current equally. Four strings would then suffice but one has to also look at the mechanical structure of the product. In this case, more physical room is available to match the size of the heatsink and the objective is to have a highly reliable product. The mechanical design allows us to place ten 7100uF at 450V capacitors arranged in five parallel

pairs in the space behind the heatsink. The capacitors operate at $740\text{V}/2 = 370\text{V}$. The total capacitance for the bank is $7100\mu\text{F}/2 \times 5 = 17750\mu\text{F}$. This exceeds the minimum of $10\,000\mu\text{F}$ needed to ensure the converter's stability.

This DC capacitor bank is oversized for many applications, but it is prudent in a flexible design. The product is likely to operate reliably even in harsher conditions than evaluated above. What is important is that it should survive some abuse inflicted by people who are used to harsher environments than an electronic lab. Once the OEMs have validated their applications, measurements performed in actual conditions can be used to optimize the converter to suit their exact needs.

After doing these preliminary calculations to get an overall design of the capacitor bank, the manufacturer's application sizing program (figure 3.16) can be used to confirm the suitability and determine the expected life the capacitors operated under the design conditions. Since the capacitor manufacturer's applet calculates one capacitor at a time, the application current is divided by the number of parallel strings; five in this case. The applet calculated an expected life of 382200h or more than 40 years at full power, 24h per day. The capacitors are not likely to be the weak link in this system and should meet the expected operating life of 20 years. Optimization of the design could be conducted to reduce the size of the capacitors, but since the relationship between ripple current and expected operating life is not linear, we don't expect a reduction of more than 20 to 30%. This may be evaluated for the next product generation if real-life operation proves that the capacitor bank is indeed oversized. Meanwhile, the small supplementary cost (~\$100 per bank) goes toward product reliability.

CDE Screw-Terminal Life / Temperature Calculator

Cross-Reference Manufacturer Type Select

Type 550C Diameter 3.5 Length 7.625

Rated DC Voltage 450 Capacitance (µF) 7100

Applied DC Voltage 370 ESR (mΩ) at 25 °C, 120 Hz 7.9

Ripple Current (A) #1 7 Full-Can Capacitance e.g. Latest Catalog Cap 7100

Frequency (Hz) #1 120 Part No. 550C712T450FN2D

☒ Calc ESR? ESR (mΩ) #1 6.9 Search Catalog

Ripple Current (A) #2 37 ☐ Attach to Heatsink?

Frequency (Hz) #2 3000 Heatsink Characteristics °C/W

☒ Calc ESR? ESR (mΩ) #2 3.8 ☐ °C

Air Speed (lfm) (still air = 50) 50 Heatsink Hole Dia (in)

Air Temp (°C) 50 Can Bottom Insulation Sleeve / End Disc

☒ Tooltips? CALCULATE Guide

Initial Power Dissipation (W) 5.61 Avg Core Temp over Life (°C) 67.9 Core-to-Case θ (°C/W) 0.5

MTBF (hours) 4.33e+7 Failure Rate (FIT, ppm/kh) 23.1 Case-to-Ambient θ (°C/W) 1.7

Rev 04-29-15 Initial Core T (°C) 62.0

Expected Life (hours) 382200

Figure 3.16 Electrolytic capacitor sizing sheet for 1/5 of the current
Taken from: <http://www.cde.com/STapplet/SingleSTapplet.htm> (December 2016)

ESR MAX. Ripple Current Max					
MFD	CATALOG NO.	@ 25°C	@ 85°C	@ 105°C	CASE SIZE
		120 Hz	120 Hz	120 Hz	
		(mOhms)	(A)	(A)	
450 VDC					
1500	550C152T450CC2B	57.5	10.9	3.9	2 1/2 X 4 1/8
1500	550C152T450DB2B	55.0	11.3	4.1	3 X 3 1/8
1800	550C182T450CD2B	49.0	12.2	4.4	2 1/2 X 4 5/8
2000	550C202T450DJ2B	42.9	13.5	4.8	3 X 3 5/8
2100	550C212T450CE2B	40.5	13.9	5.0	2 1/2 X 5 1/8
2400	550C242T450CF2B	35.4	15.3	5.5	2 1/2 X 5 5/8
2400	550C242T450DC2B	35.5	15.5	5.6	3 X 4 1/8
2900	550C292T450DD2B	30.3	17.4	6.3	3 X 4 5/8
3200	550C322T450FC2D	26.6	19.6	7.1	3 1/2 X 4 1/8
3300	550C332T450DE2B	26.3	19.2	6.9	3 X 5 1/8
3700	550C372T450DF2B	23.4	20.9	7.5	3 X 5 5/8
3800	550C382T450FD2D	22.6	22.1	7.9	3 1/2 X 4 5/8
4000	550C402T450DP2B	22.3	21.8	7.8	3 X 5 7/8
4400	550C442T450FE2D	19.7	24.3	8.8	3 1/2 X 5 1/8
5000	550C502T450FF2D	17.5	26.5	9.6	3 1/2 X 5 5/8
5300	550C532T450FP2D	16.6	27.6	9.9	3 1/2 X 5 7/8
5500	550C552T450DN2B	18.0	26.8	9.6	3 X 7 5/8
6400	550C642T450DG2D	15.2	29.8	10.7	3 X 8 5/8
7100	550C712T450FN2D	13.1	34.3	12.3	3 1/2 X 7 5/8
8100	550C813T450FG2D	11.0	38.2	13.7	3 1/2 X 8 5/8

Figure 3.17 Table of suitable electrolytic capacitors
Taken from Cornell Dublier™ 2016 electrolytic capacitor catalog

3.7 Leakage inductance management

As originally mentioned, the capacitor bank is made up of ten capacitors in five pairs in series. This also corresponds to the five IGBT modules. The physical size and the symmetry are harmonized to the IGBT spacing on the heatsinks. All these elements, combined with the laminated busbars arrangement minimize the stray inductance of the DC bus. A few researchers such as Zhul (Yi-feng Zhu¹, 2015) have covered this subject in great detail. In our case, the stray inductance at the IGBT DC terminals was measured on the prototype using an LRC meter. Even with the symmetrical and compact arrangement, it reaches 150nH. During normal operation, this inductance produces 120 volts of over-voltage when switching at the peak current of 400A in 0.5 μ s. Adding this to the DC bus voltage of 740V is well within the limits of what the IGBT can sustain (1200V). Unfortunately, life is not so simple and a short circuit condition could force the IGBTs to switch off under 2200A which is the desaturation limit for this design. In this case, up to 660V would be produced exceeding the IGBT's rated voltage and resulting in damage similar to those shown in Figure 3.25.

Fortunately, the gate driver selected has an over-voltage clipping feature where the gate drive slows down the IGBT turn-off by applying a positive gate drive (half way on the time scale of figure 3.18) if the drain over-voltage is too high at turn off. Leaving the IGBT partially on for another 400ns limits the fault over-voltage at the expense of higher switching losses. This condition is flagged to the processor to stop the switching right away, thus preventing repeated cycling. This would quickly lead to thermal runaway and destruction of the module as shown in Figure 3.25. Without this protection, the over-voltage would damage the IGBTs. To help minimize the over-voltage further, low impedance film capacitors (snubbers) were added at the IGBT's DC connections as seen in figure 3.25 (black boxes mounted on the IGBTs DC terminals).

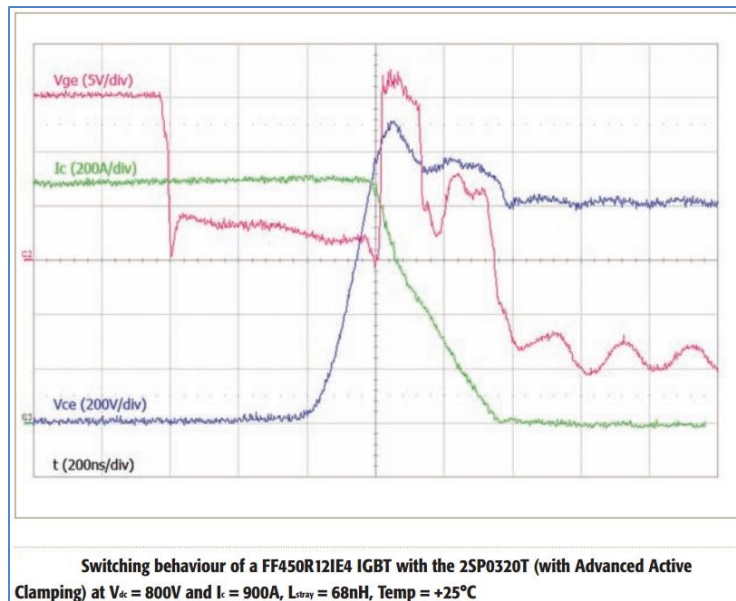


Figure 3.18 Gate driver over voltage protection

Taken from WWW.IGBT-Driver.com (December 2016)

This completes the electrical design of the DC bus capacitor bank. The next step was the construction of a ventilated case to support and protect it. This case was then mounted solidly to the heatsink assembly to minimize the mechanical force applied to the IGBTs' electrical connections during transport. Ventilation around the capacitors is crucial as elevated temperatures greatly reduce their lifespan.

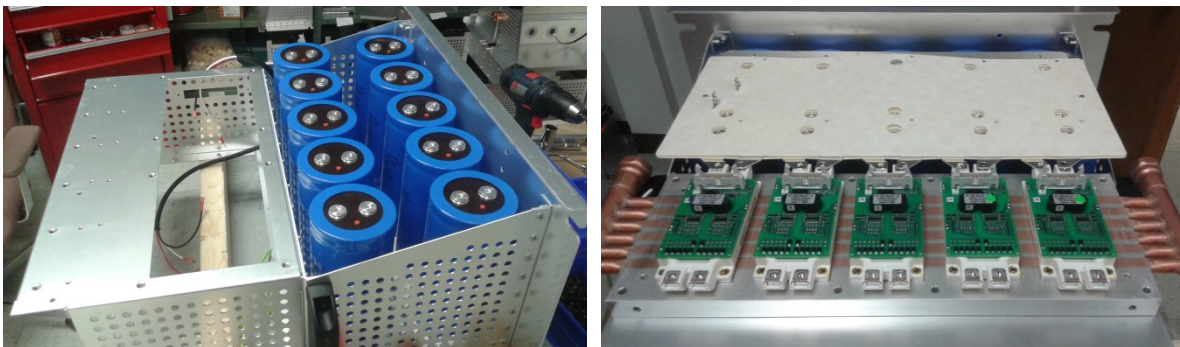


Figure 3.19 Capacitor bank, heatsink, and IGBT modules during assembly

3.8 Mistake-proofing the equipment

Another feature to make this product easier to use is to ensure that when people disconnect a cable, they are not likely to make a mistake when re-connecting it. This is done by avoiding identical connectors located side by side by adding a pin or two to differentiate them and using cables of the correct length to prevent reaching a similar connector farther away. Another crucial choice is to use polarized connectors that cannot be inserted in the wrong direction. With these strategies, it becomes difficult for someone to re-connect a cable in the wrong position.

Finally, this power electronics converter includes protections such as over-current and over-voltage shutdown and ultimate protections such as fuses. To facilitate the identification of a failed fuse, the power converter monitors them and produces a clear fault message when needed. This minimizes the electrical know-how required by the user to maintain the equipment. More details on this in the following sections.

3.9 Advanced converter protections:

As mentioned earlier, it is important to develop a converter that self-protects against the abuses it will be subjected to during its life span. We will cover the physical barriers and other external protections later in this document. For the moment, we concentrate on the protections implemented on the converter. The basic protections in decreasing speed of response include:

- The IGBT desaturation, turning it off within a few microseconds of a dramatic current overload ($\sim 2000\text{A}$);
- The shoot-through prevention caused by a software error;
- The IGBTs temperature sensor;
- The over-current protections performed by the processor (software);
- The ultimate current limit provided by the main fuses.

The protection scheme is divided into levels of severity and speed. Various articles have been presented by researchers on the subject (O'Sullivan, 2015 & Lu, 2009). Over time, the industry has developed a de-facto consensus for efficient protection of the IGBTs used in a power converter. There are other sophisticated techniques that could be used but designers must choose their battles. We went with what is commercially available.

