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Integration of Distributed Technologies – Standard Power Electronic Interfaces

Prepared for the
California Energy Commission

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Executive Summary

Distributed technologies are slated to represent a substantial portion of future additions in power generation capacity. Modern distributed generation technologies such as microturbines, fuel cells, wind turbines and photovoltaic systems invariably employ several power electronic converters such as rectifiers and inverters in them in order to provide utility grade ac power. The cost of power electronic systems represent a substantial portion of overall installation costs. This has been due to the complexity of the engineering and realization of power electronics system packaging.

It is common for families of power converter products today to be custom designed. This results in sub-optimal economic performance in terms of engineering design, packaging, manufacturing, etc. Substantial opportunity exists for wide spread application of electrical power converters if they can be made low cost, reliable, rugged, serviceable, and interchangeable. Inspiration for a new, high level approach to power converter design is found in the areas of digital electronics and computer architectures.

This report presents the results of ongoing investigations on development of high power electronic systems for distributed generation systems using standardized approaches for integrating the components that comprise a power converter. The investigations have focused on developing a modular architecture that would allow using pre-engineered and mass-produced components to develop power electronic solutions in a systematic manner.

A new framework for realization of power converter is presented called Bricks-&-Buses. This framework requires three elements: modular components or bricks, from which any practical converter topology can be constituted; buses, or connective architectures, for interconnection of the bricks; a software environment in which to describe the converter at an abstracted level and automatically generate engineering and design files.

A hardware prototype is presented to demonstrate proof of concept and explore properties of the proposed approach. Technical and practical implementation issues are introduced and discussed. These provide insight into framework strengths and limitations, and direction for future research.

A concept design review meeting with a number of participants from the power electronics industry was held to disseminate the ideas and solicit inputs. The proceedings of the design review meeting are included as appendices to the report.

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Introduction

Changes in the nature of energy use are yielding new opportunities for the application of power electronics. Questions about environmental emissions, security risk and waste disposal are pushing new fossil fuel and nuclear electrical power plants out of favor, and bringing alternative energy conversion technologies, such as photovoltaics, wind turbines and fuel cells to the forefront. Increased demands for highly reliable electricity and stress on electric transmission systems have produced markets for distributed electric generation plants and flexible AC transmission (FACTS) devices.

Power converters are integral to all of these systems and devices. Fundamental to the success of these emerging markets is the ability of the power electronics industry to consistently meet the demands of these new applications. Substantial opportunity exists for wide spread application of electrical power converters if they can be made low cost, reliable, rugged, serviceable, and interchangeable.

The current state of power converter design and manufacturing is seen to impede an ability to mass customize products for a variety of applications. While most converters are based on a few common topologies, they are designed on a custom basis. The design process typically requires performance tradeoffs between circuit topologies, semiconductor devices, control, EMI, heat transfer, packaging, interconnection, reliability, etc. Perpetual re-engineering typically produces converters that have reliability indices that are not definitively known, are unserviceable, and economical only in very high volume. Cost and performance improvements are usually tied to particular applications, with little cross-pollination of ideas or common industry vision. In addition, the interdisciplinary nature of the process makes power converter design largely inaccessible, requiring expert knowledge in several fields of engineering.

In this context, a vision of a comprehensive framework for power converter realization has been presented, known as Bricks-&-Buses [1]. This standardized approach is based on modular components connected via functional connective architectures. These physical elements enable an integrated high level software design, modeling and geometric layout environment.

This report explores the theoretical underpinnings, practical implications and limitations of this proposed new framework. This begins with inspiration from the field of digital electronics and computer design. This is contrasted with current state of power converter design and manufacturing. Following is a review of recent power converter modularization efforts. Next, vision of the Bricks-&-Buses comprehensive framework for power converter realization is presented. A preliminary analysis of the properties and limitations of the framework follows. Afterward, this theoretical discussion is grounded with an analysis of prototype hardware intended to demonstrate proof of concept. A brief review of design issues related to various power converter components are discussed to provide a context for the geometric scaling studies to develop the concept further. Finally, this document concludes with a summary of the findings and recommendations for future work.

Chapter 1 Background

This chapter outlines the background for the proposed framework for power converter realization. Key elements of inspiration were derived from developments in VLSI microprocessor design and the architecture of conventional computer systems. The advances of these two industries are contrasted with a view of the contemporary power converter design and manufacturing process. Lastly, this chapter concludes with a look at some alternative research in the areas of power electronics modularization and packaging frameworks.

1.1 Inspiration

This discussion of the background of the power electronics and the inspiration for Bricks-&-Buses begins in a somewhat unusual place – the fields of digital electronics and computers. These industries have made advancements in the area of engineering and manufacturing, and system design that have become very relevant to the field of power electronics.

The standardization of computer architecture interfaces and the connection of elements via buses provided a framework for rapid development of the computer industry. In a similar manner, many in the power electronics industry have recently begun searching for standardized approaches to unify converter packaging and interconnection. The advent of very large scale integration (VLSI) marked a revolution in the process of digital design. Like the digital electronics industry before VLSI, the current state design and manufacturing in the power electronics industry splintered and disjointed.

The connections between the VLSI design process, computer architectures, and power electronics were first described by Venkataramanan [1,2], and more recently by Lee and others [3].

1.1.1 Computer Architecture

Contemporary computer systems employ a bus or set of buses to connect the processor to other devices and components of the system, i.e. memory, inputs, outputs, external networks, etc. This bus centered approach has two principal advantages, namely reduced cost and increased flexibility. As implemented in most computer systems, the bus is comprised of a set of lines dedicated to carrying control, data, and address information. This enables straightforward interconnection of the computer subsystems to the central processor. An illustration of typical computer input/output organization is presented below in Figure 1-1 [4].

The bus centered approach reduces computer costs in several ways. First, is the fact that one set of lines connects all of the computer subsystem components. Second, reconfiguration and addition of computer subsystems is straightforward and inexpensive. Industry standard buses allow computer peripheral devices to be compatible with many different brands of computers. Thus computer peripheral manufacturers can take advantage of economies of scale.

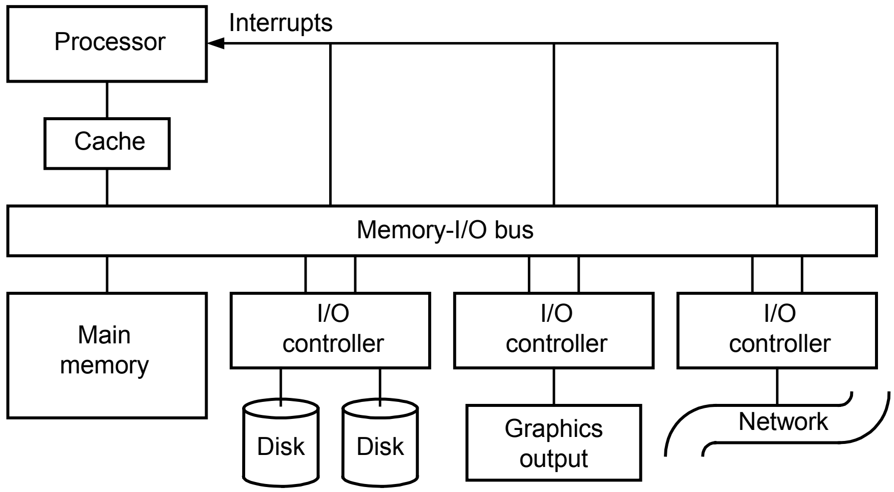

Figure 1-1 Typical collection of computer I/O devices [4].

In addition to reduced costs, the standardized bus architecture results in more flexibility. The standardized bus allows computer users to easily replace components to change functionality, replace nonfunctional components, or select among a range of component manufacturers [4].

It must be noted, however that the bus centered system is not without its disadvantages. Most notable of these is the fact that the bus can be the source of bottleneck in data throughput. Since all of the computer's subsystems are connected via the bus, management of bus access is paramount to optimum performance. In addition, the large market for peripheral components that are compatible with the bus means that there are fewer manufacturers available for custom configured products. In addition, the standardization of the bus limits the range of options for connection of the computer components. This can be problematic when an application is not well served by the range of industry standard approaches, or requires custom connectivity.

Even with these drawbacks, the bus-centered approach to system design is seen to offer several potential advantages to conventional power converters. The historical focus in power converter design, namely topological and component design, has relegated the complex and interdependent work of the designing the connective properties of the converter to second-class status. This is not dissimilar to the traditional emphasis in computer design. This topology-component design emphasis is, unfortunately, becoming the limiting factor in effective converter design. This is likewise confirmed by Patterson and Hennessy with regards to computer design, "This situation doesn't make sense…(because) I/O capability is often one the most distinctive features of the machines [4]." Hence the motivation for this work.

Due to fundamental physical differences between computers (information processors) and power electronic converters (power processors), many aspects of the bus-centered architecture will not be transferable. In computer systems, the principal metric of bus performance is bandwidth and latency. In power converter systems the principal metrics of performance are power throughput and power density. This will primarily be a function of the capability of the connective networks carrying electrical power network and cooling. The "bandwidth" of the electrical power bus is a secondary characteristic that can limit power throughput. Scalability of the bus-centered approach will also be of interest. One of the most important issues to be investigated is the degree to which the practicality of the bus-centered approach to power converters connection scales with increasing power rating.

Nonetheless, some lessons from the computer industry will be extensible to the power converter industry. For example, the nature of the specification of the bus standards is paramount to its success. A bus standard that is poorly defined, overly restrictive, does not allow for adaptation, or does not address the needs of industry will quickly become an unused relic. This will be particularly relevant when trying to introduce a new approach to converter design to a potentially skeptical industry.

1.1.2 VLSI

Inspiration for a new approach to the power electronics design – manufacturing cycle is found in aspects of the microprocessor design and engineering process known as very large scale integration (VLSI). At its advent, VLSI revolutionized the nature of the microprocessor design and manufacturing activity into a more vertically oriented process. It is believed that the aspects of the VLSI approach can be employed to transform the power electronics design and manufacturing process from a scattered, disjointed process into a coordinated, high level activity.

VLSI enables processor designers to describe the system at a high level. From this design description, after being verified, automated engineering software directly produces the wafer fabrication layout information, or patterning files. These pattern files are then processed by a foundry to produce the specified integrated circuit. This vertical orientation of the design process allows the system designer to specify the system on a functional level, largely independent of the specifics of the process technology [5]. An illustration of this process is presented below in Figure 1-2.