The fastest protections are the IGBT desaturation and shoot-through preventions implemented in the gate driver board (figure 3.20 & figure 3.21). A typical response time is $10\mu\text{s}$ at five times the nominal current. This is an ultimate protection that stresses the IGBT with the over-heating and the high inductive voltage spike at turn-off. It should only be triggered in catastrophic events such as a software or hardware malfunction;

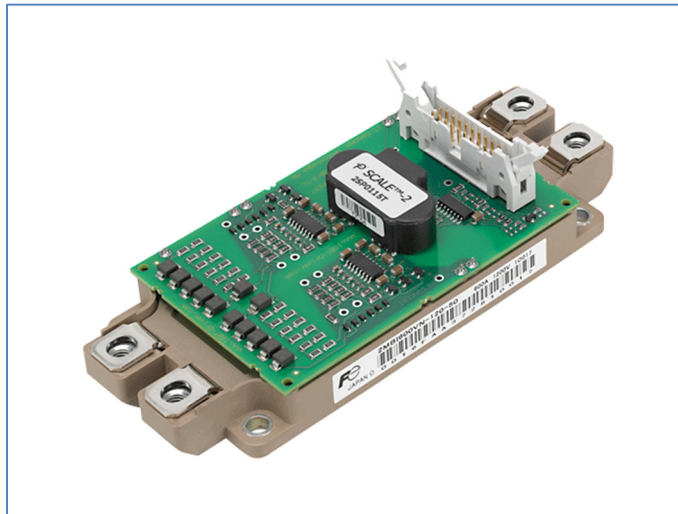


Figure 3.20 Example of an IGBT module with a matched gate driver

Taken from www.PowerIntegration.com™ (December 2016)

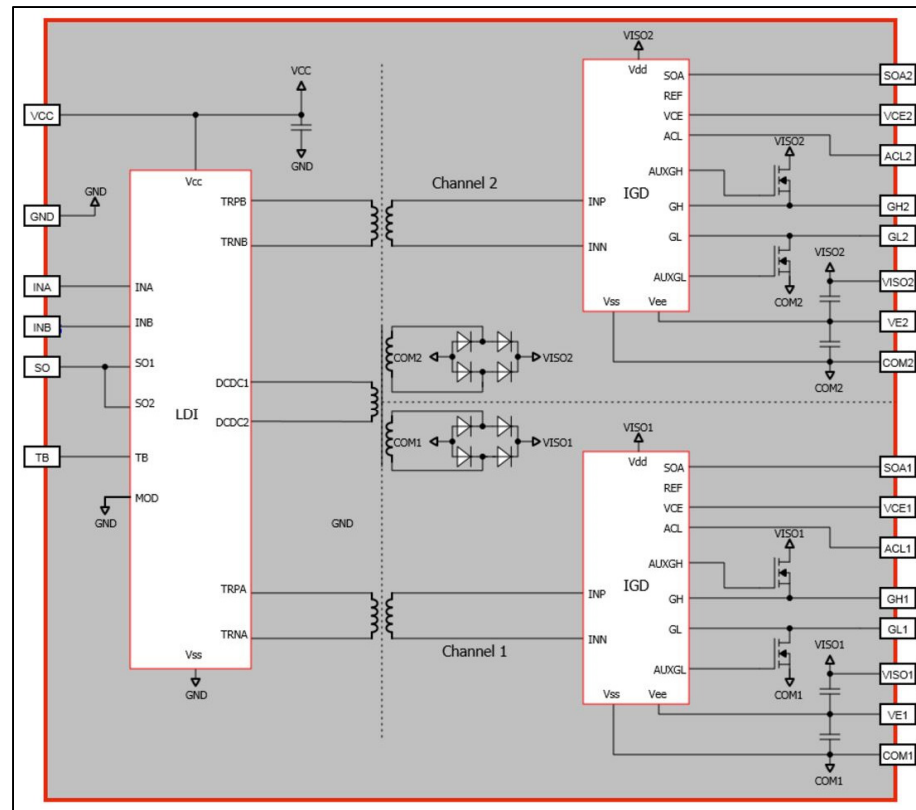


Figure 3.21 Power Integration's Scale™-2 IGBT Gate driver diagram

Taken from www.PowerIntegration™ (December 2016)

A software peak current shutdown is also implemented to turn the IGBTs off at 1.5x to 2x the rated current. This is usually within the linear range of the current sensor. The response time is in the 200 to 300µs. The IGBTs are not overly stressed when this protection is triggered. It is the main short-circuit protection;

A supplementary level of protection is also implemented by software to limit operation in overload or when the IGBTs' temperatures reach high levels. These protections respond slowly by issuing a warning to the operator and force the operation at a lower power to contain the overload from reaching the tripping level. This intervention maximizes the continuous operation of the equipment. In most applications, limiting the power available is better than shutting down a few minutes later. Since the overload and shutdown levels for the applications

are adjustable by the user, the protection strategy can be adapted to each specific application (Figure 3.22).

Converter Protection			
Converter Current High Limit RMS	P170	125	A
Converter Current RMS Delay	P171	0.10	sec.
Converter Current High Limit peak	P172	225	A Pk
Converter Current pk Delay	P173	0.2	msec.
Converter Current Imbalance RMS	P174	15	A

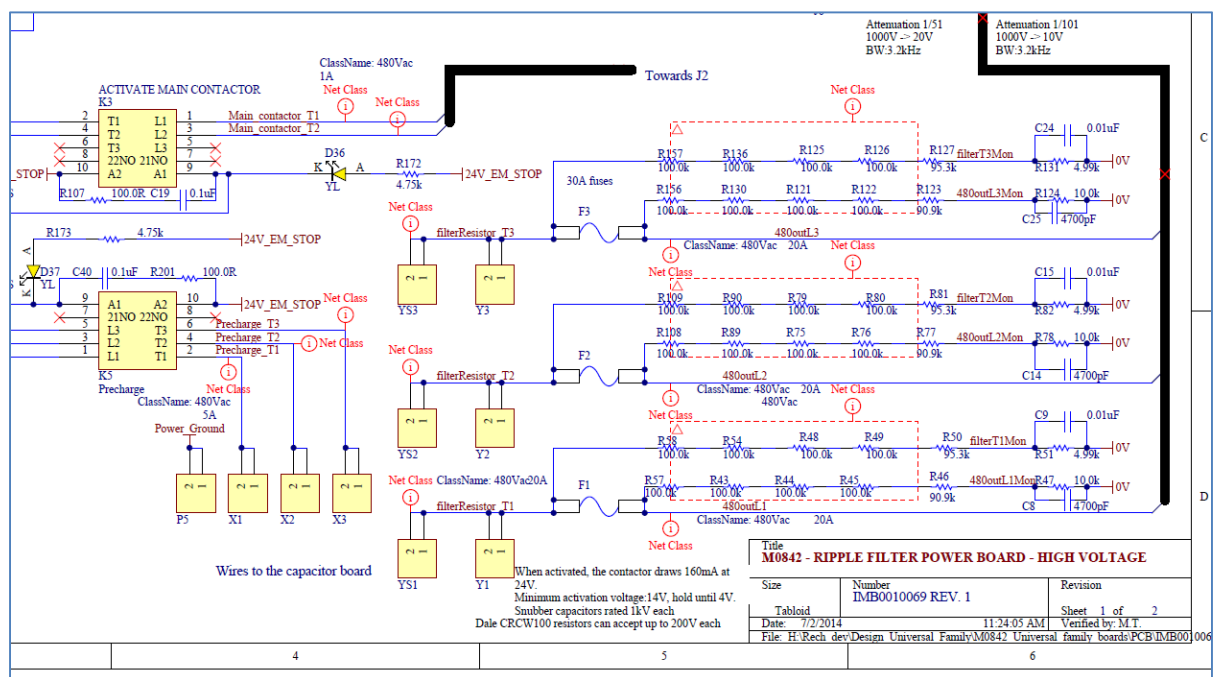
Figure 3.22 Software converter protection adjustment parameters

Unfortunately, these electronic protections are not sufficient to meet the electrical codes of most jurisdictions (NEC, CSA, etc.). One must add fuses at the power inlet to insure the personnel and equipment safety in case of electronics malfunction. The coordination of the fuses with the tripping electronic protections is relatively easy as they are an ultimate fire-prevention device operating at much slower speed. Contrary to thyristor converters, the fuses are not intended to protect the IGBTs as they take care of themselves in an over-current situation. Even the fastest semiconductor fuses are likely to activate only once an IGBT has already failed.

This protection scheme is generally followed in the industry. One area where this converter distinguishes itself is in the wealth of supplementary protections available on the converter. These protections are there to facilitate maintenance and diagnostic. The simplified list includes:

Fuse monitoring that provides a clear identification of the failed item to help the operator. The detection is done by measuring the voltage difference across each fuse using a voltage divider and a differential amplifier as shown in Figure 3.23;

- Ambient condition monitoring, including the temperature, humidity, and airflow used to cool the auxiliary equipment;
- Ripple filter performance monitoring to measure the effect of the ripple current on the line voltage and detect anomalies;
- Most sensors and cables are monitored to ensure that they are connected. Disconnected cables are often the source of trouble and false diagnostics;
- A reversed phase rotation alarm is useful to protect the auxiliary cooling water pump and other phase-sensitive equipment;
- Capacitor bank life monitoring as discussed below;
- The very demanding compliance with arc-flash protection norms is facilitated by the built-in web server and oscilloscope to help keep the users' hands away from the electrical power.



3.10 Long life design philosophy

When designing for a long life and reliable operation, all of the components must be sized conservatively. For example, even if the IGBTs can operate with a junction temperature of 150°C, it should not be used as a design target. One must include a safety margin for unexpected operating conditions. Protecting the electronic boards from corrosion, humidity and dust found in industrial applications is done by applying a conformal coating on them. In recent years, the design community has been forced to move to surface mount components and use lead free solder to meet environment regulations such as RoHS. The removal of lead and other metals from the electronic assemblies has had the adverse effect of increasing the prevalence of short circuits from tin whiskers. This often limits the life of electronic devices. The use of larger size components and integrated circuits with wider lead spacing in combination with the conformal coating minimizes the chances of short circuits by tin whiskers. A very interesting presentation of the extensive research conducted by NASA can be found in the literature (Panashchenko, 2012; Fraunhofer, 2012).

Another important factor affecting reliability is connector failure by intermittent contacts so common in electronic products. The use of gold plating on all the signal connectors with voltages below 10V and currents below 10mA minimizes this, as described by this connector manufacturer (Tyco_Electronics, 2004).

3.11 Component life monitoring:

Some components used in the converters have a limited lifetime or a limited number of cycles in their useful life. Based on the research done by others on power converter reliability (Huai, Ke & Blaabjerg, 2012; Patil et al., 2008), this includes:

- IGBT (thermal cycles);
- Electrolytic capacitors (drying up at high temperatures, over-voltage stress).

In addition, we include some component failures witnessed over the years:

- Electromechanical contactors (electrical switching and mechanical cycles);
- Cooling-water valves (mechanical cycles, scaling);
- Heatsink (corrosion, scaling);
- Air blowers (bearing running hours);
- Fuse failure (fatigue from overload cycles).

In the following section, we cover how some of these components are monitored to warn the operator when preventive maintenance is needed.

3.12 Innovative capacitor bank life monitoring

Electrolytic capacitors are widely used in inverter and converter capacitor banks. They offer the best price/performance ratio in most applications. An unfortunate characteristic of these capacitors is that they age rapidly under thermal stress. Using a larger bank or increasing cooling prolongs their life, but this comes at a cost. This is why in an optimized product, one wants to keep the capacitance to a minimum to meet the application. Unfortunately, there will always be some applications where the user pushes the equipment harder past its limit. A tactic to avoid increasing the equipment cost for those cases while avoiding a catastrophic failure is to warn them ahead of time that the capacitor bank is reaching the end of its useful life and needs some preventive maintenance. The trick is to find a way to measure the capacitor bank life without increasing the production cost of the product. This means a software solution using the hardware already used by the converter. Various researchers have covered this subject in detail- most authors added sensors in series with a capacitor (Vogelsberger, Wiesinger et Ertl, 2011). Their technique likely works well to monitor one capacitor, but is expensive to implement on a whole bank. This is especially true for a bank containing many capacitors connected in series and in parallel, including discharge resistors, as is often the case in real life.

To overcome these limitations, we developed a simple way of measuring the capacitance of the whole capacitor bank in order to evaluate its residual life. This is done without the need of adding any supplementary hardware to the converter. A software timer inserted in the operation sequence provides us with an evaluation of the residual life. This is based on the time it takes to discharge the bank.

As discussed by Mr. Parler from Cornell Dubilier (Sam G. Parler, 2014), the equivalent series resistance (ESR) is the first parameter to increase as the capacitor ages, but we couldn't find a simple way to measure it on an operating converter. The next best parameter to monitor is the capacitance itself. One could use the current sensors and the DC bus voltage to measure it in operation but the switching noise makes this extremely challenging. We found that the shutdown period of the equipment is particularly suitable to measure the capacitors' discharge time. The transistors' switching activity has stopped and the main factors affecting the capacitor bank voltage are the discharge resistors and the internal leakage of the capacitors. We then measure the time for the DC bus voltage to decrease between two fixed values (example between 600V and 400V). This is a repeatable measurement that is a function of the time constant of the circuit. The discharge resistors are relatively stable components over time and temperature, but the capacitor's leakage current isn't. Fortunately, the leakage current is small with respect to the discharge resistor current; its variation with temperature has a small effect on the result. One could always measure the capacitor temperature to evaluate the leakage current but the precision improvement may not lead to a meaningful gain.

For example, according to the manufacturer, the leakage current is $\leq 3\sqrt{CV} \mu\text{A}$, 4 mA max, 5 minutes (Dublier, 2016) (Note that C is in μF and V is in volts). In our case, the 7100 μF , at 300V gives less than 4mA. The current flowing through each discharge resistor during the monitoring period is up to $300\text{V}/22\text{k}\Omega = 13\text{mA}$. We have ten capacitors and resistors operating in the bank averaging their specific variations.

The net result is that we get a new discharge time reading at the end of each run cycle. As the capacitors age, this time is reduced from the lower capacitance and the increased leakage current. This shorter time eventually triggers a warning message. Typical reductions in time are between 20% and 50%, depending on how much overcapacity the designer had included in the bank. An added benefit of this technique is that an increase of the discharge time by more than four or five percent is indicative of a failure (open) of one of the discharge resistor(s). This is an urgent situation that requires a maintenance activity. Losing a discharge resistor on a bank made up of series-connected capacitors is destructive as it leads to un-even sharing of the voltage and eventually to failure of the capacitors. This failure can be dramatic as some capacitors simply overheat and explode, as seen in figure 3.24. When this happens, collateral damage from the arc flash is often present, such as bent busbars and burn marks on adjacent components.



Figure 3.24 Damage to a capacitor bank from imbalanced series connection

This monitoring technique works as well with film capacitor banks. The “negative” aspect of this technique could be that one only gets a result every few days or weeks when a typical industrial system is switched off. This is not usually a problem as the capacitor’s life span is measured in years, which means that the warning will come in a timely fashion. Further

research could be done to improve the precision of the results at different temperatures, but it is outside of the needs for this product.

3.13 Other component life monitoring techniques

Most of the other wear and tear is the result of cycling of components. This is easily handled by counters saved in the processor's memory. Some components are sensitive to overloads and the counter can be incremented faster under these conditions. As an example, the main fuses experience very little stress when the equipment operates a low power but can take a limited amount of thermal cycling produced by excursions between low and very high current. We therefore drive the fuse cycle counter with a large hysteresis on the line current. Refinements to the technique could be used, but it is beyond the requirements for this product generation.

As we saw in this section, the functionalities of these converters are oriented toward reducing the power electronics know-how required to operate this product. We started with an IGBT bridge configuration that has been proven to operate in industrial conditions. We then included functionalities and protections to obtain an “automatic” operation with as much self-monitoring as commercially achievable. In the next chapter, we will present the software and auxiliary components needed to produce a complete system.

3.14 Safety aspects of capacitor banks

This capacitor bank has a capacity of 18mF at 750V. It can hold 5100 Joules of energy or 1.42 Watt hours. This is small compared to other storage equipment like batteries, but what makes most capacitor banks dangerous is their extremely low impedance. The whole content can be discharged in roughly three time constants or $3 * 18\text{mF} * (13\text{mOhms} * 2/5) = 280\mu\text{s}$ if we

neglect the low inductance of the busbars. This is an instantaneous power of $5100\text{J} / 280\mu\text{S} = 18.2\text{MW}$, enough to produce a sizeable arc flash (explosion).

We have experienced one during the prototype testing phase, when an error in the firmware reduced the IGBT dead-time to zero. The resulting failure reduced the IGBTs to smoke and propelled the gate driver board a meter away as shown on the Figure 3.25. A plasma jet is often produced with arcing damage found up to five centimeters away, also shown on the melted busbars corners. The desaturation protection of the gate driver didn't save the IGBTs because they were already at their maximum operating temperature when it was triggered and couldn't absorb the supplementary heat. The likelihood of this type of accident was later reduced by using the following steps:

- The IGBT gate driver was configured with a hardware minimum dead-time function to supplement the software;
- The IGBT temperature sensor protections were implemented;
- Pull-down resistors were used on all IGBT driver input and main contactor command signals from the processor. This way, all the transistors are turned off and the energy source is disconnected when a reset is performed on the processor, resulting in all its outputs going into high impedance. This is likely to happen during development, triggered by the software development tools, the accidental push of the reset button during operation, or the software watchdog timing out on various software errors.

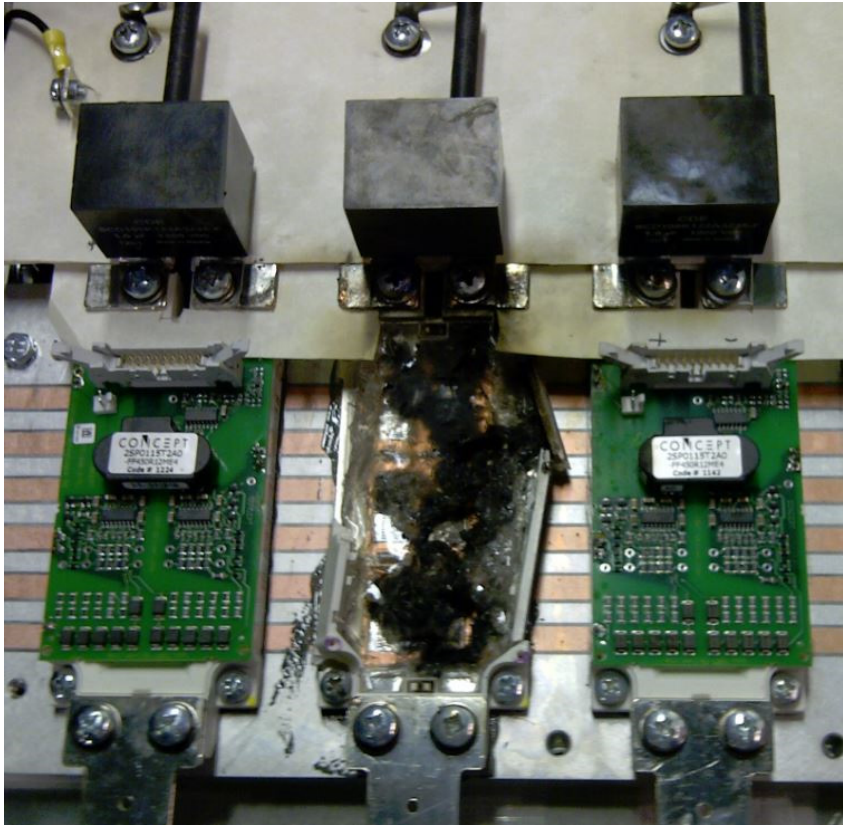


Figure 3.21 IGBT damaged by an explosion

Any sizeable energy storage component capable of releasing its content rapidly must be considered a potential hazard and treated as such. This is one of the reasons why we have limited our converter package to 200kW. When a larger system is needed, we place many complete converters in parallel. This increases the system capacity without increasing the energy that can be released from a single point of failure. We also mount them in the opposite way (figure 3.26) to minimize the chances of cascaded failures. If an arcing event happens on one of the banks, the plasma jet is unlikely to trigger a short circuit in the next bank as it could in the case of facing capacitor bank mounting. Notice the transparent protective barriers over the power board and the yellow warning stickers.

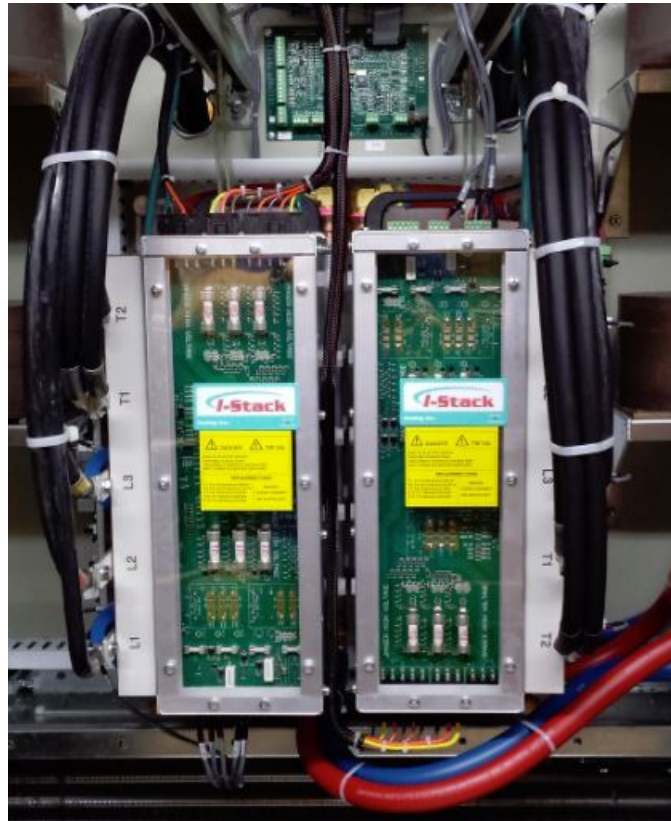


Figure 3.26 Two I-Stacks mounted in a cabinet with auxiliary components

The other risk generated by large capacitors banks is their holding of dangerous potential after the power is turned off. It is a common safety practice in the industry to “lock up and tag out” equipment when maintenance activities are needed. This minimizes the risks that the technician could be electrocuted while coming into contact with a live conductor. The problem with energy storage components like a capacitor bank is that they keep their charge for a long time after the system is powered off. This poses a great danger to technicians who may believe that all power sources are disabled. This is why discharge resistors are placed on most high-voltage capacitors. They are sized to ensure that the voltage is reduced to a safe level within a reasonable time. A common value is ten minutes, when ample warning signs are given as shown in Figure 3.26. In general, the time it takes to “lock up and tag out” the equipment exceeds ten minutes, minimizing the chances that the waiting time is “ignored” by an impatient technician. We also added a LED indicator in the front plate of the I-Stack that stays on with

constant brightness until the DC bus is below twelve volts. This indicator does not depend on any external logic or auxiliary supply, making it a relatively safe warning.

The safety tips presented above also apply to multi-level power converters having floating capacitor banks or any capacitor exposed to high voltage for that matter.

3.15 Other safety aspects related to power converters

Other general safety measures are needed in all power converter work. Most of them apply to all the phases of their useful life. Safeties are implemented at design time and are absolutely needed during the product development period. This list may not meet all the local regulations, but is a minimum that a designer should follow:

- An emergency stop circuit must be implemented in hardware to rapidly cut power to the system in case of emergency. One does not have the time to search for the main breaker while a colleague is being electrocuted. One or many suitable emergency stop buttons must be installed in the prototyping area and on the equipment. The stop command must directly turn off the power to the main contactor or breaker. One cannot rely on the processor or logic gates to implement this safety function as they may freeze;
- Physical barriers to prevent accidental contact with live parts, hot components, or mechanical pinch points. These should have many levels and many sections to maintain the maximum level of protection if one needs to remove one barrier to access a section of circuit. This starts with a proper enclosure supplemented by various shields and covers. Notice the Nomex™ insulation paper on top of the capacitor bank on the right side of Figure 3.19. It is not needed for normal operation. Its function is to cover most of the DC busbars to reduce the chance of an arc flash if a tool or another conductor is dropped on it;

- Warning labels and signage to warn visitors of the dangers;
- Proper wiring of the setup with conductors arranged neatly. This improves safety by reducing the clutter, minimizing the chances of error. See Figure 3.26 and Figure 5.3 for examples. One of my mentors told me in my early years: “If it looks messy, it won’t work well”. My twenty-five years of professional experience have proven him right. Take the time to clean up your prototype wiring and work area. Have some room to safely move away if catches in fire, as it probably will at some point;
- Use the proper tools for the job. NEVER use a “de-grounded” oscilloscope by removing the power cord’s ground prong or by using an isolation transformer to take “floating” measurements. You must use high voltage differential probes and ensure sufficient voltage rating. Your safety outweighs the cost of the tool;
- Always know what to expect before taking a measurement in order to use proper tools. If you are not certain, investigate. A typical multimeter is only safe to 1kV. It may explode in your hands if you use it to check a 4kV source. Knowing what is in front of you before approaching is the first rule of safe work.
- Your meter is your guardian angel. It should be the first thing touching conductors, not your fingers. Always check every exposed conductor for DC and AC voltages before touching the conductors. Capacitors can keep their charge for a long time, especially if a malfunction happened and the discharge resistors have failed. Never rely on the breaker to completely open the circuit because the contacts could be welded together. Even protection equipment can malfunction. Always double check that the power is off;
- In a lab setup, where a lock-up, tag-out procedure may not be convenient, use at least two disconnect devices to isolate the power source when working on your converter. This insures that someone does not power up your setup by mistake when trying to power their

own. This means at minimum, turn the breaker off, cover it to identify that it must stay off and unplug the power cable.

Reading about safety regulations such as the examples listed below is a good start to understand the risks and learn about recognized procedures aimed at improving safety.

- CSA 22.2: Industrial electrical machinery;
- NFPA 70E: Safety rules for working on an energized electrical panel;
- Local electrical code.

There are many others that are enforced by the legal system and must be followed. Safety concerns must be addressed early in the equipment design. If one waits until the end, it often becomes very difficult and expensive to modify the product to meet regulations. This is why basic functions such as capacitor bank self-discharge, hard wired emergency stop circuits, and energy limiting, just to name a few, have been included in the I-Stack design from the beginning:

As we saw in the preceding sections, the I-Stack hardware was designed to facilitate its use by an OEM. This is industrial equipment built with ample safety margins to survive continuous operation over many years, even when exposed to some abuse. The hardware includes many sensors and monitoring features intended to make it easy to use and maintain. In the next section, we will see how the software was developed to take advantage of these features.

CHAPTER 4

SOFTWARE DEVELOPMENT FOR THE I-STACK™

4.1.1 Software for everyone; the “Power PLC”

An important feature of this power converter is that it is programmable by the OEM product designers. This requires a design strategy different from what is usually implemented by other power converter manufacturers. This unique concept was developed in the spirit of making it easy for the OEMs to modify the control strategies to meet their needs. This “easy to modify embedded software” targets microcontroller-based boards, not the “embedded PCs” running Linux or Windows operating systems. This choice was made to keep the converter cost down and use hardware that the OEMs would use in a production run. This facilitates their transition from prototype to production. Since users can modify the converter’s control application at will, they end up having the equivalent of an automation PLC developed for the power electronics industry, hence the “Power PLC”.

To achieve this, the power converters should use a programming language familiar to OEMs so that they can adapt the examples supplied for their own application. This self-programming by the user minimizes the need to divulge their ideas to the power converter’s manufacturer. In our opinion, this will increase the number of “inventors” willing to test a power electronics solution, as they like to keep their findings to themselves.

To find a suitable programming language, we looked at C and C++ used by professional programmers but found them to be inconvenient for most OEMs, as they are unlikely to have these expert programmers on staff. We also looked at the open source programming languages used by “hobbyists”, or “makers” like Java or Python. While often easier to learn than C++, these languages still require a steep learning curve and are not yet popular with OEMs. They also tend to be resource intensive, intended for powerful operating systems. The most

promising languages we found were graphic-based as they are often used by many of the OEMs' engineers and scientists. Using graphic languages helps them to modify the examples provided in a short time. These graphic languages include ladder diagrams, function block diagrams, and GRAFCET™, used in Programmable Logic Controllers (PLCs). They are also familiar with instrumentation languages such as National Instruments' Labview™ or Keysight's VEE™, and the simulation languages such as Maple™, or Simulink™. The language also needs to be compiled into embedded software that can be loaded into the converter's control boards. Since the converter's logic is complex, large models and libraries are also needed which excluded those graphic languages where the screen becomes too busy as the program grows. After a few tests at the beginning of the design phase, we chose Mathworks' Simulink™ for its wide-spread use in the scientific community, its popularity with engineering schools, and its C compiler that makes its code easy to integrate into an embedded controller. The new generation of engineers has been trained with this software, making it the tool of the future. An added advantage of Simulink is that developers can integrate part of their simulation models into the controllers to obtain the desired control strategy. Compared to what is being done by other converter manufacturers, this should save development time by reducing the painful debugging work normally required when translating the simulation logic to the embedded controller language.