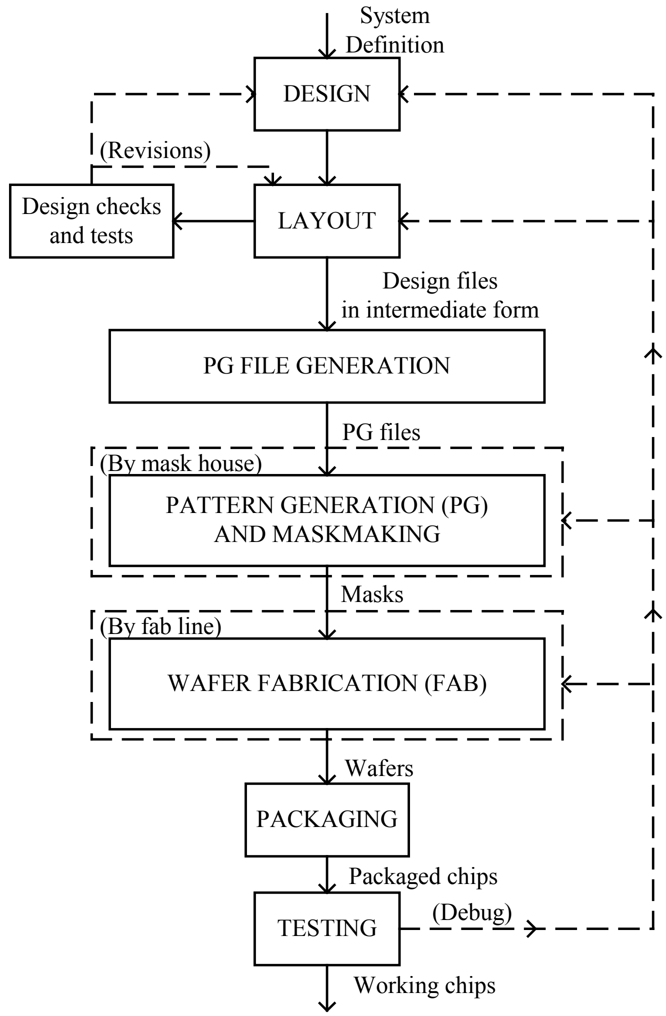

Figure 1-2 Overview of implementation of a VLSI integrated system [5].

It is believed that the power converter design activity can be oriented in a similar manner. In such a system, the power converter designer could specify the power converter functionality and a handful of key parameters in a high level graphical environment. Complete design and manufacturing information describing the converter is generated in an automated manner drawing on a range of standardized components, within the rules of the architectural framework. Obviously, there are several pieces have to be in place before this process can be implemented. Specifically, the range of standardized components and connective frameworks must exist and be clearly defined in the design and manufacturing environments.

1.2 Contemporary Power Converters

In contrast to computers, microprocessors, and products from other electrical industries, the process of power electronics design and manufacture is rather archaic. While the range of types and ratings of power converters is rather large, most follow a similar path from concept to production. Recent attempts to increase converter performance and cost have focused largely on the integration and packaging of the switching devices of a converter. These efforts still neglect the increasingly costly balance of system components and, more importantly, the mechanisms by which these components are connected.

1.2.1 Custom Design and Manufacturing

An overwhelming fraction of contemporary power converters are designed on a per application basis. Design information (component selection, circuit layout and packaging and mechanical design, thermal analysis) must be reengineered for each design. Due to the complex and interdependent of converter engineering, the design process is usually splintered across several software platforms. Accurate characterization of converter performance and product design typically requires the following collection of software tools: circuit simulation; finite element analysis (FEA) (for thermal and electromagnetic behavior and predicting lumped parasitic circuit properties); solid modeling (for design of packaging and assembly, and generating the FEA model);

engineering software for control and system design (e.g. MATLAB-Simulink); CAD for printed circuit board layout;

In a similar manner, the manufacturing process changes for each design. Power converters commonly employ many layers of packaging. Inductors, wiring assemblies, stacked circuit boards, and converter subassemblies typically require assembly and integration by hand.

Figure 1-3 Manual assembly of power electronic converters [6].

This costly process often comprises a very large fraction of the total converter assembly cost, especially when compared with other electronics assemblies, such as personal computers and consumer electronics.

While this custom design and manufacturing process makes sense for some types of applications, it is certainly suboptimal for many others. Converters that are smaller in size and are produced in high volume typically warrant this custom approach to design and manufacturing. These converters usually come in industry standard sizes (brick, half brick, rack units, etc.), are rated up to 500 W, and are configured to process DC/DC or

AC/DC. The most common applications for these converters are in personal and industrial computers, telecommunications equipment, industrial process equipment, automobiles, and the like. In some cases, low power electric drives produced in sufficiently high production volume also warrant this customized design and manufacturing process.

It is the combination of high production volume and relatively small size makes the customized process economical. The high volume allows the manufacturer to amortize the nonrecurring engineering costs and custom manufacturing setup over many units. In addition, the small physical converter size (and presumably small cost) makes it more practical and economical to replace the entire converter in the event of a component, device or subsystem failure. Even among these smaller custom built commodity converters, there is an increasing push for industry wide standardization [7].

In contrast to the smaller commodity converters, high power converters used in utility applications, power supply backup, wind and photovoltaic conditioning, and high power electric drives are typically much larger in physical size and produced in smaller volumes. The customized approach becomes quite costly when this large production volume – small physical size pairing does not exist. Nonetheless, these larger converters are still designed and manufactured in a customized manner. As a result, the initial engineering and manufacturing setup costs typically constitute a much larger fraction of the unit costs.

Secondly, these high power converters are typically too expensive to simply replace completely in the event of a subsystem or component failure. Unfortunately, the customized nature of the design makes repair of these larger converters very costly. Each converter design, while often fundamentally similar on a topological level, differs in implementation, layout, component package selection, etc. Servicing a disabled converter requires considerable knowledge of the specific design. As a result, the customized approach is a double penalty for these larger converters.

1.2.2 Integrated Power Modules and Component Packaging

Recent industry efforts to improve power converter performance, power density, reliability and cost have focused largely on the packaging of power switching devices. The result of these efforts has been increased integration of power devices [8]. In many applications, discrete packages are being replaced in favor of integrated power modules (IPM). At a minimum, IPMs incorporate multiple power switching devices into one package. A common example of this is a 6-pack, which contains six insulated gate bipolar transistors (IGBT) and anti-parallel diodes in a 3 phase inverter configuration. External and internal pictures of 6-pack IGBT modules are presented in Figure 1-4 and Figure 1-5.

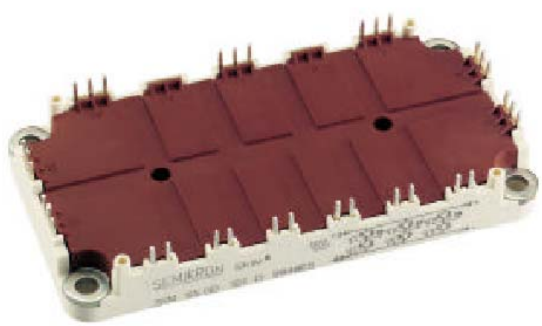

Figure 1-4 External view of 6-pack IGBT module manufactured by Semikron [9].

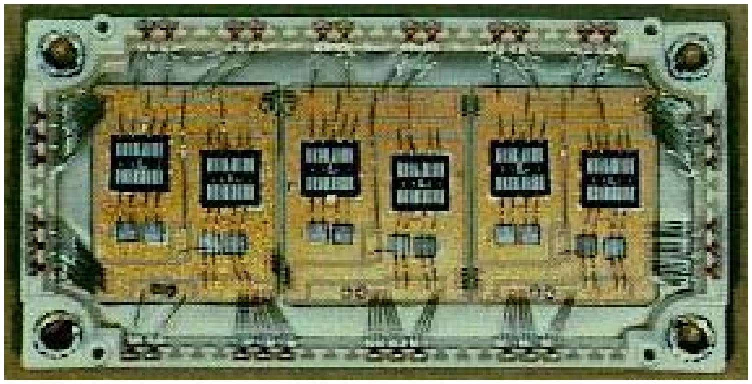

Figure 1-5   Internal view of 6-pack IGBT module manufactured by Infineon [10].

Many IPMs are going beyond just the power devices and incorporating some or all of the following ancillary power device functions: gate drive; protection; auxiliary snubbers; logic; isolated power supply; sensors; digital and/or analog control. Examples of this approach are presented in Figure 1-4 through Figure 1-6.

Figure 1-6   3 phase IGBT-diode IPM with integrated control, gate drive and other functions, manufactured by International Rectifier [11].

The emphasis on packaging and push toward increased integration does not, however, extend very far into the components that make up the balance of system for most converters. These components, such as inductors, capacitors, fuses, EMI filters, fans, heatsinks, connectors, etc. make up an increasing fraction of the component and assembly costs of typical converters.

Many components are available in de-facto industry standard packages, and geometries. Unfortunately, this standardization is rather limited in scope. In most cases the standardized package is driven by one particular application or market. In other cases the design of the standardized package is narrowly on the component itself, and does not consider the context of a typical application. Standardized packages for semiconductor devices and passive components are rather disparate and usually geometrically incompatible. As a result, integration of these components into an electrically, thermally and volumetrically compact design is rather difficult. In addition, any particular layout is at the whims of larger market forces; a shift in packaging by one driving industry (like telecomm power supplies) can result in component or package obsolescence.

Only recently, have some in the power electronic industry begun to realize the importance of a coordinated effort in the packaging of the entire converter [12,13]. These efforts have focused only on medium and low power DC/DC converters. Even still, packaging is only part of the picture.

1.3 Current Research

The proposed Bricks-&-Buses framework for power converter realization is not entirely without precedent. One of the most relevant examples is the power electronic building block (PEBB) program. Other interesting research has been done to create a new framework for power packaging, and incorporating computer automation to the power electronics design process. Unfortunately, however, the primary focus of these efforts is still on the power device itself. As a result, the remaining elements of a power converter system and their connection get scant coverage.

1.3.1 Power Electronic Building Blocks (PEBB)

PEBB is the product of research sponsored by the Office of Naval Research and the Department of Defense. The goal of the PEBB project is to enable increased electrification of the Navy's propulsion, actuation and high power weapons systems on ships, submarines and aircraft. PEBB aims to achieve this through increased power density, plug and play modules, and multifunctionality. The intended result of this effort is a set of universal power processors that are capable of sensing source power and automatically producing the required output power [3,14,15,16]. PEBB has recently been proposed for a range of other applications, including utility power electronics and commercial appliances [17, 18].

The PEBB approach proposes using modular components to make up a power converter. PEBB, however, is highly centered on the development of the module containing the converter switching devices. Essentially this is an extension of the IPM development. As a result the remaining elements of a converter and the network of connections between converter elements are as secondary issues.

Flexibility of the PEBB architecture is also a concern. Excessive integration and specialization of the IPM can quickly limit applicability. The lack of focus on a generalized approach to integration of the entire converter will inevitably produce a system that is only suitable for select application. In addition, PEBB is historically rooted in a set of specific applications that are of particular interest to the Navy (60 to 400 Hz converters, motor drives, circuit breakers). As a result, the PEBB framework is not explicitly designed to allow for flexibility in the areas of topologies and design goals.

Still, the PEBB program has produced some developments that may be applicable to the proposed Bricks-&-Buses framework. IPMs and similar modules may be incorporated into the Bricks-&-Buses geometric framework in some fashion. Lessons from the PEBB – derived virtual test bed (VTB) software engineering environment may also be extendable [19]. In addition, the PEBB program does address some important issues with regard to layers hierarchical control within the subsystems of any one converter [20]. Likewise, some PEBB – related research has proposed a coordinated approach to interconnection of power converter elements [21].

1.3.2 Packaging Framework and Automated Design

One of the more interesting works outside of the PEBB program has been the work by Hopkins et al. on a framework for developing power electronics packaging [22]. This framework intended to provide a guide for power electronics packaging design and development. It is important to note, however, that the framework appears to be intended to aid in the custom design process. As such, it does not explore the prospect of standardized system as proposed by the Bricks-&-Buses approach. Nonetheless, it presents several ideas that may be applicable to the Bricks-&-Buses effort.