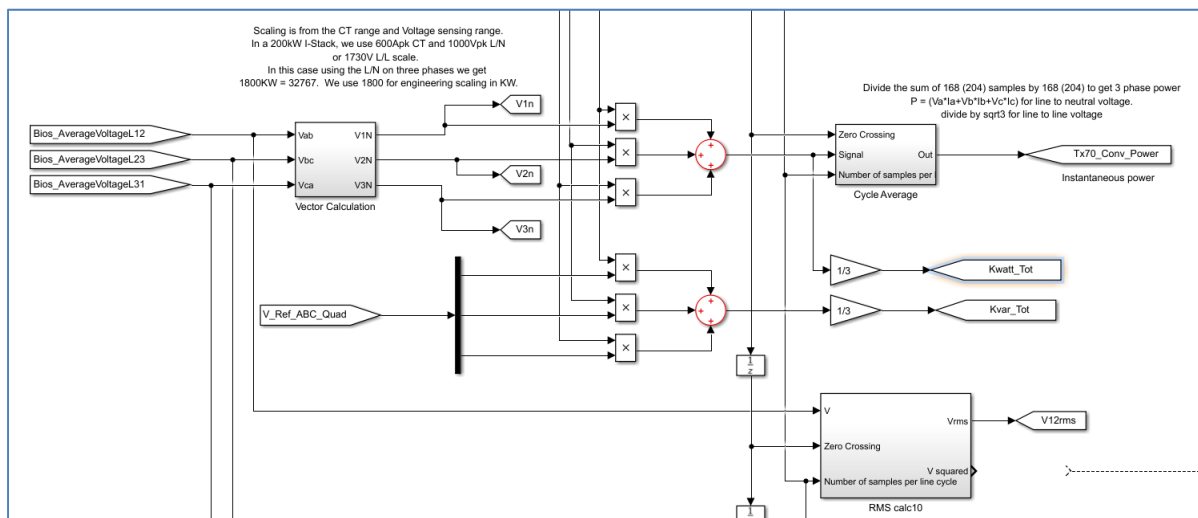


Figure 4.1 Example of power calculation code (partial) using Simulink(TM)

```

/* UnitDelay: '<S24>/Unit Delay5' */
rtb_UnitDelay5 = A_I_CONV_100uS_DWork.UnitDelay5_DSTATE;

/* Outputs for Triggered SubSystem: '<S78>/Triggered Subsystem' */
A_I_CONV_100_TriggeredSubsystem(A_I_CONV_100uS_DWork.UnitDelay5_DSTATE,
A_I_CONV_100uS_DWork.FixPtUnitDelay1_DSTATE_a2, rtb_Switch4, &V23rms_100uS,
&A_I_CONV_100uS_PrevZCSigState.TriggeredSubsystem_p);

/* End of Outputs for SubSystem: '<S78>/Triggered Subsystem' */

/* Math: '<S75>/Math Function' */
rtb_DataStoreRead7_o5 = (int16_T)(rtb_DataStoreRead7_o5 *
rtb_DataStoreRead7_o5 >> 15);

```

Figure 4.2 Code snippet of a power calculation function using "C" language

4.2 Graphical programming example

Simulink™ is well known for its use in simulation of physical processes. Researchers often use it to simulate elaborate controllers for their power converters using powerful multi-processor platforms such as dSPACE™. Unfortunately, this platform is not suitable for field applications because of its size and cost. We had to develop our own processor boards and software to use Simulink models in our power converter. The PWM board is mounted on the I-Stack as shown in Figure 0.1. The two ARM-based processors run compiled versions of the Simulink models. This way, the power of Simulink is combined with the efficiency of the RISC assembly code. The math and control algorithms are restricted to 16 bits fixed point numbers as much as possible to avoid overloading the processors as the critical control loops are executed every 100µS.

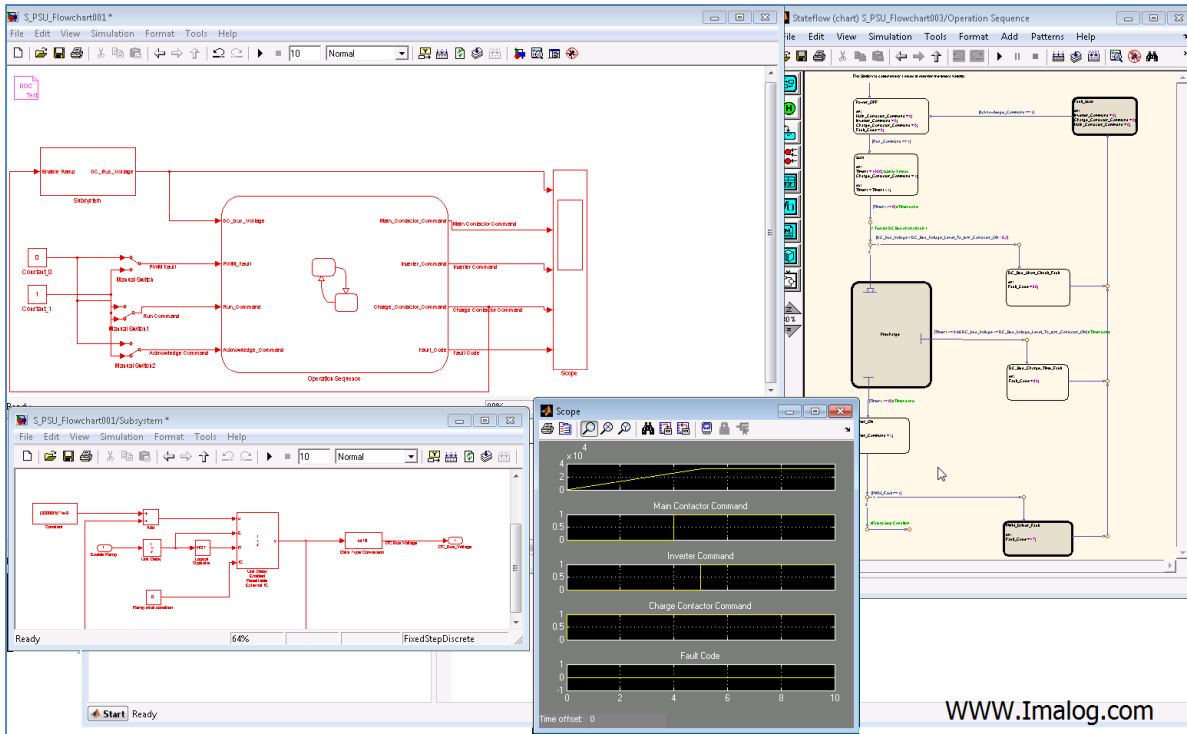


Figure 4.3 Graphical programming example

4.3 Diagnostic adapted for a wide audience

A common problem that can discourage the use of a new technology is the “brick effect”. This happens when using an advanced technological device as a black box, that is, not understanding the details of how it works. For most people, it is impossible to fix the black box when something fails or is configured improperly. A simple failure like a disconnected sensor or the wrong setting can turn the black box into an expensive “brick” that simply gathers dust in a corner. Therefore, diagnostic functionalities must be included in any power converter intended to be used as a black box. These diagnostic functions must also be supported with documentation intended for non-experts in the field of power electronics. As an example, the machine should indicate clearly that the “Phase ‘A’ current sensor cable is disconnected” (the real cause) as opposed to “Current control loop I1 saturated” (the symptom) or “fault code 52”

(un-intelligible jargon). A suitable fault message can also include a hyper-link to a picture of the sensor location, and potentially a video clip explaining how to conduct the repairs. Gone are the days of reporting fault codes that need to be looked up in the manual or be reported to the manufacturer for interpretation. This is where artificial intelligence (AI) can be used to properly interpret the symptoms. While it exceeds the scope of this work, a new field of engineering is opening with the IoT, M2M, and fog computing, bringing AI to everyday equipment (MANNION, 2016).

In addition to the diagnostic features intended for the end users, some tools are needed during the power converter's development phase and for future product support. The use of oscilloscopes and meters is a must on this type of product. To take measurements on high voltage circuits safely, and for convenience, these tools can be integrated into the power converter. This eliminates most dangerous activities such as probing live circuits to verify a waveform. An internal oscilloscope can have hundreds of channels probing various sensors and internal control nodes. This is more information than one can get from a physical oscilloscope with various probes, and can be available remotely when product support is needed. The following section concentrates on the subject of remote monitoring, see the diagnostic.

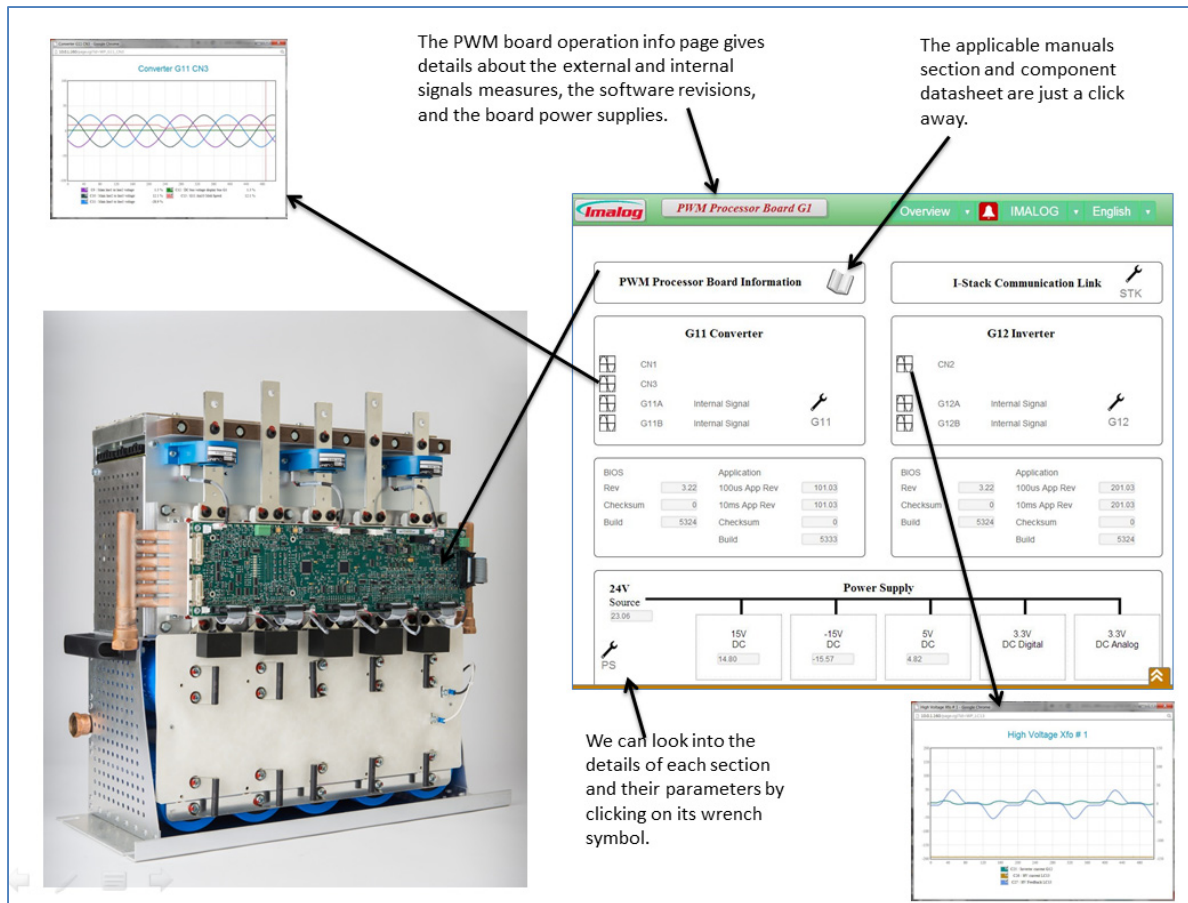


Figure 4.4 Oscilloscope and diagnostic information

In this relatively self-diagnostic system, most of the sensors and components are monitored to attest to their proper operation. A disconnected sensor is difficult to find if the loose connection is not in a visible location. It is even harder if the faulty connection is intermittent. Therefore, this power converter monitors dozens of major components and provides easy to understand warnings and alarms as needed when they operate outside of their range.

Finally, any power electronics equipment, especially when used in a prototype system, must include protections, such as over-current and over-voltage limits that cannot be disabled by a software error. These protections are there to limit or remove the power rapidly when something is out of control, which happens regularly during prototype development. Ultimate protections such as fuses are also needed for legal reasons. UL or CSA will not accept that a

power converter operates without suitable fuses or breaker limiting the energy in case of a fault. The problem with fuses is that they eventually perform their intended function and open. Replacing them usually requires the know-how of a technician trained in power converter diagnostic. This technician may not be available at an OEM plant specialized in mechanical or chemical processes. To facilitate this task, as part of the diagnostic functions, the I-Stack power converter monitors each fuse and clearly identifies which one needs to be changed in case of a failure. The technician can then power off the converter before replacing the fuse. This functionality keeps the personnel away from the equipment while powered, facilitating the compliance with arc-flash regulations enforced in most plant.

4.3.1 Remote diagnostic

As described in Section 4.3, a common problem that can impede the use of a new technology is the “brick effect”. It is usually caused by the operation of equipment as a black box. It is virtually impossible to fix the black box when something goes wrong. Even the simplest thing like a disconnected sensor or the wrong setting can turn the black box into an expensive “brick” that simply gathers dust in a corner. Therefore, advanced diagnostic functionalities must be included in any power converter intended to be used by somebody who doesn’t understand its internal operation. The power converter designers must come up with ways to make them easier to use.

To make the converter easier to operate or troubleshoot, online manuals and training videos are being developed. Using the embedded web server technology, we could split the user manual in sections accessible by clicking on the problem area (Figure 4.6). To supplement the manual, information about the components helps the maintenance technician to quickly locate them if a replacement is needed (Figure 4.7). This is a very important concept as accessing the schematics and the manuals is often difficult for the maintenance people working on the plant floor. Manuals are often locked up in some office for safe-guarding or even worse, lost or destroyed during previous maintenance activities. Embedding the documentation into the product is an innovation that will reduce the maintenance cost of the products using this technology.

To help the users, we added functionalities so that most of the sensors and components are monitored to attest to their proper operation. Experience in diagnostic various machines taught us that a disconnected or intermittent sensor can be difficult to find. Therefore, the job to monitor them was given to the embedded processors. This power converter monitors dozens of its major components and provides easy to understand warnings and alarms as needed to facilitate its maintenance.