The foundation of the framework is a four-dimensional design space based on the following criteria: user requirements; levels of packaging; interfaces and pathways; four forms of energy. This framework is interesting in many respects. First, the high degree of abstraction allows the framework to be broadly applicable. Second, the framework addresses the complex issues of converter scale and layering (via the levels of packaging axis) and both the elements of the converter and the connective paths (via the interfaces and pathways axis). In addition, the circuit or switch-centric approach to power electronic design is replaced with an emphasis on forms of energy and energy flow. The theoretical framework is followed up with an application to a specific design process [23].

Another interesting paper presents results of an object oriented software tool for power electronic design automation. This system allows the engineering to design the converter on a schematic / topological level and employs an inference engine to select optimum components from a database [24]. Such a system might form the foundation of a more comprehensive software tool for automated design of the integrated Bricks-&-Buses converters described in the following chapters.

Chapter 2 Bricks-&-Buses

This chapter lays out the vision for the Bricks-&-Buses framework for power converter realization. The foundation of this approach is a more generalized view of the electric power conversion process. Properties of the constitutive physical elements of this approach, namely the bricks and the buses themselves, are described. Upon this foundation of physical elements is built a high level design environment. This chapter concludes with a discussion of the envisioned Bricks-&-Buses design and manufacturing cycle. Practical implications and limitations of the framework introduced in this chapter will be explored in Chapter 3.

2.1 A New Perspective

Historically, improvements in the process of electronic power conversion have been tied developments in semiconductor switching device technology and circuit topologies. This is understandable. Performance and cost of early converters were constrained by the limitations of these technologies. However, sustained research in these areas has resulted in significant strides in device performance and topological development [25,26].

Another result of this research emphasis is the traditional view of a general power electronic conversion system, as shown in Figure 2-1.

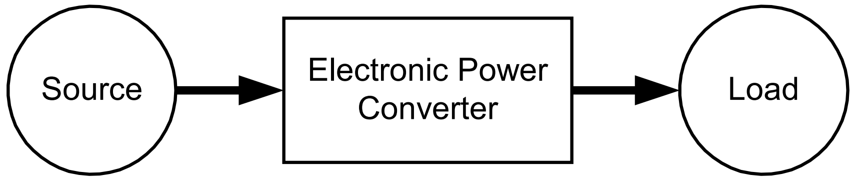

Figure 2-1 Conventional view of the generalized electronic power converter

This view is accurate to the degree that the primary function of an electronic power converter is to condition electrical energy from a source into a form that is easily digestible by a load. However, as a consequence of advances in the "electronic" aspects of power converter technology, this view no long incorporates the increasingly important and costly aspects of power converter design and research. As a result of device improvements (smaller sizes and increased switching frequencies) issues which had largely been ancillary to converter design (physical interconnection, packaging and thermal management) have consistently become limiting factors in achieving high performance low cost converter designs [22].

As a result, the electro-centric view of a power electronic converter artificially influences and restricts research activity on the other increasingly important aspects of design. An alternative and slightly lower level view of the general function of a generalized power converter is presented below in Figure 2-2.

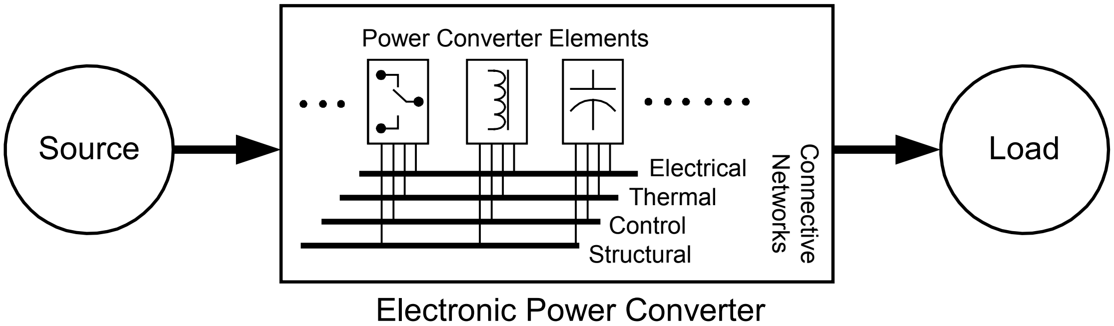

Figure 2-2 New perspective of view of the generalized electronic power converter.

This illustration, while still maintaining the central role of electrical power processing, highlights the increasing importance of other power flows and mechanism by which the elements of the converter are interconnected. This properly emphasizes some of the most fruitful directions for productive research in the field of power electronics.

2.2 A Comprehensive Engineering Process

The vision of the Bricks-&-Buses framework for power converter realization is rooted in an engineering process that facilitates power converter design. This is achieved by abstracting much of the power electronics engineering process to a high level. This abstraction requires three pieces. First, an array of modular components, or bricks, from which any practical converter topology can be constituted. Second, a range of connective bus architectures that allows for straightforward interconnection of the bricks. Third, a software environment for describing the converter at an abstracted level, and that translates the abstracted description of the converter topology into engineering and manufacturing files, based on the predefined bricks and buses. For those familiar with computer programming, the proposed Bricks-&-Buses framework can be likened to a compiler for power converter design.

On a physical level, the brick and bus specifications dictate the nature of the electrical, thermal and mechanical interconnection of the functional components of a prospective converter. This is realized by requiring geometric compatibility between all of the functional components, or bricks, of a converter. This allows the bricks to be aligned along a common face(s), and connected via the appropriate electrical, mechanical, thermal and control networks, or buses. The bus connections and nature of brick-bus interface are standardized to ensure the proper functional operation of each brick, and to prevent cross-brick interference, such as electrical loading, EMI, data loss, excessive heating, mechanical misalignment, etc.

These specifications for the physical interaction and connection of the common elements of a power converter serve as the foundation of an engineering process that enables high level converter design. This engineering process provides a mechanism for automated translation of topological converter designs into hardware specifications. These hardware specifications can be readily used to manufacture the specified converter based on the standardized brick and bus components at a converter fabrication facility.

The proposed framework is believed to have significant benefits for the power electronics engineering industry. Some of the expected benefits include reduced costs, increased serviceability, accelerated performance improvements, and a cleaner design & manufacturing cycle. Conceptually, of course, it is not particularly difficult to imagine that such an integrated system for power converter realization can be created. However, it is less clear whether or not the benefits of such a system would outweigh the potential drawbacks. In order to provide a context for this discussion, the following sections of this chapter explore the constitutive elements of the Bricks-&-Buses framework.

It is important to note, that the following description of the Bricks-&-Buses framework is not an attempt to rigidly define the technical specifications and performance features. This description is intended to provide a general vision of the physical and practical properties of the element in the proposed approach. Complete design and specification of the specific technical properties of the bricks and buses will require significant collaboration among the most visionary and experienced engineers in the power electronics industry. This would likely be the result of an on-going industry consortium or committee of the IEEE and/or other Power Electronics societies.

2.3 Bricks: Modular Components

The viability of the Bricks-&-Buses approach for power converter realization requires a range of commercial available, modular, standard components that fit the appropriate connective framework. Beyond this, the bricks are seen as natural divisions of the power converter, with ideally no interference or cross coupling (such as thermal, electrical, EMI, etc.) between them. The success of these bricks, or modular components, in fulfilling their role in the converter framework is dependant on the following: first, the degree to which the components or subsystems of most power converters can be reengineered and repackaged into bricks; second, the degree to which this division into subunits is efficient for the converter as a whole.

The decision to package the converter elements as bricks is not an arbitrary one. This geometric configuration allows for the alignment of these components along one or more common faces. This facilitates the connection via the various buses. In addition, the brick shape makes it more straightforward to achieve high density converter designs. This, of course, assumes that the bricks themselves are designed for efficient use of volume (i.e. high power density or capacitance density, etc.).

In many cases, engineering and packaging of a typical converter elements into bricks is not difficult to image. Many of these elements amenable to being shaped as bricks. One example is a printed circuit board with power semiconductor device modules, associated gate drive circuitry, and isolated gate drive power, attached to a rectangular air-cooled heat sink. Other elements, such as electrolytic capacitors, may require more re-engineering to be converted into an efficient brick-like component.

Examples of representative converter bricks are be presented in the following subsections in order to provide a frame of reference for this analysis. The bricks described are: Power Switching Brick; Voltage Stiffening Brick; Current Stiffening or Transformer Brick; Control Brick; Sensor Brick; Auxiliary Utility Brick; Input Output Brick. This list is not necessarily exhaustive or exclusive. Other standard bricks that are not listed here may also be appropriate. In addition, certain applications may require creation of a custom brick to perform unique functions.

2.3.1 Power Switching Brick

The Power Switching Brick is the workhorse of most power converters. It contains power semiconductor devices responsible for the control of power flow. The generalized electrical topology for this brick is that of a single pole – double pole switch. Depending on the specific design, this brick would be the functional basis of a DC/DC or AC/DC converter. The specific Power Switching Brick device topology would vary with application. A particular power converter assembly might have various Power Switching Bricks, for rectification, DC voltage conversion, and inversion. If necessary, multiple bricks may be configured in tandem (parallel or series) to achieve the necessary power rating for any one conversion step.

The Power Switching Brick device configurations would be standardized in order to be suitable for a broad range of conventional topologies. As expected, the physical configuration of the Power Switching Brick would vary depending on power rating, voltage and device technology. Switching device technology could include Thrysitors, GTOs, IGBTs, MOSFETs, etc. The devices may be discrete or packaged as a module. The shape and packaging of the Power Switching Brick would likely change with device technology.

In addition to the power semiconductor devices, this brick would likely house some of the following: gate drive; power device protection; isolated power supply; signal isolation devices; heatsinks and thermal management; sensors; local voltage decoupling capacitance; snubber networks; soft switching networks. As such, it may be rather natural use an IPM or PEBB switching module as the foundation of the Power Switching Brick. This would be an excellent way to leverage those developments into the broad-reaching Bricks-&-Buses framework. In some cases, the IPM and PEBB modules may be overly integrated for the Bricks-&-Buses architecture.

Complications arise as IPMs incorporate more and more power semiconductor devices. It can be difficult to achieve even heat dissipation on the module substrate [26]. In addition, the increased number of devices in a module may make IPMs less attractive for the Power Switching Brick. It may be more optimal for a 3 phase inverter to be configured with 3 single phase inverter Power Switching Bricks as opposed a single 3 phase Power Switching Brick. Nonetheless, the IPM / PEBB will likely fit into the Bricks-&-Buses framework in some fashion.

Due to the presence of the heatsink, which is commonly brick shaped itself, the whole Power Switching Brick readily forms a brick-like shape. Representative air and water cooled Power Switching Bricks are presented in Figure 2-3 through Figure 2-6.

Figure 2-3 Representative air-cooled Power Switching Brick (1 of 2).

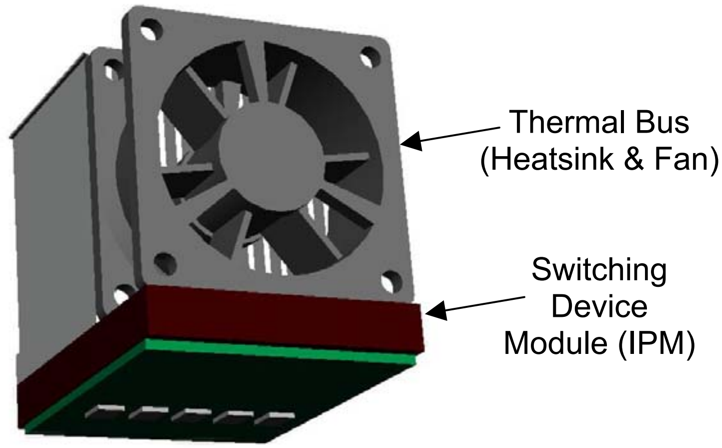

Figure 2-4 Representative air-cooled Power Switching Brick (2 of 2).

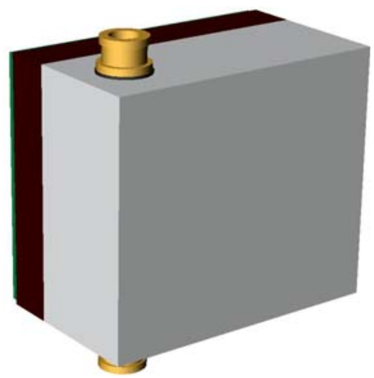

Figure 2-5 Representative water-cooled Power Switching Brick (1 of 2).

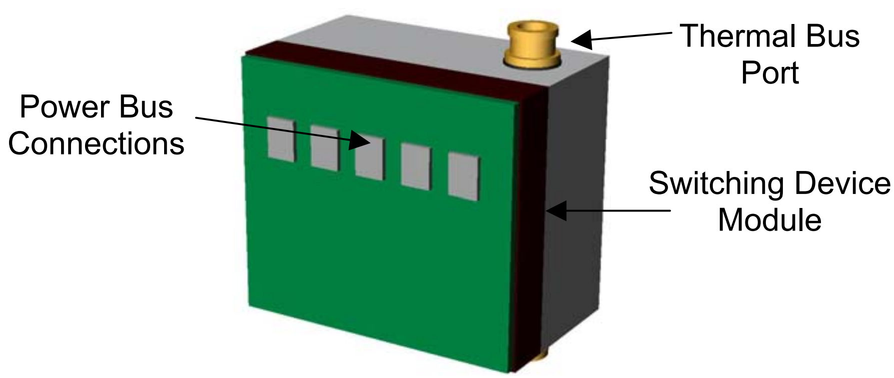

Figure 2-6 Representative water-cooled Power Switching Brick (2 of 2).

Electrical power connections to the Power Switching Brick are achieved via the Power Bus on the bottom side as indicated. Thermal bus connections will vary with power level and thermal extraction medium. In some low power cases, the Thermal Bus will degenerate to simply a force air heatsink, as shown in the first Power Switching Brick figure. Control Bus connections may, in some cases, occur along the same face as the power bus connections. Power Bus to Control Bus EMI will need to be investigated. Much of these variations depend on the power level and associated bus structure for the application.

The Power Switching Brick would be designed and packaged so as to mitigate the possibility of cross coupling between itself and any other sensitive elements of the converter. Specifically, this might include local voltage decoupling capacitance or snubbers to limit EMI inducing currents, heatsink design and thermal management to prevent heating of adjacent bricks, etc.

The Power Switching Brick functions according to commands received via the control bus. In the simplest case, these commands may be logic level gate signals. Or they may be more advanced, with a schedule of duty cycle commands. Internal sensors and signal isolation devices provide feedback information to the Control Brick, again via the Control Bus. Sensor data is converted into a digital format at the point of sensing. The sensor information could range from device voltages and currents to fan speeds and case temperatures. Sensors, logic and gate drives receive power from the Auxiliary Utility Brick via dedicated auxiliary power lines on the Control Bus.

2.3.2 Voltage Stiffening Brick

Not surprisingly, the Voltage Stiffening Brick is principally comprised of bulk capacitors. Electrolytic capacitors are typical for bulk DC decoupling applications. AC decoupling and high frequency filters will use various capacitor technologies, such as oil filled, film and others as appropriate. In some cases this brick may also include other passive elements to form a Π filter section. These bricks may also include various voltage and current sensors for use in feedback control or to limit Voltage Stiffening Brick capacitor ripple current.

It is slightly more difficult to image a brick shape with efficient use of volume made from conventional electrolytic or other cylindrically packaged capacitors. The cylindrical electrolytic package contains the rolled layers of the conducting plates and dielectric. A representative illustration of a Voltage Stiffening Brick from cylindrical capacitors is presented in Figure 2-7. An illustration of the rolled layers is presented below in Figure 2-8.

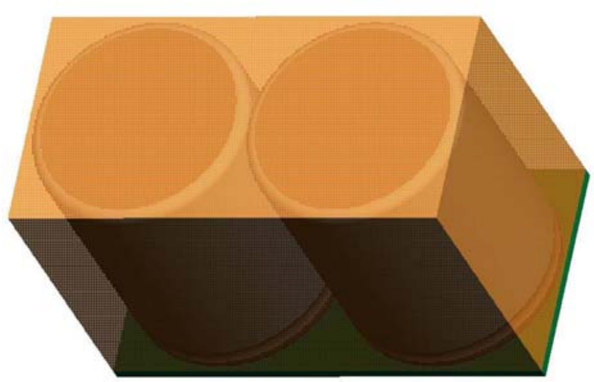

Figure 2-7 Representative Voltage Stiffening Brick from cylindrical capacitors.

Figure 2-8 Rolled electrodes in a cylindrical electrolytic capacitor.

Assuming that this shape is currently dictated by convenience and not physical reasons, there should be no reason why electrolytic capacitors (and other technologies as well) cannot be repackaged into high density brick-compatible shapes. One such to electrolytic capacitor package is presented in Figure 2-9. A Voltage Stiffening Brick made from these capacitors is presented in Figure 2-10.

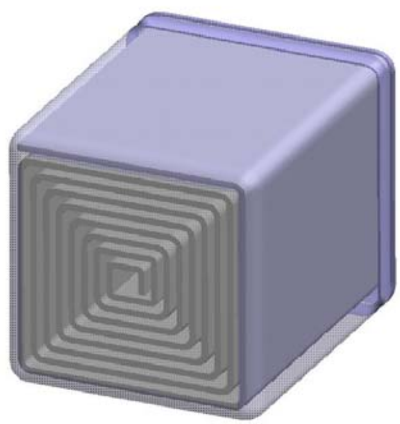

Figure 2-9 Electrolytic capacitor with electrodes repackaged in cubic shape

Figure 2-10 Representative Voltage Stiffening Brick from cubic electrolytic capacitors.

Electrical power connections are achieved via standard connectors to the Power Bus on the bottom of the Brick. Most Voltage Stiffening Bricks would have no Thermal Bus connections. Thermal management of Voltage Stiffening Bricks would usually be achieved with passive convection to the ambient air. However, in cases where limiting the capacitor temperature is very important (i.e. for electrolytic capacitor lifetime management), the Voltage Stiffening Brick could have explicit connections to the Thermal Bus. Integrated temperature sensors, if warranted, could be monitored by the Control Brick via the Control Bus in order to achieve reliability goals.

2.3.3 Current Stiffening Brick / Transformer Brick

The Current Stiffening Brick and Transformer Brick are described together due to their physical commonality and reliance on engineering of magnetic materials. Not surprisingly, Current Stiffening Bricks are essentially inductors. Even more obvious is the Transformer Brick.

Like electrolytic capacitors in the Voltage Stiffening Bricks, most inductors and transformers require some degree of reengineering to be efficiently fitted into the brick package. Torroidal inductors, for example, are not naturally inclined to efficient packaging in rectangular volumes. Nonetheless, several existing magnetic forms, such as E-cores, lend themselves to more straightforward conversion into an efficient brick package. These could be made form soft powdered iron or other similar material. Likewise planar magnetic technologies might also be adaptable to the brick format [27, 28]. An illustration of such an E-core is presented in Figure 2-11. A Current Stiffening Brick / Transformer Brick made from such an E-core is presented in Figure 2-12.

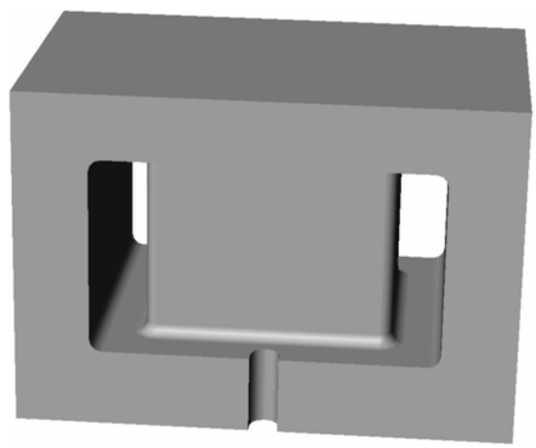

Figure 2-11 E-core for integration into brick package.

Similar to the Voltage Stiffening Brick, electrical power connections are achieved via standard connectors to the Power Bus on the bottom of the bricks. Most Current Stiffening Bricks and Transformer Bricks would not have Thermal Bus connections. However, as for the Voltage Stiffening Bricks, explicit Thermal Bus connection may be appropriate for some applications. Integral current or voltage sensors could be monitored by the Control Brick as a part of a feedback control system.

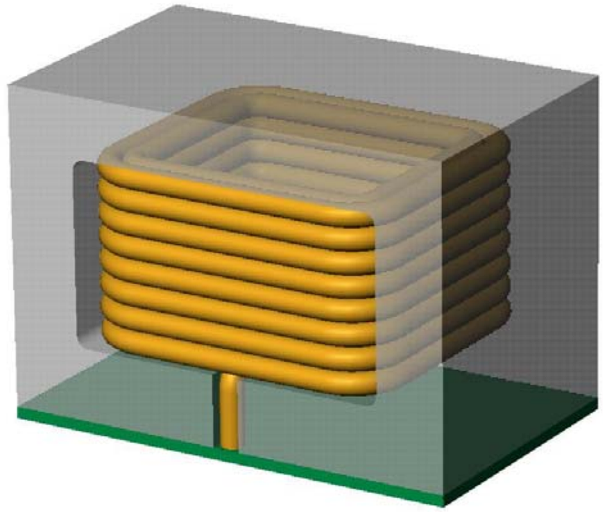

Figure 2-12   Representative Current Stiffening Brick or Transformer Brick.

2.3.4 Control Brick

The Control Brick forms the brains of a typical Bricks-&-Buses converter. The core of the Control Brick is typically some type of digital computer, such as a digital signal processor (DSP) or other microprocessor. Depending on the application, the Control Brick might also contain memory, a field programmable gate array (FPGA), logic isolation circuitry, and a port for external communication (TCP/IP, wireless, or infrared), and voltage regulation. The block diagram of a typical Control Brick is presented in Figure 2-13.