4.3.2 Fault recording and analysis

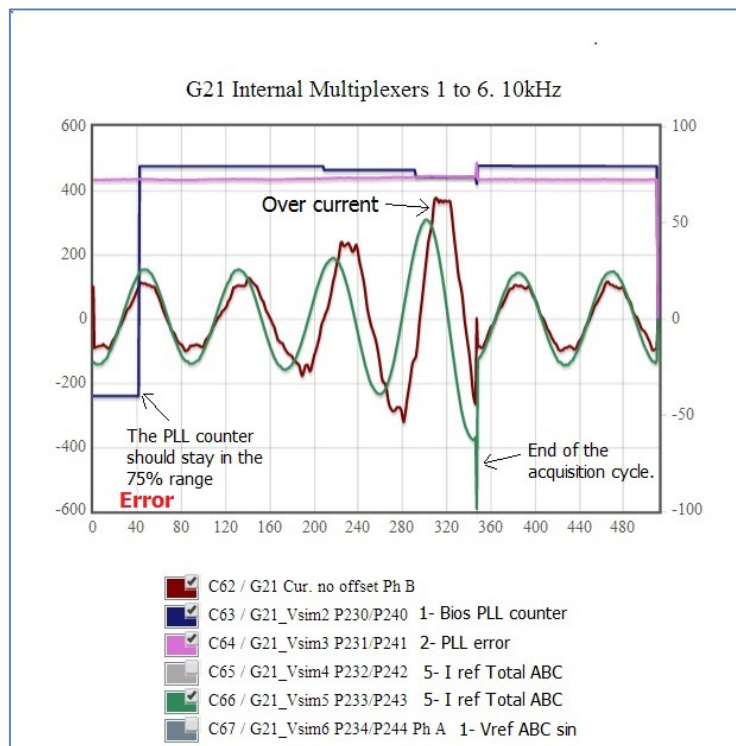
One important aspect of diagnostic power electronics systems is that most of the time, faults happen very quickly and the conditions disappear as fast as they came. It then becomes very difficult to re-trace what exactly happened and figure out why it did. Modern systems provide a list of text alarms, which help but are often insufficient. Most plants these days have process trend archiving that can also help, but it is usually too slow and too general to provide the exact information needed to troubleshoot power electronics converters. Therefore, we built a fault-triggered, waveform archiving function in the I-Stack. Since there is too much happening in real time in the equipment to archive everything, we use the fault type to select the information to be saved on the SD FLASH memory. This way, the appropriate group of oscilloscope waveforms are saved with each fault event for future reference. This provides valuable real-time information to the technician in charge of figuring out what happened.

Figure 4.5 is a real example of a diagnostic report produced by an engineer regarding an overcurrent condition experienced sporadically on an early prototype.

Title: G21 over current trip.

Description: We were getting a converter over-current fault once or twice a day. It happened on either G11 or G21. It was more frequent at setpoint higher than 50%. We used the internal oscilloscope to track the fault. We expected an external cause but to our surprise, the I-PSU internal oscilloscope showed that an internal signal was the cause.

Date and time: 2014-04-14 8:07AM



Waveform interpretation: We can see that the PLL counter (channel C63 in blue) gets an erroneous value between time 0 and 40. This causes the PLL to lose its phase synchronization with the line, resulting in an increase of the converter current (C62 in red) reaching the trip limit. We see that the internal reference in green also increased, confirming that the internal PLL logic was “mislead” by the incorrect count information.

Solution: With this information, we quickly realized that we were getting surplus line zero crossing interrupt from noise. We solved the problem quickly once the cause was identified.

Figure 4.5 Service report
Taken from Imalog service report (2014)

The above example illustrates that having the correct information is very important in order to find and resolve intermittent problems. This is an important contributor to the improvement in diagnostic functionality of every product.

4.3.3 Connectivity

With the advent of the IoT and the M2M, one cannot imagine a new product without including a high level of communication. This is needed for the product operation, its maintenance, and its diagnostic. Nowadays, most machines are built with communication links to exchange information with people and other machines. Only certain security functions such as an emergency stop or physical access guarding are still hard wired. Ethernet links are becoming an industrial de-facto standard and allow for integration onto the plant network. This link can also be used to operate and troubleshoot the equipment remotely. This is extremely powerful as the service personnel do not need to travel to site for most diagnostic activities, which saves time and money.

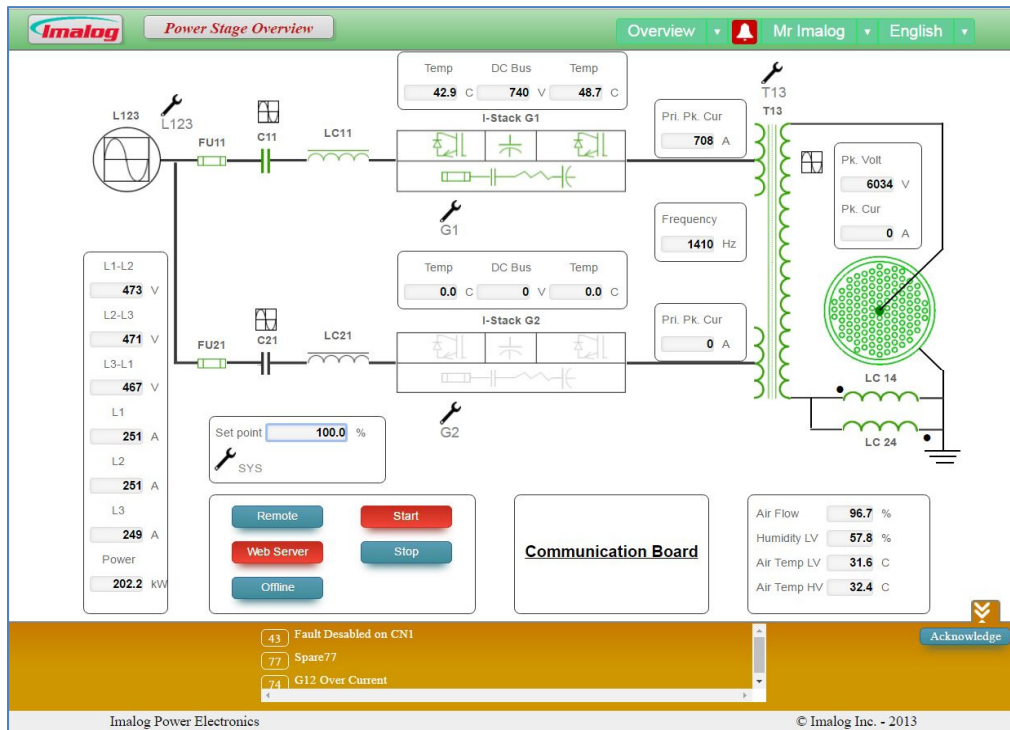


Figure 4.6 Example of the maintenance web page that can be viewed remotely

We included an Ethernet communication link and a web server into the power converter to facilitate the access to large amounts of internal information. This information can also be converted to a MODBUS™ table for interaction with other machines (M2M) if a control network is used. MODBUS is widely used in the industrial community. Other protocols are possible and will be implemented as demand increases.

4.3.4 Web Interface:

Web browsers are a convenient user interface that can be used to visualize a wide range of information from various locations. Using communication protocols originally developed for the web, one can produce an embedded server that permits the visualisation and the control of a power converter. A short list of the information available on the web server includes the overall schematics, the user manual sections related to the selected equipment, the oscilloscope showing the related waveforms, the operation levels such as voltages, currents, power, and

frequency, the spare parts ordering information, and more. We can even include some training videos on how to perform specific maintenance tasks as shown in Figure 4.7.

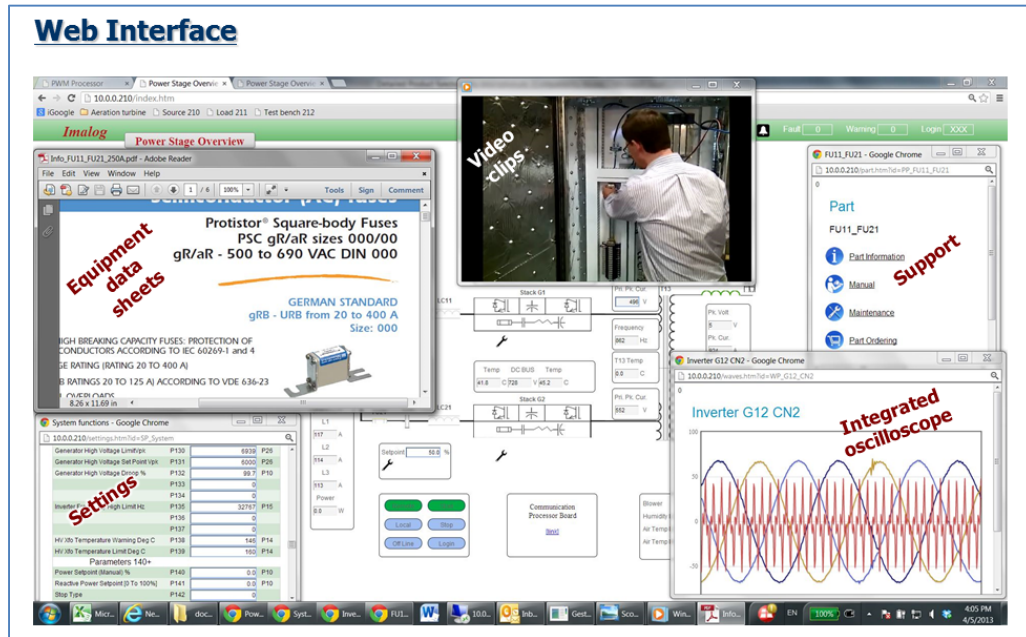


Figure 4.7 Web interface with pop-up information windows

CHAPTER 5

TOWARDS A COMPLETE SOLUTION

5.1.1 Presenting the I-Pack™. The complete power electronics converter package.

On its own, the I-Stack™ power converter presented in the chapter 3 is not likely to be suitable for OEM use. As discussed in Section 2.2, auxiliary components such as inductors, contactors, and fuses, must be added to the converter bridges to produce a complete system. Selecting all the auxiliary components requires specific power electronics know-how, so it is best done by the power converter manufacturer. We called our complete package the I-Pack. As mentioned in the introduction, the main objective of this work is to facilitate the integration of power electronics solutions into OEMs' applications without them needing to become power electronics experts. Our solution to this objective is the I-Pack power converter system presented in Figure 5.1.



Figure 5.1 The I-Pack™ power converter

The I-Pack contains an I-Stack power converter with the auxiliary components common to many applications. It includes the active front-end converter's three line inductors, a main line contactor, main line fuses, an emergency stop circuit, cooling system, and a high level digital

controller with field IO's to interact with the rest of the plant. The only components missing are those specific to the OEMs' application. These specific components may be batteries, transformers, or DC inductors to be mounted in a separate cabinet by the OEM.

For some applications, we placed all the components in a convenient enclosure on wheels for easy integration into the OEMs' application, but it is not the only cabinet arrangement possible. The next chapter shows how the I-Pack components are mounted in a larger cabinet integrating the application specific components to form an ozone generator power supply unit (PSU).

While the original application for the I-Pack was the upgrade of legacy ozone generator PSUs, it became evident that it could be used in many other applications requiring the conversion of bi-directional three phase AC power into single phase, variable frequency AC or DC power. As discussed in Chapter 1, many applications such as plasma generation, solar panel inverters, energy storage and peak shaving, induction heating, magnet drives, and others are well served with this topology.

A simplified electrical diagram for the I-Pack is provided Figure 5.2. In most applications, the utility power line is connected on the left side while the OEM's application is connected to the right side. Since the IGBT converters are four quadrants, the power can flow in either direction. The basic arrangement is intended for three phase to single phase conversion but if a three-phase load is needed, a second I-Pack can be joined to the first one by linking their DC busses directly or using their inverters as DC/DC converters.

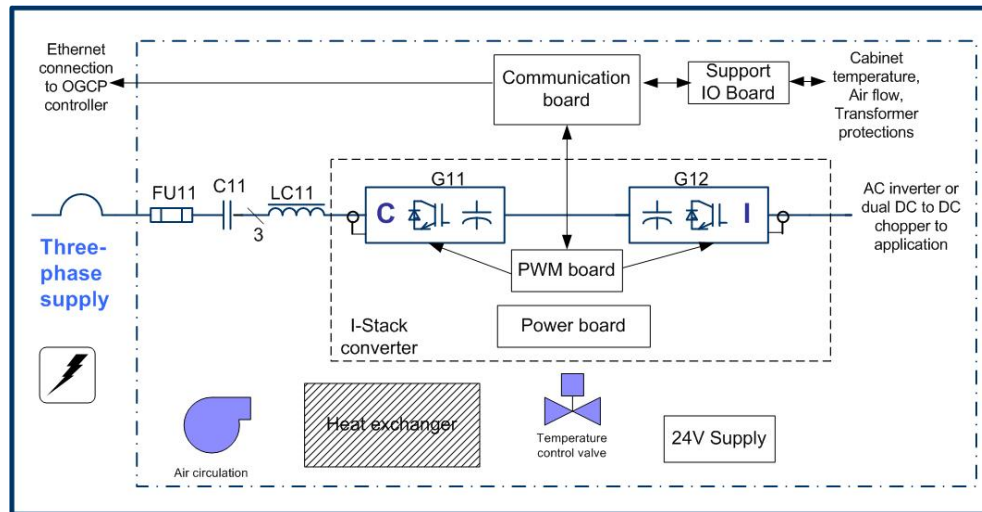


Figure 5.2 Single line diagram for an I-Pack



Figure 5.3 I-Pack with the front open showing the I-Stack, contactor, fuses, and line inductors in the background

As we saw in this chapter, the I-Pack is close to being a complete power converter solution. All that is missing is the application specific hardware. This could be DC inductors when supplying power to a plasma torch or a high voltage transformer when feeding an ozone generator. The next chapter gives examples of applications where the I-Pack is used.

CHAPTER 6

APPLICATION EXAMPLE

This section illustrates an example of an application where the I-Stack is used. It presents how the basic programming in the second converter (H-bridge) has been adapted to the application without hardware modifications to the I-Stack. However, some specific hardware was added for the application as the electrical requirements of the load is unique.

6.1 Ozone generator power supply

The first commercial application for the I-Stack was a power supply for an ozone gas generator. Ozone is a very powerful oxidant often used in large quantities for the treatment of potable and waste water, as well as in industrial chemical applications. Ozone is usually produced in pressure vessels (generators) using high voltage corona discharges into an oxygen-rich gas. To prevent intense arcing, one of the electrodes is coated with a dielectric material. This technique is called Dielectric Barrier Discharge (DBD) and is used to produce cold plasma in the gas-filled electrode gaps. For manufacturing convenience, the electrodes for large systems are produced in tubular shape as shown in Figure 6.1. The objective of the power supply unit (PSU) is to drive the ozone generator as efficiently as possible and protect the electrodes from high voltage or high power density.