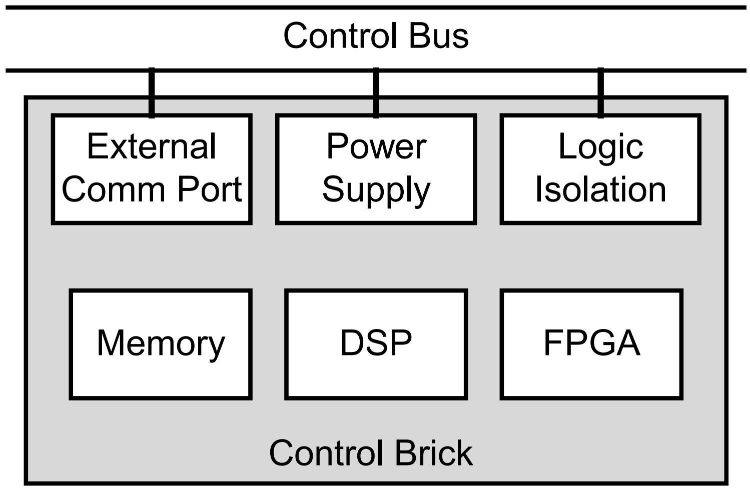

Figure 2-13 Block diagram of a Control Brick.

The Control Brick communicates with the other converter components via the Control Bus. Communication is regulated to achieve real-time data exchange via controller area network (CAN) or other appropriate protocols. The Control Brick receives power from the Auxiliary Utility Brick via dedicated auxiliary power lines of the Control Bus. Aside from the Control and Structural Buses, the Control Brick requires no other bus connections. The Control Brick will likely be shielded to prevent electromagnetic interference problems due fast switching currents and voltages from the rest of the power converter

Control Brick software can be generated automatically based on the control objectives specified during the high level design process. In addition to voltage and current regulation, the control can be designed to limit device and component temperatures, and coordinated control objectives with other converters. A master-slave or distributed control architecture may be implemented if multiple Bricks-&-Buses converters are required to achieve power throughput or performance goals. As such, the

Control Brick may interface with an external control bus to enable networked real time control.

2.3.5 Sensor Brick

An explicit Sensor Brick (SB) may be necessary in cases where voltage or current sensors imbedded in existing bricks are insufficient. Many types of sensors options are available beyond voltage and current. In addition, the Sensor Bricks may infer the property of interest through an observer or state estimator.

The sensor brick communicates with the Control Brick via the Control Bus. All of the sensor data is converted to a digital format at the point of sensing within the Sensor Brick to improve noise immunity. The Sensor Brick receives power from the Auxiliary Utility Brick via dedicated auxiliary power lines on the Control Bus. The Sensor Brick may also connect to the Power Bus or Thermal Bus as necessary for measurement purposes.

2.3.6 Auxiliary Utility Brick

The Auxiliary Utility Brick houses much of the hardware necessary for proper converter operation. Specifically, the Auxiliary Utility Brick may provide EMI filters, inrush current limiters, toggle switches, relays, circuit breakers, lights, etc. These components, while not typically emphasized in most power electronics research, constitute a nontrivial amount of engineering time, volume and cost in a typical converter.

In addition, the Auxiliary Utility Brick may also house the Auxiliary Power Supply, if that power supply is not broken out in its own brick. The Auxiliary Power Supply provides power for operation of the various subsystems in the converter, such as: Control Brick; gate drive, sensors, and fans in the Power Switching Brick; sensors in the Voltage Stiffening Bricks and Current Stiffening Bricks; Sensor Bricks; etc. Auxiliary power is transmitted via dedicated lines of the Control Bus. Further segmentation of the dedicated lines may be necessary for logic level DC power and high frequency AC power for the isolated gate drive power supplies.

The Auxiliary Utility Brick will connect to the appropriate lines of the Power Bus to power the Auxiliary Power Supply and operation of the other components (current limiters, EMI filters, etc.). Thermal Bus connection may also be necessary for cooling of the Auxiliary Power Supply, or other Thermal Bus functions. Control Bus connections enable the supply of auxiliary power and receipt of commands from the Control Brick.

2.3.7 Input Output Brick

The Input Output Brick provides a locus for external converter connections. At the minimum, input and output power connections will be accessible through this brick. In specific applications, the Input Output Brick may also accommodate connections for external control signals to the Control Brick and channels for external supply of the Thermal Bus working fluid (i.e. coolant input / output ports).

2.4 Buses: Connective Architectures

The Bricks-&-Buses approach for power converter realization requires a set of connective architectures, or buses, to enable efficient, predictable, high performance operation of the various bricks within the converter. The buses are functional division of the connective networks of a converter. The role of buses, while complementary to the bricks, is just as important to the success of this approach. The success of the buses in this converter framework is dependant on the following: first, the degree to which the connective aspects of most power converters can be separated on a functional basis; second, the degree to which these buses can be reintegrated with the bricks to achieve high performance converter designs.

The connective networks with the converter divided on a functional basis in order to facilitate modular converter construction. As described in section 1.1, the Bricks-&-Buses architecture is inspired by the bus – centered architecture of conventional computer systems. Extending the bus concept to a power converter results in multiple buses; responsible for handling electrical power, thermal energy removal, control and sensor information and structural support. These buses are named Power Bus, Thermal Bus, Control Bus, and Structural Bus.

The buses are designed so as to take advantage of the natural geometric alignment of the bricks. Brick-bus connections are made along common converter faces. Fasteners are designed to be naturally positive locking, and require few or no tools for disassembly, exchange, and reassembly. Examples of representative converter buses are be presented in the following subsections in order to provide a frame of reference for this analysis.

2.4.1 Power Bus

The Power Bus is the central artery of a Bricks-&-Buses power converter. The Power Bus is responsible for all of the high power electrical connections between the bricks of a converter. In most applications, the Power Bus will connect the Power Switching Bricks, Voltage Stiffening Bricks, Current Stiffening Bricks, Sensor Bricks, Auxiliary Utility Bricks, and Input Output Bricks as specified by the converter topology.

The materials and design of the Power Bus will depend largely on the power rating (voltage and current ratings) of the converter design. However, most of the proposed designs are planar in nature. This structure has characteristically low per unit length inductance and resistance and excellent high frequency conductivity.

One option for a medium power rated Power Bus is an etched copper board, much like a high current PCB. A higher current and voltage Power Bus may be created from a stack of laminated copper bus bars. In both cases, the routing of the conductive paths of the Power Bus would be generated automatically from connectivity specified during the high level design process.

Electrical connections between the various bricks and the Power Bus would be mechanically straightforward. The most preferable connection system requires no tools and achieves a reliable, high conductivity connection between the bus and the electrical terminals on the bricks. Spring tabs or other compression related connectors on the bricks could be held against the terminals on the Power Bus from the compressive force of the Structural Bus connections.

Laminated bus bar assemblies from two different manufacturers are presented below in Figure 2-14 and

Figure 2-15.

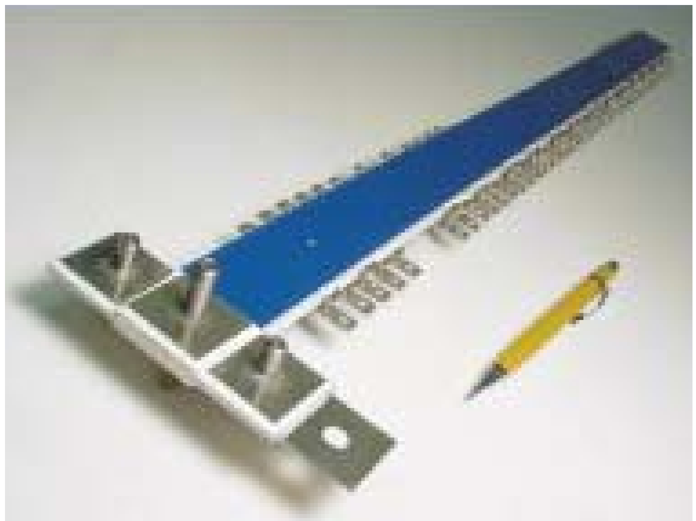

Figure 2-14 Laminated bus bar assembly, manufactured by Bussco [29].

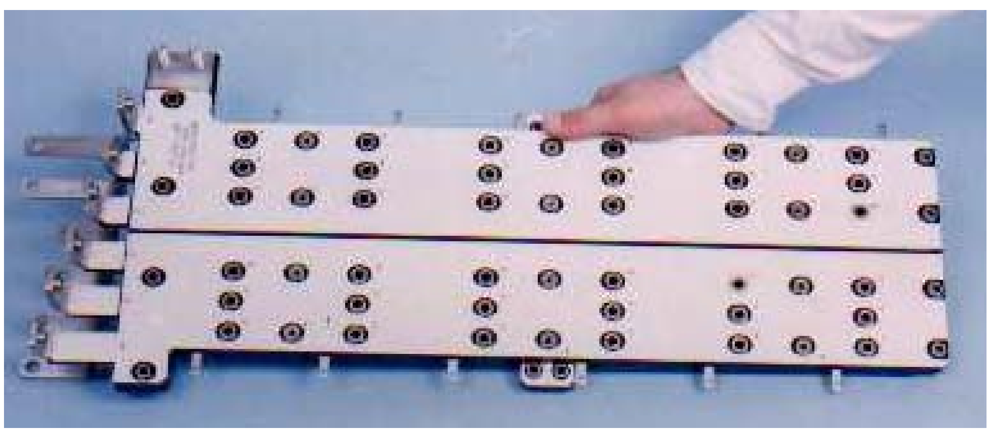

Figure 2-15 Laminated bus bar assembly (300 V, 500 A), maufactured by Eldre [30].

These two assemblies are not intended to be representative of specific Power Bus designs. They, instead, illustrate the feasibility of creating a high power rated Power Bus with current bus bar technology.

2.4.2 Thermal Bus

The Thermal Bus is responsible for heat extraction from the Power Switching Bricks and other hot spots in the converter. A typical Thermal Bus will draw in a low temperature fluid form an external source, direct it across high surface area heat spreading elements (i.e. the fins of a heat sink or channels in a water cooled block) and return it at a higher temperature to an external sink. In most cases the Thermal Bus will use either air or water as the coolant medium.

Specific bricks will typically regulate their own coolant flow, whether by fan or valve, as commanded by either the brick itself or from the Control Brick. In converters where coolant flow is not regulated on a brick-by-brick basis, the Thermal Bus must be designed so as to minimize the effects of thermal loading. The coolant distribution must not excessively cool bricks closer to the low temperature coolant source at the expense of the bricks that are further away.

For low power, air-cooled converters not operating in a vacuum, the Thermal Bus may not even be an explicit connective network. Instead, all bricks requiring cooling will have independent heatsinks with dedicated fans. The fans will be controlled to achieve the required device temperatures. In this case, the Thermal Bus is trivial. The air is drawn from and returned to the ambient environment. However, the converter has less control over the thermal extraction process with such an open Thermal Bus. Some air-cooled converters could have an actual enclosed network, directly channeling air to bricks that require cooling.

Most water coolant based Thermal Buses will employ a network of piping to direct the coolant to the appropriate bricks. The piping may be a set of machined channels in a two piece bar, or a set of pipes fit together to achieve the necessary connectivity. Needless to say, it is paramount that the system be highly reliable with regards to leaking and seal integrity.

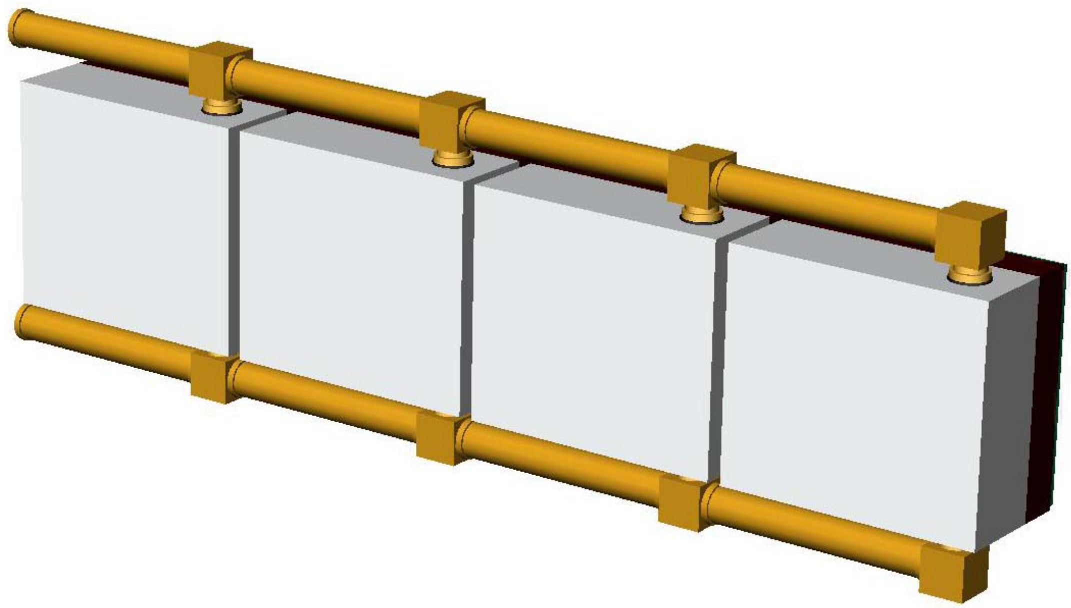

Figure 2-16 Representative water coolant-based Thermal Bus with four Power Switching Bricks.

2.4.3 Control Bus

The Control Bus is responsible for carrying control and sensor information and other data between the bricks. Dedicated lines of the control bus will also carry auxiliary power from the Auxiliary Utility Brick. The connectivity of the Control Bus will be automatically generated as a part of the high level design process.

In most cases the Control Bus will be comprised of a set of electrical conductors that carry digital logic signals in the range of 5 volts. The electric conductors will likely be in the form of either a ribbon cable or some type of printed circuit board (PCB) or printed flex circuit. These conductors will be connected to the bricks via snap in connectors. The Control Bus must provide immunity from dv/dt and di/dt induced EMI from the Power Bus, through either shielding or tight electrical layout. Special applications may warrant fiber optic interconnections or a local wireless network, such as Bluetooth, for the data connections.

Several options exist for Control Bus data format. One of the simplest is a set of address and data lines that are arbitrated by the Control Brick. The Control Brick indicates the brick to serve as the source or destination of the information in the data lines by use of the address lines. A master clock can be used to synchronize converter-wide sensor acquisition or command updates in all of the bricks. Alternative Control Bus approaches may use a controller area network (CAN) or other appropriate data protocol.

2.4.4 Structural Bus

The Structural Bus is simply an abstracted term for the mechanical connections that provide mechanical strength and form to the converter. In most cases the Structural Bus will be some type of mechanical chassis with mounting sites for connection of the various bricks and other buses of the converter. In addition to providing mechanical form to the converter, connections to the Structural Bus may provide compressive force to the electrical connections to the Power Bus and Control Bus.

The materials and design of the Structural Bus will depend on the physical size of the converter. One design option is a central beam on which the Power Bus and Control Bus are mounted. Converter bricks are then mounted off of each side of the central beam. The Thermal Bus is attached to the back side of the rows of bricks. Another option is a rectangular frame that encompasses all of the bricks and buses of the converter. Most Structural Bus realizations will likely be assembled from standardized aluminum or steel channel pieces.

2.5 Converter Assemblies

2.5.1 Individual Converters

This section presents some representative Bricks-&-Buses converter assemblies and a brief description of their properties. Both converters are roughly the same physical size and have the same general topology – a passive 3 phase diode rectifier, DC link and 3 phase IGBT inverter. The specific bricks and buses have not been optimized themselves, but are intended to be representative of components that would be used in the 5 to 20 kW range. The air-cooled 3-phase converter is presented in Figure 2-17 and Figure 2-18. The water-cooled 3-phase converter is presented in Figure 2-19 and Figure 2-20.

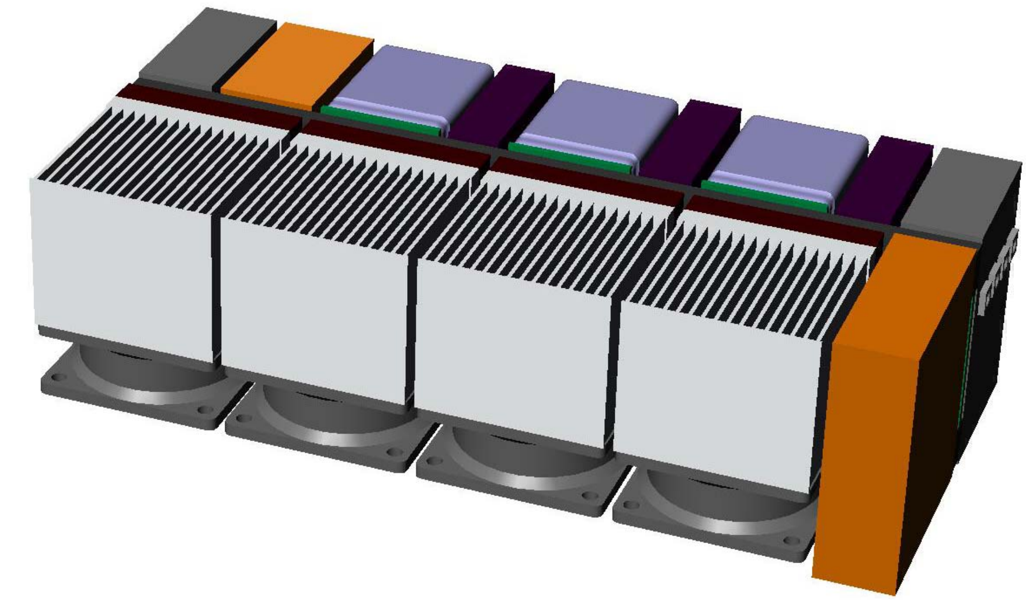

Figure 2-17 Air-cooled 3-phase AC/DC/AC converter (1 of 2).

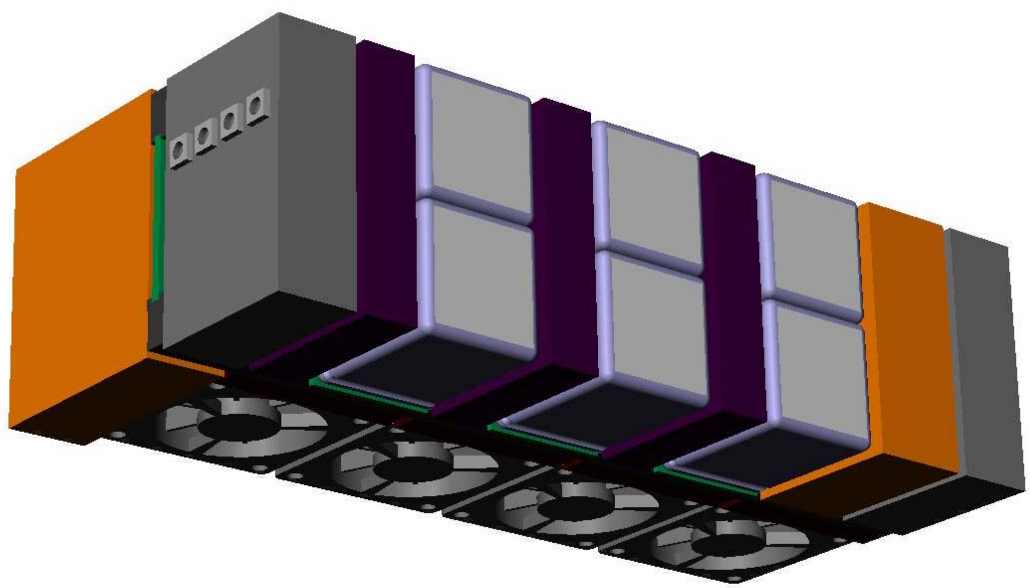

Figure 2-18 Air-cooled 3-phase AC/DC/AC converter (2 of 2).

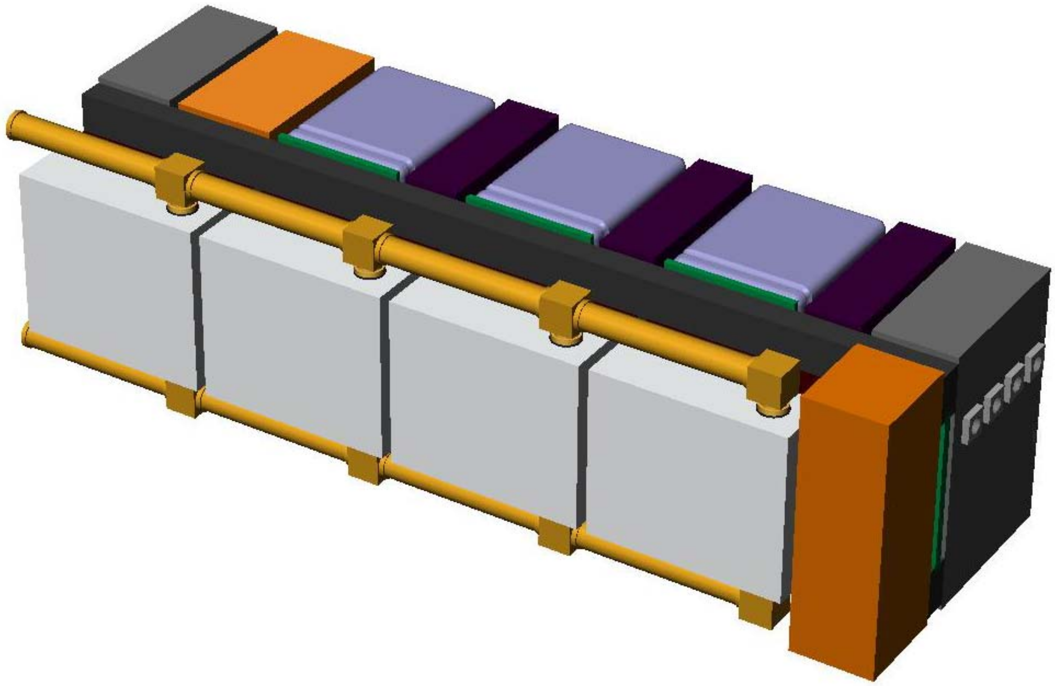

Figure 2-19 Water-cooled 3-phase AC/DC/AC converter (1 of 2).