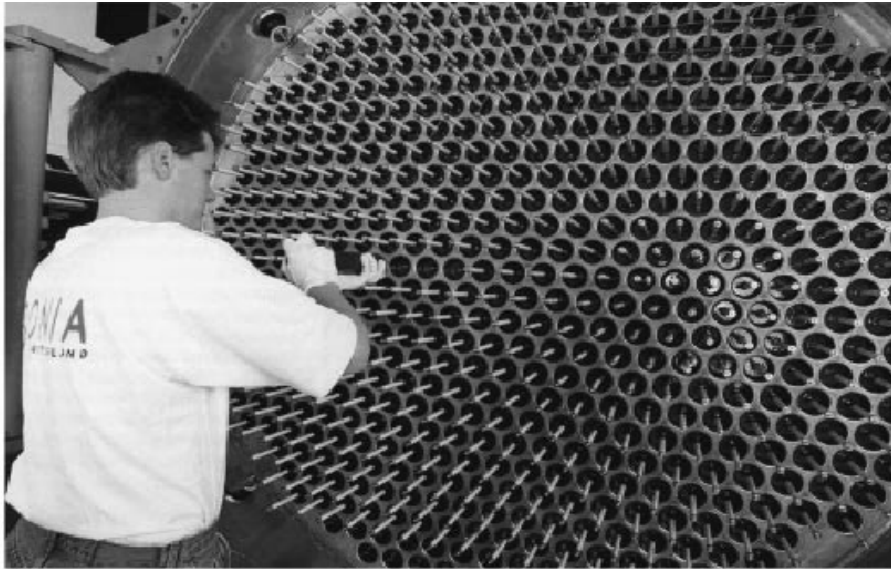


Figure 6.1 Ozone generator showing the tubular dielectric electrodes

Courtesy of Ozonia

One can describe the ozone generator load as atypical. The dielectric insulator and the gas gap inserted between each pair of electrodes form a compound capacitor. This gas/ceramic dielectric capacitance is one of the main components in the generator load model. It is worth noting that the corona discharges in the gas gap have a non-linear power dissipation response to the applied voltage and are highly affected by the process conditions. Many researchers have worked on the development of electrical models for ozone generators. An interesting example of how the electrical model is derived can be found with these authors: (Koudriavtsev et al., 2002; Murata et al., 2004). Their model is shown in Figure 6.2.

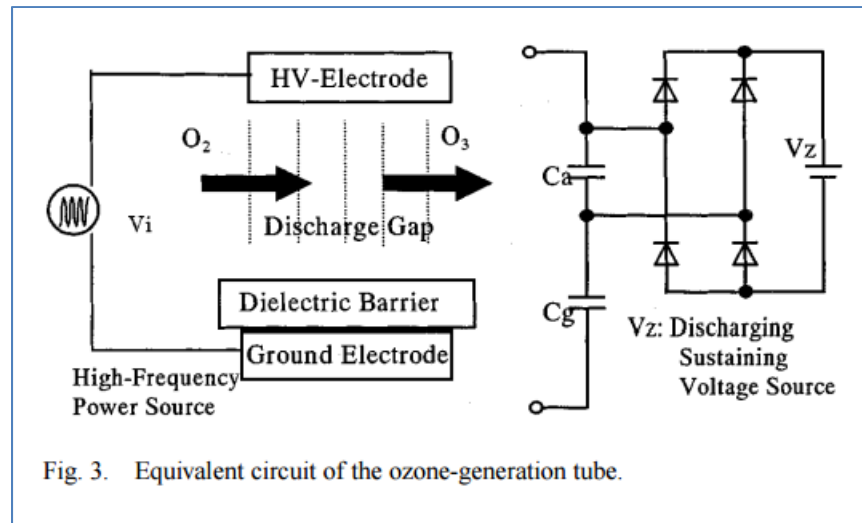


Figure 6.2 Ozone generator electrical model

Taken from O. Koudriavtsev et al., (2002)

A typical ozone generator contains between dozens to thousands of dielectric electrodes. When exposed to the intense electric field developed in the gas gap between the electrodes, some of the oxygen molecules (O_2) flowing ionize with a small fraction, re-combining into ozone molecules (O_3). The production of ozone is energy intensive, with a low efficiency of approximately twenty percent. Any efficiency improvement results in a competitive advantage. Efficient ozone production is affected by the ozone generator construction and the PSU losses. Refer to studies on this subject (E.M. van Veldhuizen; Lopez, 2011; Vezzu et al., 2009) for more details.

From the above electrical model, we see that operating the generator with an AC voltage below the “ V_z ” does not draw any power, hence no ozone is produced. While substantial AC current may be flowing at low voltage, only electrical losses are generated in the transformer, the inverter, and the generator parasitic resistors. This is one of the reasons why some PSU technologies have a minimum operation threshold of 10-20% of capacity. This minimum voltage issue was solved using a variable frequency inverter using voltage pulses of high amplitude.

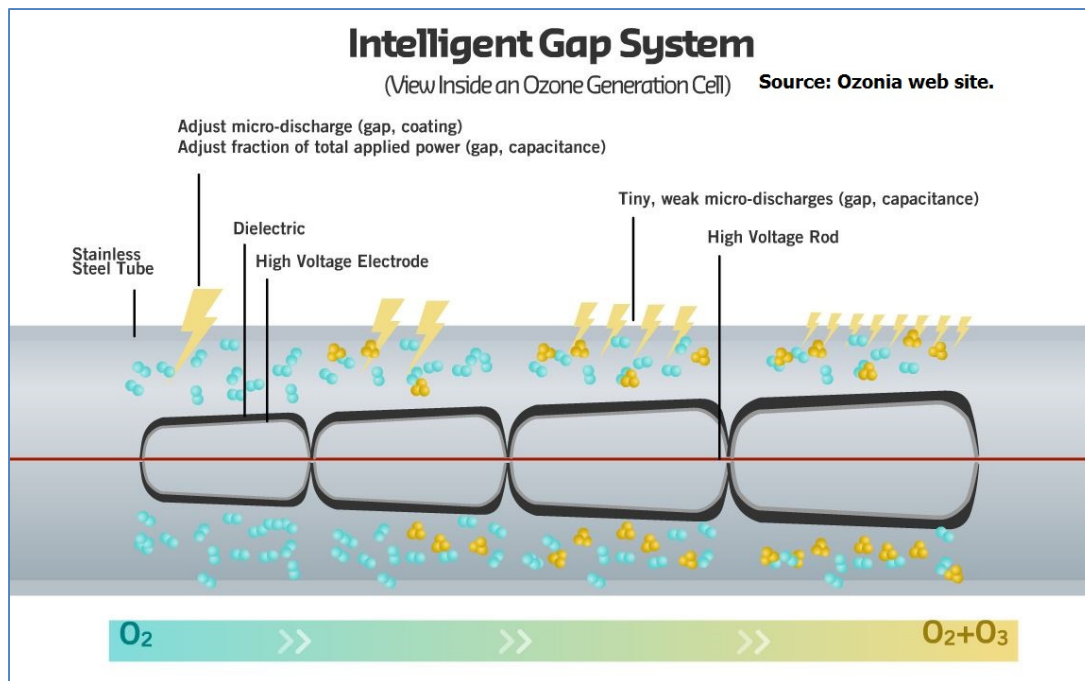


Figure 6.3 The process of producing ozone in a generator

Taken from www.Ozonia.com (December 2016)



Figure 6.4 A 400kW ozone generator and its PSU in the background, where we can see in the foreground the process piping, valves, and various meters used to control the gas and the cooling water flowing into the generator vessel

6.2 Legacy PSU technology

To understand where we are going, we must know where we came from. In the 1990's, large ozone generator PSUs were often implemented using three phase thyristor bridges to rectify the AC power source into a DC current. This current was then inverted to AC using a single-phase thyristor bridge taking advantage of the capacitive load offered by the generator to commute naturally.

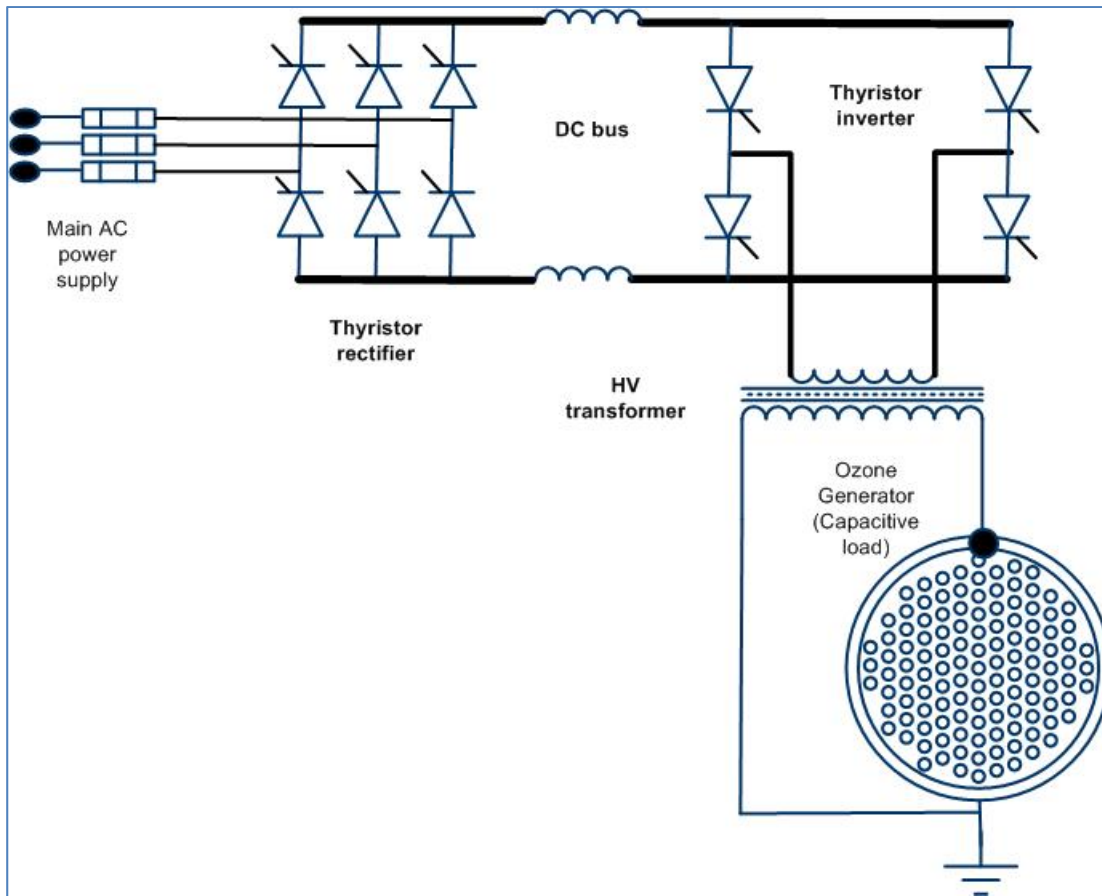


Figure 6.5 Thyristor PSU schematic diagram

These thyristor PSUs produced large quantities of harmonic currents in the line and had a low power factor. Expensive passive filters and multi-pulse configurations were often needed to maintain an acceptable level of power quality in the plants. Figure 6.6 shows the line current and its analysis for a typical thyristor rectifier using a current DC bus. The 30% current distortion (I_{thd}) and the low power factor (~ 0.5) near full power were cause for complaints in most plants.

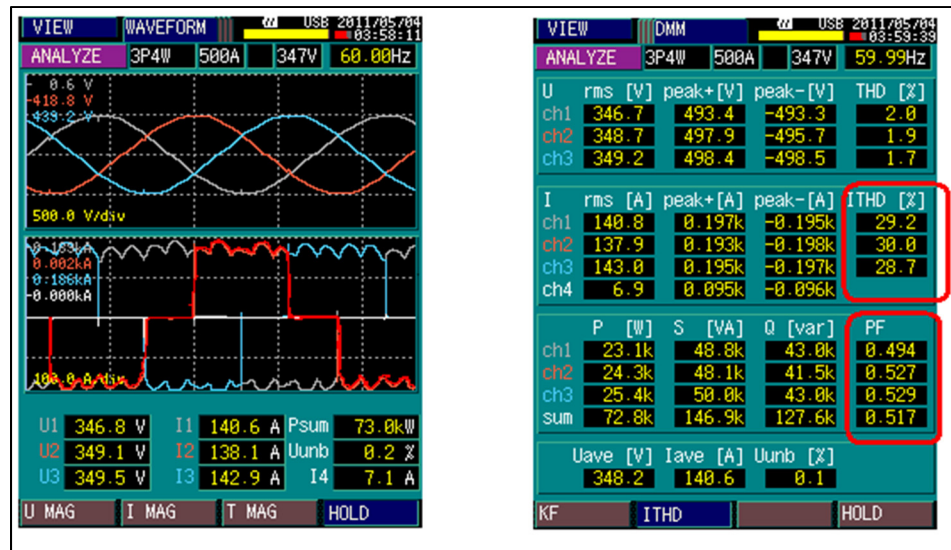


Figure 6.6 Thyristors PSU, rectifier waveforms, and power quality results

The reliability of these PSUs was low compared to today's results. Thyristors and snubber diodes often failed. The medium frequency operation ($\sim 800\text{Hz}$) and the relatively high operating voltage of the inverter ($\sim 950\text{V}$) were pushing the limits of the power components of that era. The high voltage, medium frequency transformers were sometimes pushed beyond their limits and failed. Power electronics was in its infancy.

The thyristor inverter was finicky to operate as it relied on the ozone generator characteristics to commute. This meant that extreme process conditions would regularly compromise the operation. This was especially prevalent on installations where the ozone generator was exposed to contamination and humidity affecting the dielectric tubes. A shorted (failed) dielectric tube would also prevent the inverter from oscillating. The plant operators had plenty of opportunities for hands-on experience with these old systems, as they had to intervene on a regular basis.

The electronic controller's diagnostics for these 1990's designs were minimal as most problems resulted in an "inverter short circuit" fault. This is because the inverter was of a self-commutated design where all the conditions had to be within a narrow range to turn off the previously conducting pair. Most problems (rectifier current or generator impedance too low, thyristor mis-firing, component failure) would cause the four thyristors to short the DC bus.