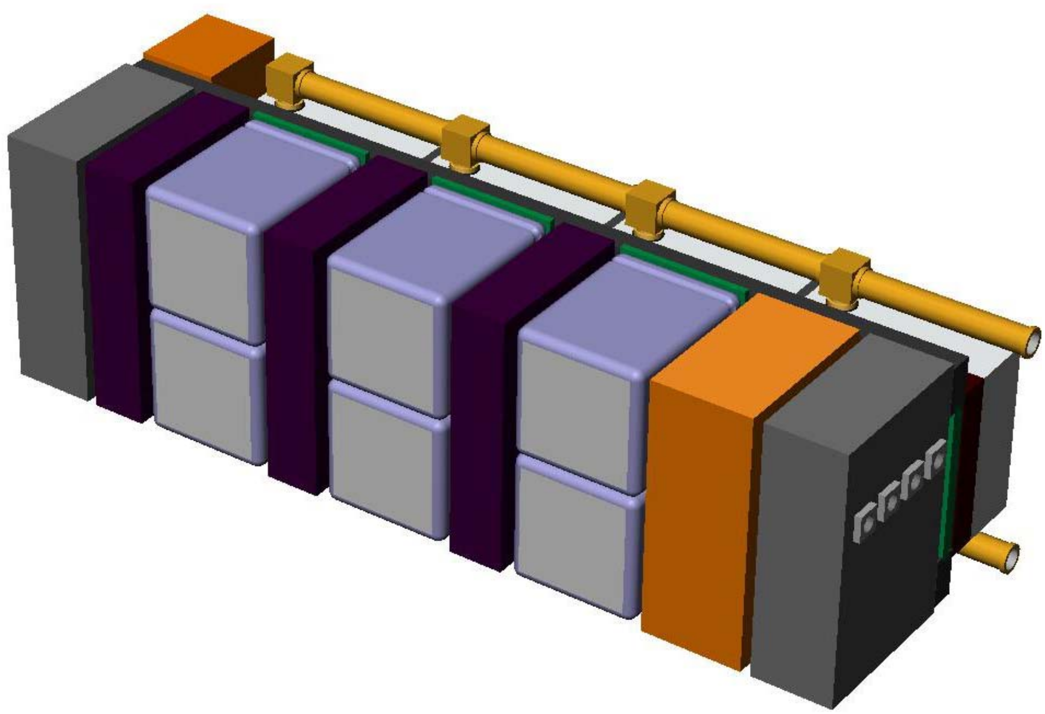

Figure 2-20 Water-cooled 3-phase AC/DC/AC converter (2 of 2).

These converters are roughly the same physical size – approximately the size of a large shoe box. Both converters are bus-centric – the Power Bus, Structural Bus, and Control Bus separate two rows of bricks. This configuration is largely the result of findings from the prototype hardware examined in Chapter 3. It allows the Voltage Stiffening Bricks to be located directly across from the Power Switching Bricks to increase the electrical stiffness of the DC voltage bus.

The Structural Bus of both converters is a mechanical frame that holds the Power Bus and Control Bus. The bricks attach to this frame via fasteners (not shown) on the top and bottom of the assembly. The Power Bus is made from a high current printed wiring board. The Control Bus is also made from a printed circuit board, and is located below the Power Bus in the same plane. Tight electrical layout and shielding, if necessary, should prevent any EMC problems.

The Power Switching Bricks on each converter are comprised of an IPM module and heatsink. In the case of the air-cooled converter the heatsink and fan on each of these bricks comprise the Thermal Bus. The heatsink on the water-cooled converter is connected to an explicit water supply and return network. The translation of the 3-phase AC/DC/AC topology to the bricks is as follows. The 3 phase diode bridge rectifier comprises one Power Switching Brick. The 3 phase inverter is comprised of 3 single phase inverters. This simplifies cooling and control.

Immediately across from the 3 single phase inverter Power Switching Bricks is a Voltage Stiffening Brick for decoupling the DC voltage bus. Next to each of the Voltage Stiffening Bricks is a Current Stiffening Brick for the pole of each of the inverter legs.

The remainder of the converter bricks are an Auxiliary Utility Brick, a Control Brick, a Input Output Brick and a second Auxiliary Utility Brick containing an EMI filter.

2.5.2 Multiple Converters

Multiple converters can be connected in series or parallel if power or other performance requirements cannot be met with an individual Bricks-&-Buses power converter assembly. The Bricks-&-Buses concept of modular units and connective architectures can be extended. In this scale, individual converters are bricks and are connected via buses (Power Bus, Thermal Bus, Control Bus, and Structural Bus) within a rack or complete assembly.

2.6 High Level Design Environment

The Bricks-&-Buses converter design process occurs in a computer aided design (CAD) environment at a high level. The basic converter topology is described with a graphical layout tool. The CAD system translates the graphical layout and key design parameters into a power converter manufacturing file. This converter manufacturing file provides sufficient information for the complete manufacture of the converter by an automated fabrication house. These elements of the high level design cycle, as currently envisioned, are described further below.

In most applications the converter design process begins with specification of the converter topology. This typically includes definition of both the circuit topology and a basic control block diagram at a high level. Specific components values and devices are not explicitly specified in most cases. Instead, several key converter performance and design parameters are specified along with the topological definition. An example of these would include maximum power, voltage, and current throughput, switching frequency, filter bandwidths, voltage and current ripple limits, reliability indices, and control objectives.

From this basic converter definition, the CAD translation engine generates a converter manufacturing data (CMD) file. The CMD file is functionally akin to the artwork used to describe the layers of a VLSI digital system or printed circuit board (PCB). However, in contrast to the data files from those two manufacturing processes (VLSI and PCB), the manufacturing file in the Bricks-&-Buses process does not graphically describe a layout or prescribe the coordinates of a photo etching or exposure tool. Instead the CMD file contains a listing of the bricks used in the converter, and their nodal connectivity via various specified buses. The CMD file can be used by a converter fabrication house to assemble the converter, through the use of the standardized Bricks-&-Buses elements. The envisioned manufacturing process will be described further in section 2.7. An illustration of the Bricks-&-Buses converter design and manufacturing process is presented in Figure 2-21.

Some design efforts will require more specification of the converter's low level properties. In those cases where specific or custom devices, component values or buses are required, the high level CAD tool will enable manual specification of the desired property. For example, a specific bus architecture or maximum parasitic inductance between two components is can be specified during the layout file translation process. Integration of a custom component into the design process simply requires introducing a brick definition file into the design library and manually inserting the custom component into the layout file.

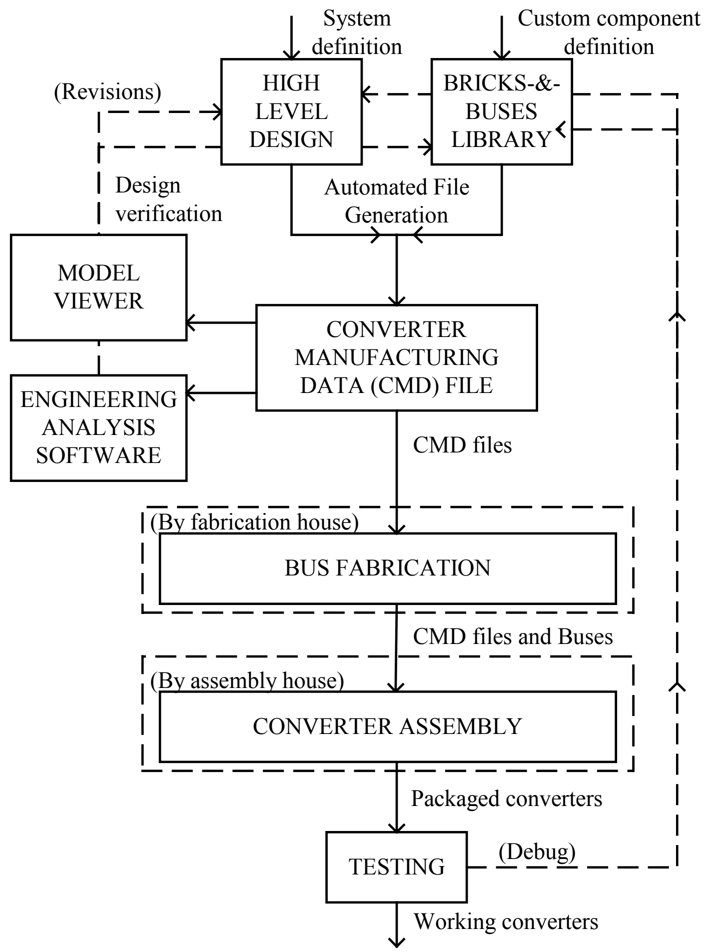

Figure 2-21 Bricks-&-Buses converter design and manufacturing process.

The layout translator will then integrated the custom component or manually selected device or component property into the remainder of the automatically generated converter design.

In many cases the design process requires an in-depth analysis of converter performance and operation prior to fabrication. As such, the CMD together with the brick and bus element definition library file can be used to extract specific physical properties about the converter design. In the simplest case the converter design can be verified at a lower level with an electrical circuit viewer, thermal circuit viewer, control topology viewer, solid model viewer, etc. For a more thorough analysis, the low level converter design data can be extracted for simulation or finite element analysis in any one of a number of engineering software tools such as PSPICE, SABER, EMTP, MATLAB-Simulink, Solidworks, ProEngineer, I-DEAS, etc. If necessary, the design can be changed in the graphical layout tool, and reconfirmed with the analysis tools and model viewers. Iteration on this process can be used to optimally tune a converter design for unusual applications.

2.7 Manufacture and Assembly

The Bricks-&-Buses production process begins with the converter manufacturing data (CMD) file generated during the design activity. This file, along with any custom bricks built to be integrated into the final converter, are all that is necessary production. This process of converter realization is intended to be entirely automated, eliminating costly custom setup and manual production design. The bricks and buses are selected from a range of manufacturers that meet the specifications of the industry standard framework.

2.7.1 Bus Manufacture

The buses are custom manufactured from standard components and processes to meet the specifications of the Bricks-&-Buses framework and achieve the connectivity specified in the CMD file. The specific technologies and processes of the bus manufacture process will depend on the Bricks-&-Buses specifications selected for a particular converter design. A description of a representative Power Bus manufacturing process is presented as follows.

The technology used building the Power Bus will obviously depend on the desired power, voltage and current rating and other requirements. A laminated stack of copper bus bars would be a likely technology for handing in the neighborhood of hundreds of amps and volts. The manufacturing house would be able to completely fabricate the complete bus from the data contained in the CMD file.

The CMD file would specify a small quantity of key information. First, would be the name (or identification number) of the Power Bus class in the Bricks-&-Buses framework. This would determine the gauge of bus bar to use, and the basic geometric framework that the final bus is to fit into (i.e. maximum number of layers, connection spacing, etc.). Second, the CMD would specify the Power Bus nodal connectivity between the connections of the various bricks and the bus. From this CMD information and a library file containing the standard bus specifications, a translation engine could generated the specific executable file for computer aid manufacturing process equipment (such as bus bar stamping, hole cutting, layering and laminating). A lower rated Power Bus might be made from a printed or etched circuit board. One can imagine similar automation of the printed circuit board layout and fabrication process.