Fortunately, the DC bus was a current source typical of the thyristor applications of the time, preventing further damages. The diagnostic support of the time was limited to a basic alarm annunciator and analog meters mounted on the cabinet door (Figure 6.7) and a seven segments LED display on the thyristor rectifier giving numerical codes. Later generations were improved with the use of small graphical operator interfaces displaying more information, but diagnostic was still difficult as every section of the PSU had to be operational for the system to run. The inverter could not oscillate if the generator or the high voltage transformer were in bad shape or if the thyristor rectifier did not release its current pulse at the right moment. Identifying the cause of a failure required skills and luck as it wasn't always obvious which of these components did not performed as needed.

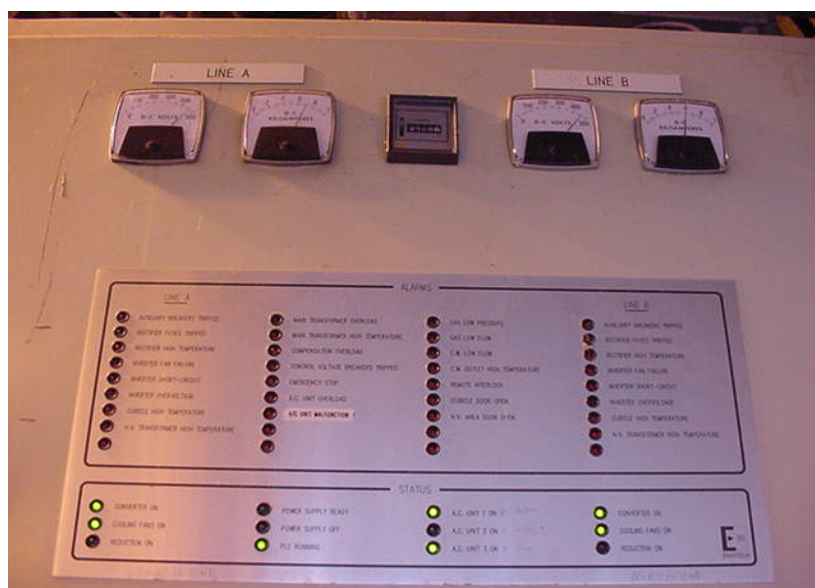


Figure 6.7 Door-mounted alarm annunciator and analog meters

6.3 System improvements when using the I-Pack™

A generation of IGBT PSUs followed in the early 2000's using a simple design philosophy directly inspired from the thyristor PSUs (Figure 6.8). The IGBTs and early digital controllers helped improve the performance, but maintenance and diagnostic were still difficult.

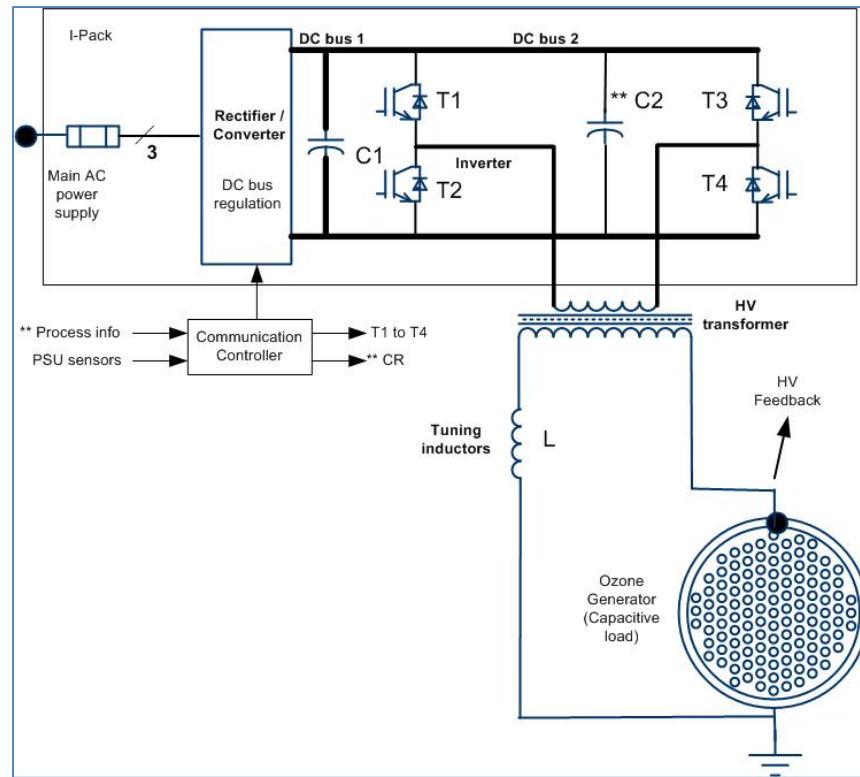


Figure 6.8 Simplified diagram of an IGBT PSU with an ozone generator based on an I-Pack power converter system

To facilitate maintenance and to take advantage of the newest technologies, the I-PSU was developed between the years 2011 and 2013. The I-PSU is composed of an I-Pack power converter system (or its equivalent) driving a high voltage transformer connected to the ozone generator. This next section explains how the I-PSU improved operation over the previous generations of thyristor and early IGBT PSUs.

One of the first things that the end-users notice with the I-PSU is the absence of line harmonics generated by the PSU compared to competitor products. This is shown in Table 6.1 with measurements taken on site while operating at full power (400kW).

Table 6.1 Power meter measurements from an I-PSU operating at full power (400kW)



The heart of the I-PSU is the I-Pack power converter system. It brings many advanced features that make the I-PSU even more reliable and easier to use than previous generations, as described in the previous chapters.

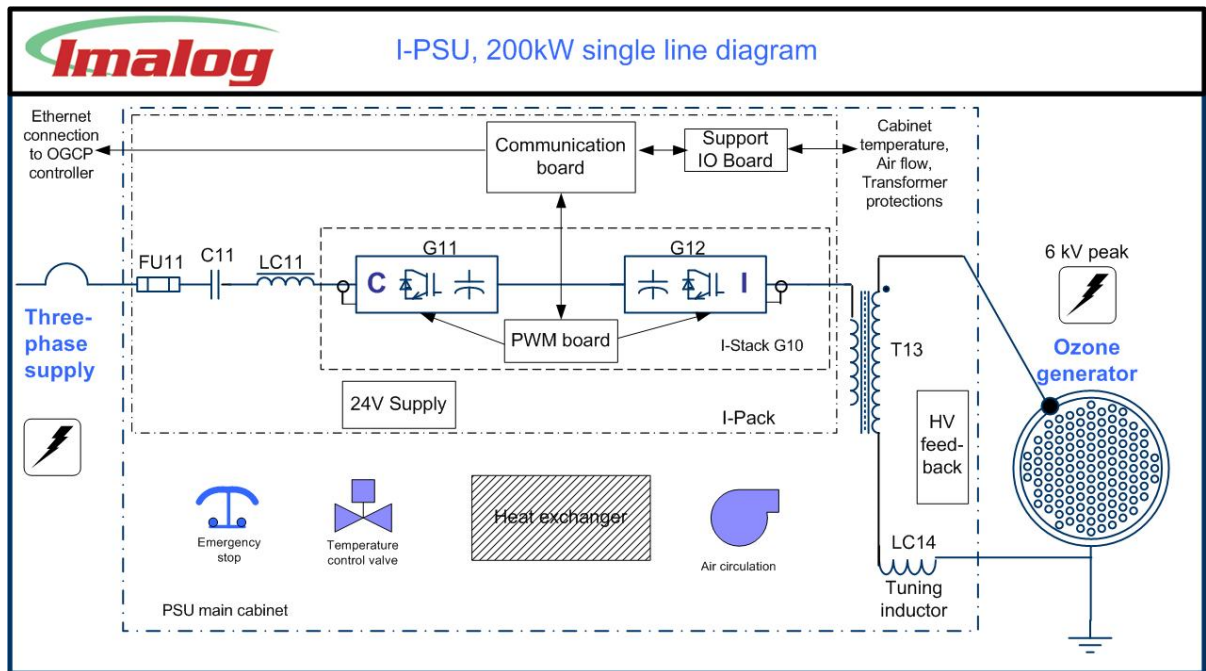


Figure 6.9 complete I-PSU™ system constructed from an I-Pack power converter, application specific HV transformer T13 and tuning inductor LC14. Supplementary air cooling is also added in the main cabinet

Since some ozone generators can reach multi-megawatts in size, multiple I-Packs are often used in parallel to supply the required power. The larger PSUs use a different mechanical design than the I-Pack but the components are essentially the same. A typical block diagram for a small I-PSU is shown in Figure 6.109 and a large one in Figure 6.10. A picture of a 1.2 MW three power stage PSU is provided in Figure 6.11. The water-cooled I-PSU covers a range of 50KW to 2.4MW using up to six power stages sharing the load. Air-cooled models operate at about half of the power due to the lower cooling capacity of air. Special power balancing and synchronisation techniques are used in the inverters to share the load but their discussion is beyond the scope of this work. The generator's electrical network is divided in multiples of 200 or 400kW that correspond to the maximum capacity of water-cooled I-Stacks. Each section containing one or two I-Stacks with the components are neatly arranged in a large cabinet. The high voltage transformer and auxiliary equipment are added to the I-Stacks to become an independent power stage. When multiple power stages are needed, the parallel operation adds a certain amount of partial redundancy where the rest of the PSU can keep

operating if one power stage is down. This increases the “availability” of the system, a highly desirable feature.

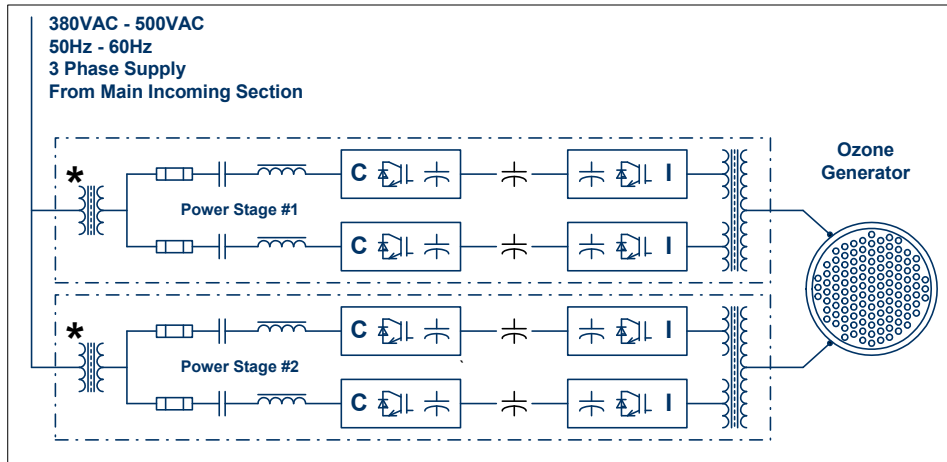


Figure 6.10 Single line diagram for a dual power stage I-PSU™

Figure 6.11 shows a 1.2MW ozone generator I-PSU™ combining water-cooled I-Stacks™ and cabinet. Three power stages using two I-Stacks each share the load. The cabinet doors have been removed for clarity.



Figure 6.11 A 1.2MW ozone generator I-PSU™, doors removed for clarity

6.4 Details of the application

In this application, the inverter operates as a variable frequency source, transforming the DC bus voltage into an AC output voltage driving the high voltage (HV) transformer's primary winding(s). The resulting high-voltage, variable frequency source is used to control the amount of power applied to the ozone generator. The ozone production is more or less proportional to the power applied to the generator.

The basic inverter program has been modified to operate at variable frequency with a range covering between 1Hz and 1500Hz, meeting the variable plant production requirements. The amplitude of the voltage generated is also controlled in order to adapt to the generator's variable impedance caused by process variation or losses of dielectric tubes. Active current limiting through the cycle also protects the generator from process changes. Figure 6.12 shows a typical inverter waveform at about 20% of power followed by operation at 100% power. In a typical installation, when the power setpoint is raised from zero, the inverter frequency starts at about 1 Hz. As the setpoint increases, the frequency increases to reach the power target. The

large inverter frequency range produces a stable generator operation at a power level below 0.1% for low-demand periods. This gives a load turn-down better than 1000:1, exceeding the needs of all ozone plants produced in the last thirty years.

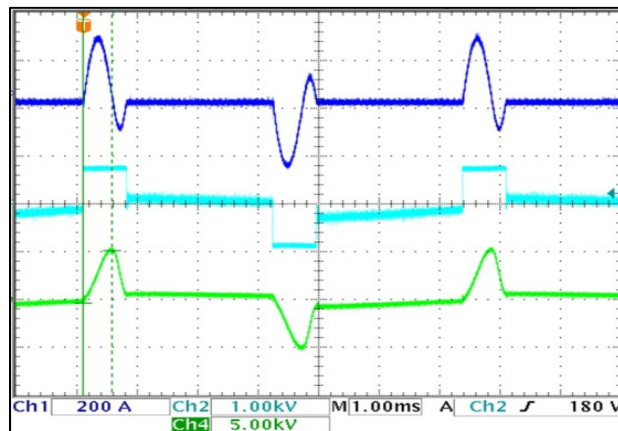


Figure 6.12 Low power: inverter current on top,
inverter voltage in the middle,
followed by the load voltage at the bottom

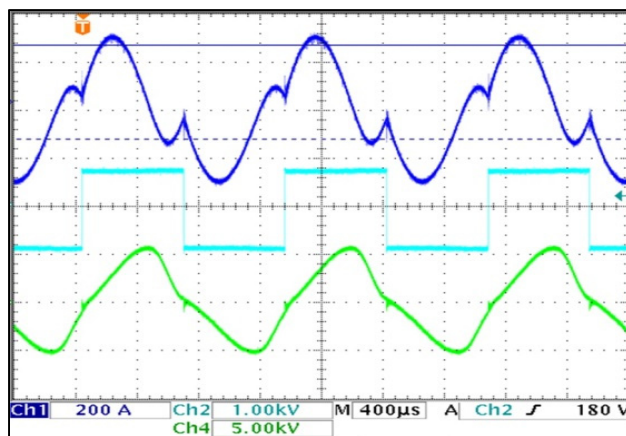


Figure 6.13 High power: inverter current on top,
inverter voltage in the middle,
followed by the load voltage at the bottom

6.5 Alarms and faults for the ozone PSU

We took advantage of the power of Simulink to add many diagnostic features that were only partially available in previous PSU generations. This section lists the main ones we developed. The objective is to increase the equipment reliability by controlling the operation during abnormal conditions. This concept is called “Fault Ride-Through” and while it is not new, it is not common and its development is extremely difficult. Most equipment simply shuts down to prevent damage from abnormal conditions:

- Line voltage amplitude: measured before closing the converter’s contactor to protect the power electronics from low or high voltage conditions. It can be narrowed down for specific applications. A typical value would be between 440V and 520V to detect if the line voltage is acceptable on a 480V nominal feeder;
- Line phase rotation: measured before closing the converter’s contactor to protect the auxiliary equipment such as water pump and chiller compressors. The converter itself is bi-directional but other auxiliary equipment is not. We limit the flexibility of the converter to protect the rest of the system;
- Line voltage frequency: measured before closing the converter’s contactor to protect the auxiliary equipment, such as water pump and chiller compressors. The converter itself can operate between 48 to 62Hz, but other auxiliary equipment may not. We limit the flexibility of the converter to protect the rest of the system. Protection is normally used when the PSU is first installed in the plant. The line frequency shouldn’t change afterwards unless operating on an emergency diesel power generator;
- HV transformer polarity: in ozone PSUs, we verify the proper connection of the HV transformer to the inverter by monitoring the polarity of the output voltage pulse with respect to the inverter polarity. This protection is mostly used when first installed in the plant;

- Generator open or short circuit: In operating ozone PSUs, there is always a sizeable current flowing if the generator is connected. This current flow must produce high voltages in the generator. These conditions are monitored by correlating them with the expected operation to help the operator identify load connection issues;
- Sensor and other cable disconnection: cables are often disconnected during maintenance operations, and detecting which cable has not been reconnected can save hours of frustration and diagnostic;
- Temperatures too high or too low: it is crucial to maintain adequate operating temperatures for the components. In a water-cooled system, reaching freezing temperatures is as dangerous as reaching high limits;
- Magnetic component over-temperature switches: large magnetic components, such as transformers, are often equipped with high-temperature switches. This is to protect them in case of an overload that could push their temperature beyond limits even when the cooling air and the ventilation are adequate;
- Cabinet high humidity: a high-humidity condition can be the symptom of a cooling water leak or simply come from a leaky door gasket when operating in tropical climates. A high humidity condition can cause condensation on water-cooled heatsinks if the water is cold. This condensation can drip onto electrical components which can cause short-circuits. This is why it is important to warn the operator when the humidity is too high;
- Water leak detection: simple sensors can be placed on the equipment floor to detect large leaks before they cause long term damage;
- Board power supplies: multiple sensors can be added to a system but they are likely to give false readings if the power supply feeding them is out of range. It is important to monitor each power supply to validate the sensor results;

- Low air flow: a thermal mass-flow sensor is used to detect a low air flow that could be caused by clogged filters, a damaged fan or blower, or even too much air escaping out of the cabinet when the door is open. This warns the operator that something is wrong before the system needs to shut down because of over-temperature.

6.6 Final word on ozone PSU application

As we saw above, the I-PSU has been designed using the I-Pack as a basic module to supply an ozone generator with electricity in a suitable form. The application section of the inverter program has been adapted to meet the particularities of the load. It includes most of the advanced features of the I-Pack such as the web server for remote control, the internal oscilloscopes, and advanced diagnostic.

The I-PSU also corrects the line power factor and harmonics issues encountered by the users of the previous technologies. This is important as some plants are limited by the KVA capacity of their feeder. Any improvement of the power factor allows them to produce more with the same electrical feeder. The improved performances were achieved by taking advantage of the I-Stack active front-end power converter.

This new PSU controls the ozone generator precisely, and the diagnostic is facilitated by its modular construction. The automated diagnostic leads the operator to the exact cause of the problem most of the time. This PSU can be tuned to operate on a wider range of ozone generator sizes and operating conditions. The inverter starts every time, even when many dielectric electrodes are in overload conditions and it reports the issue. It is a good example of taking a standard I-Stack and, through software modifications, adapting it to an application.

6.7 Flexibility for other applications

As we saw in Section 2.5, back to back converter topology has been used to facilitate the use of this converter in different applications. The H-bridge inverter can be re-programmed for different switching strategies driving inductors or transformers. This opens the door to applications in high voltages such as RADAR supplies or low voltages such as electro-plating. Meanwhile, the active front-end rectifier section of the converter stays the same, maintaining its exceptional performance with respect to power quality.

CONCLUSION

In this thesis, I have presented a flexible power electronics converter and the design philosophy behind it. The objective of this work was to define what is needed to implement an easy-to-use power converter. This objective has been partly met, as illustrated by the easier-to-use power converter presented in this document. This is a relative comparison to the industrial equipment that I encountered in my 30 years as a professional engineer. I sincerely hope that others will follow in this direction.

In the first chapter, a case was built for making power electronics more accessible to OEM designers. After all, they are the ones developing the products that are used in everyday life. Some anecdotal evidence and research papers were used to show that power electronics is a key component for the advanced infra-structure desired by our society. The difficulties in generalizing its adoption were identified. The main conclusion is that the power electronics industry will thrive by designing power converters accessible to OEM product designers. It is our challenge to make power electronics one of their favorite tools. This “make it easy to use” philosophy was used to direct the development of the I-Stack power converter presented in subsequent chapters.

The presentation the I-Stack in the following chapters skipped over the circuit and control details to concentrate on the important factors such as the ease of use and the reliability. Our solutions to these challenges were presented to inspire other designers to follow suit and to come up with better solutions. The user interface, in the form of a built-in web server, gives a powerful and affordable way of monitoring the internal operations of the I-Stack as well as providing the user with built-in documentation and manuals. Since nobody wants of a product that would malfunction regularly, elaborate hardware and software protections were combined with prudent component selection to obtain high reliability. Advanced diagnostic support was presented to help the users deal with the high complexity of this type of equipment. In remote applications, advanced diagnostic can supplement remote diagnostics when the problem is particularly difficult to solve. These maintenance functions are very important to

reduce the cost of ownership of equipment and increase its availability. An example of real diagnostic using the advanced web interface was given to show the usefulness of the technology.

The last chapter presented a real-life application for the I-Stack as part of an ozone generator power supply unit (PSU). We saw how the basic converter / inverter functionalities can be extended to adapt them to the specific applications. The use of the Simulink programming tool makes software modifications and maintenance easier than it would have been with most computer languages. We have shown examples of how the I-Stack's active front-end converter technology improves the plant's power quality compared to thyristor based equipment. We also mentioned the advantages for the system operation.

I hope that presenting this design philosophy will give an example of how the power electronics design community can simplify the use of its equipment. This simplification is necessary to help more OEM designers take advantage of power electronics converters to improve the performance of their products.

Future work and recommendations:

Advancing the design philosophy for large power electronics converters to make them more attractive to end users is a continual endeavor. We will continue to reach for this goal as it is key to facilitate the adoption of power electronics in a wider market. This will be achieved by including more sensors with a simplified web interface to facilitate local and remote diagnostics. It is likely that some form of artificial intelligence will be needed to analyze the data generated to provide a clear report of the possible issues hindering operation.

While we developed an (almost) complete solution for the ozone market, our modular design needs to be refined to benefit other applications. Both the software and the hardware should be made easier to modify by the OEMs. The present system requires the use of specialized

compilers that are not easy to use. We would like to find an online tool that would be accessible to the OEMs. The I-Stack is presently optimized for ozone generation, but other applications could easily be developed. Examples are DC sources for plasma torches, inverters for microgrids, wind generators, and solar panel interfaces. These applications would require a slightly modified version of the I-Stack hardware. The various versions should become standard products with appropriate documentation.

Advanced diagnostics is a promising subject for future development. While a large amount of information is presently available from the converter, it is still a reactive system that protects itself from exceeding limits once a fault condition is detected. For the next generation, we see a higher level of diagnostics using a combination of sensors and history of operation to anticipate potential issues and warn the operator with text messaging or emails. The controller presently looks at “what it is” but in the future, we want to look at “what it should be”. To achieve this, a larger amount of information will need to be pre-processed to produce clear diagnostics that can be understood by the operators, even if they are not experts in power electronics. Statements such as “High line current distortion caused by the failure of a IGBT module x” is easier to understand than “High ITHD warning line x” even if the ITHD is the variable that is exceeding the limit when the IGBT fails. We cannot expect that a trained technician is readily available on site to pull out the correct oscilloscope waveform and identify which IGBT is not switching properly. The interaction with the operator will need to be “humanized” even more as the present look of the web server can be overwhelming to many. Artificial intelligence would bring us to the point where the machine would have an elementary awareness of its “needs” and its “status”. It would also interact in a more natural fashion with the operator. We would probably ask the machine “how are you doing?” and get a report with a technical level adapted to whoever is asking.

ANNEXE I

List of potential applications for power electronics converters

Advanced power sources:

- Inverter, pure sine wave AC/DC or AC/DC/AC or DC/DC or DC/AC power supplies;
- Battery chargers / re-conditioners / simulator;
- Capacitor banks charger / controllers for impulse discharge;
- Resonant power controller;
- Frequency changer power supplies;
- Electro-magnet power supply;
- Active loads (AC or DC);
- Electric discharge machining (EDM);
- Pulsed power;
- High power high voltage modulators (solid state & vacuum tube);
- Radar transmitters;
- Switchgears test equipment (circuit breaker, transfer switches, UPS...);
- Regenerative load banks with variable load profile, PF, transients, harmonics... for diesel / hydro/ steam/ micro generators, transformers;
- Test jig to test and run life cycle of windmill transmission and blades at full power while re-circulating the energy. We can apply varying torque at different speed to the gearbox while sending the load side energy generated to the line. The total power consumption is just a few percent of losses in the motor, generator and of course the gearbox;
- Test instruments applications; the strength of this power converter is that the load power is re-cycled allowing testing at high voltage and current for a long time. One can use a simple power feed from the utility company and multiply the capacity by 10-20X for the test supplying only the losses.

Heat source controls:

- Induction heating;
- Silicon smelter power supplies;
- Thyristor controllers;
- Arc furnaces;
- HF welding;
- Plasma coal burner.

Motors drives:

- Magnetic bearings / levitation;
- Low harmonics motor drive;
- Linear motor;
- Solenoid / voice coil driver;
- Electric / hybrid vehicles' motor drives and auxiliaries;
- Electric vehicle charger with peak shaving and rapid charging from recycled battery pack;
- Variable speed drives for fans and pumps;
- Variable speed compressor for air conditioner, compressed air;
- Variable speed drives for electric planes, propeller and auxiliaries;
- Electric racing power drives (700-800VDC);
- Dynamic braking;
- Regenerative braking;
- Boat electric drive system with low harmonics;
- AC Servo/Spindle/Robot;
- Plasma propulsion engine driver for space exploration.

Chemistry / process applications:

- Chlorine generator. (Sodium hypochlorite);
- Dielectric discharge ozone generation;
- Electro-catalytic cell drivers;
- Electro-coagulation of wastewater;
- Electro-polishing of metal surfaces using DC currents;
- Electro-reduction of Carbon Dioxide;
- Electro-winning, electrolytic removal/recovery;
- Electrochemical machining (ECM);
- Electrolysis bath (Hydrogen, Electro-reduction);
- Electrolytic ozone using proton exchange membrane similar to fuel cells;
- Electro-migration or electro-kinetic;
- Electro-osmosis and electrophoresis;
- Electro-separation. (Petroleum extraction, oil removal from other substances);
- Electro-sterilization of waters, waste waters;
- Gas reforming. (CO₂, Methane, H₂);

- Metal separator using electro-magnetic fields and induction properties;
- Plating bath power supplies. (Pulsed or constant);
- Soil de-contamination, sterilization for greenhouses;
- Ultrasonic processing;

Plasma technology:

- Ozone generator power supplies;
- Plasma torch power supplies (AC or DC);
- UV lamp ballasts;
- Visible light ballasts.

New energies:

- Windmills;
- Solar power inverters and controllers;
- Grid-tie Inverter System for Solar and Photovoltaics;
- Wave and tide energy inverters and controllers;
- Thermo-electric energy recovery systems using Pelletier effect Inertial energy storage;
- Peak shaving;
- Micro grid applications;
- M2G (motion to generation) converter;
- Shock absorber driver and energy recovery;
- Fuel cell load / simulator / inverter;
- Inertial electrostatic confinement.

Power quality:

- Active power filter. Industrial, marine;
- Uninterruptible Power Supplies. (UPS);
- Instantaneous reactive power controller / voltage regulator;
- STATCOM (Static compensator);
- Educational system using a load / source simulator.

Special drivers:

- Ultrasonic transducers;
- Piezoelectric transformers;
- Radar pulse generator;
- Magnetron / Thyatron drivers;
- High-energy labs (Particle colliders);
- Rail gun drivers;
- Electroforming of parts (EM pulses, thermal);
- Active corrosion inhibitor for marine applications;
- EMP (Electro Magnetic Pulse) generator;
- Lightning strike power supply;
- Marx generator driver;
- Tesla coil drivers;
- Contact less magnetic manipulator in 2D/3D of devices;
- Wireless power transmission for chargers or heaters;
- Energy efficiency, peak shaving devices. Includes power meter and oscilloscope functions;
- Pulsed energy power supplies;
- Discharge generators;
- Hybrid plane development system;
- AC hysteresis synchronous motor drive test platform;
- Dynamometer with energy recovery permits testing systems many times larger than the available power source.

Biomedical application:

- Particle motion control using magnetic fields;
- Prosthesis adjustment using magnetic fields.

Test equipment:

- Transformer test under full load and harmonics;
- Transformer K tests;
- Harmonics and power factor generator / simulator;
- Power line frequency response injection and measurement for harmonics and resonances;
- Fuel cells / batteries / capacitors programmable loads for life test;
- Power source component testing e.g.: Inductors, capacitor banks, harmonics filters;
- Educational system using a load / source simulator;
- Test load to simulate electric motor, transformers, magnetics, battery packs and other machinery for normal operation and fault conditions;
- Primary injection relay test equipment (Switchgear protection relays and breakers test);
- The electrical grid simulator.

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