Likewise the Thermal Bus, Control Bus and Structural Bus would all be fabricated in a similar manner. The CMD file would list the identification number of the particular bus class from the Bricks-&-Buses framework. Second, the CMD would specify the nodal connectivity between the various bricks and buses. This would be translated into executable for an automated manufacturing process.

2.7.2 Integrating the Bricks and Buses

Assembly and testing is the last step of converter production. The manufactured buses and the CMD file are sent to an assembly house for the final converter integration. The CMD will specify the arrangement of the bricks within the converter. Bricks that meet the specification of each class of the Bricks-&-Buses framework will be available from a range of manufacturers.

The Bricks-&-Buses framework is intended to facilitate automated converter assembly. This is achieved through a comprehensive and unified approach to connection in all aspect of the bricks and buses design specifications. An absolute priority will be to eliminate hand assembly operations.

All connections will be designed to be as simple as possible and require a minimum number of tools and fixtures. Positive locking brick to bus connections will improve reliability. With pre-built integrated bricks and custom bus assemblies, the number of connections to be made during assembly will be considerably reduced. This should accelerate assembly and help keep costs down.

In addition, the location and nature of the connections will be designed so as to be “automation friendly”. This can be achieved by having all of the connections positioned along one or two exposed faces. Another useful feature is to have the electrical connections (Power Bus and Control Bus) occur as a direct result of the Structural Bus connection. The Power Bus and Control Bus brick to bus connections result from mechanically securing the brick to the Structural Bus.

Chapter 3 Prototype Demonstration

3.1 Prototype Hardware Realization

A prototype hardware converter was designed and constructed in order to test the viability of the Bricks-&-Buses concept and more fully examine the practical implications and/or limitations of a standardized architecture. The focus of this prototype converter design was on geometric constraints, interconnection, modularity, parasitic bus effects, and interference. Consequently, many important aspects of conventional converter design were not emphasized, such as power density, optimization of brick form factor, etc.

The topology of the Bricks-&-Buses prototype is a single-phase AC/DC/AC converter. A solid model of this converter and a photograph of the as-built hardware are presented in Figure 3-1 and Figure 3-2. The high degree of conformance between the solid design and physical realization is readily evident.

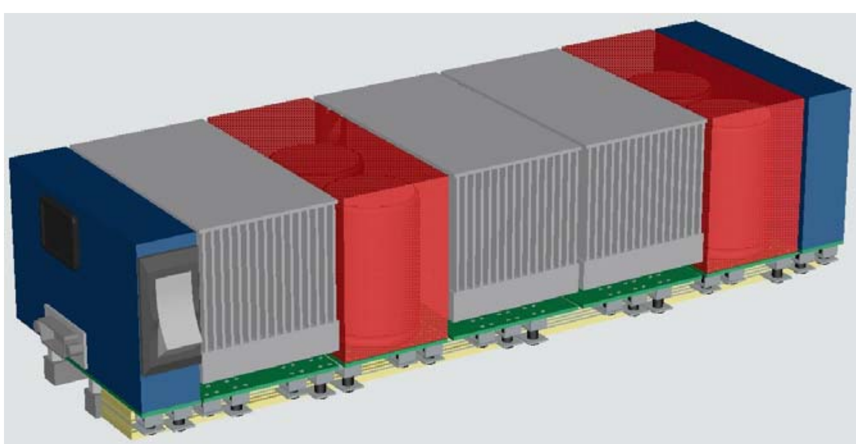

Figure 3-1 Solid model of the converter as designed in SolidWorks.

Figure 3-2 Photograph of prototype hardware.

3.1.1 Prototype Bricks

As the hardware was built during the process of the framework development, the bricks of this converter do not exactly correlate to those described in the previous chapter. From left to right, the functional bricks of this converter are as follows: Input Brick (blue), Power Switching Brick 1 (single phase diode bridge rectifier), Voltage Stiffening Brick 1 (red), Power Switching Brick 2, Power Switching Brick 3, Voltage Stiffening Brick 2 (red), Output Brick (blue). Power Switching Bricks 2 and 3 together form a single phase leg of an IGBT-diode inverter. Individually these two Power Switching Bricks can operate as a positive or negative referenced buck converter. A Control Brick, which would otherwise be part of the converter, has been omitted from this prototype to accelerate testing. The total dimensions of the converter are approximately 34 cm x 9 cm x 8.5 cm.

Power Switching Bricks 2 and 3 have isolated gate drive circuitry for the IGBT, and local bypass capacitance (0.4 μF) to limit switching device voltage overshoot. Power

Switching Brick 1 is a passive diode bridge rectifier. Fans are mounted on the back face of each heatsink to draw air in from the front – the Thermal Bus. The Power Switching Brick may be considered to be prototype integrated power electronics module that is thermally self-contained.

Control signals and source power enter the converter from the Input Brick on the left. The Input Brick contains routing for the Control Bus and Power Bus electrical connections. In addition the Input Brick has inrush current limiters, switch and circuit breaker. The output power connections are made via connectors on the right face of the Output Brick.

3.1.2 Prototype Bus Architecture

The buses of the first generation prototype were designed for simple bench top fabrication and assembly, while maintaining flexibility for reconfiguration. In this prototype the Control Bus, Power Bus and Structural Bus are physically independent but are all attached on the bottom face, as shown in Figure 3-3.

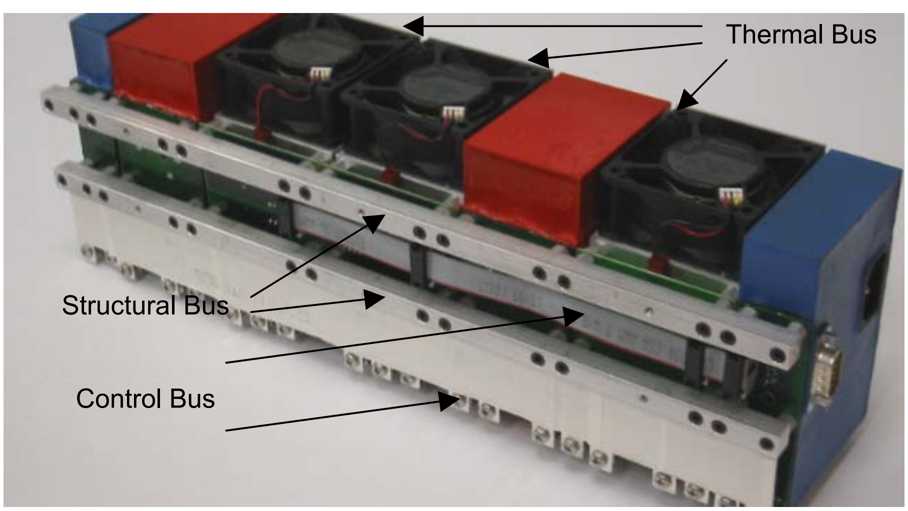

Figure 3-3 Bottom / back face of converter showing bus connections.

Locating all of the electrical and mechanical brick-to-bus connections on one exposed face facilitates automated manufacture. This also allows for easy brick removal and replacement in the event of component failure.

The Power Bus is made from insulated stacking of single conductor copper bus bars from the Eldre Corporation [30]. The appropriate bus-bar-to-brick electrical connections are made via screws to PCB-mounted terminals. This design choice for the realization of bus planes proved to be much more flexible and effective than that of a typical laboratory prototype. The converter is easily reconfigured from a split bus DC/AC inverter to a buck converter. Because of their flat cross section and small loop area, these bus bars have relatively low parasitic inductance.

The Structural Bus, Control Bus and Thermal Bus of the prototype converter are relatively primitive realizations of the vision laid out in reference [1]. The Structural Bus was fabricated from two pieces of aluminum bar stock. The bricks of the converter are attached via screws into standard hexagonal aluminum PCB standoffs. The Control Bus, a 10 conductor ribbon cable, provides gate signals and auxiliary power to fans and gate drive circuitry in Power Switching Bricks 2 and 3. This is simple but effective for this low complexity converter. As mentioned previously, there is no explicit network for the Thermal Bus. It is, instead, simply the ambient air through the fans and heatsinks on the Power Switching Bricks.

3.1.3 Parasitic Inductance of Power Bus

The electrical parasitic properties of the power bus can have a significant influence on the operating range of the Bricks-&-Buses architecture. In particular, parasitic self-inductance can produce device damaging voltage overshoot and limit the maximum switching frequency as a result during device turnoff. This section presents a first order analysis of the physical properties of Power Bus design as they relate to parasitic inductance in order to develop guidelines for future design revisions.

Voltage transients due to power bus self inductance are particularly problematic during device turnoff, potentially destroying the power switching device. A simplified electrical model of the DC bus as seen from the switching device is presented below in Figure 3-4.

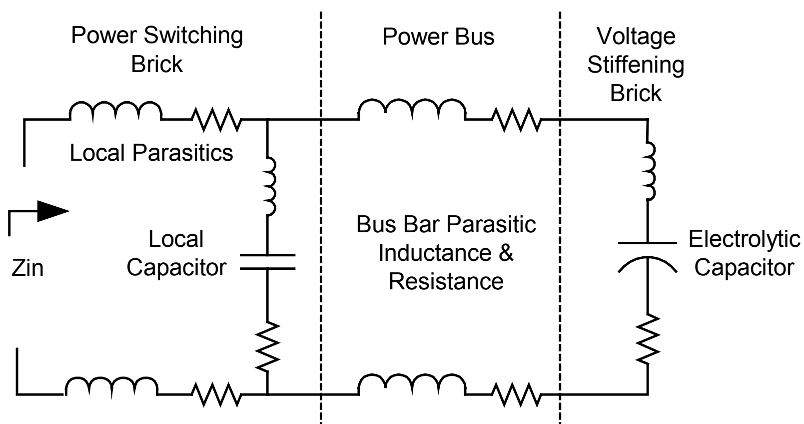

Figure 3-4 Electrical model of Power Switching Brick, Power Bus, and Voltage Stiffening Brick.

This model is appropriate for a first order analysis, neglecting higher order effects such as the distributed parasitic nature of the power bus, power bus capacitance, and the skin effect. The corresponding device voltage overshoot is a function of the device current turn off profile. To a reasonable approximation, the slope of the current transition, di/dt, is equal to the on state current divided by the fall time. While the minimum fall time is limited by the device characteristics, acceptable fall times for a specific application are often larger to limit EMI and overshoot. The effects of decoupling capacitance on the performance of the bus have been studied in detail in [31], and would serve as a springboard for further investigations.

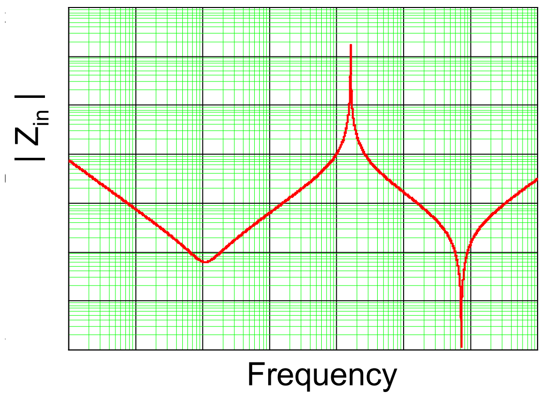

Figure 3-5 Typical normalized impedance seen by the switching device.

The input impedance presented in Figure 3-5 shows a pole with very high Q which is typically responsible for the voltage ringing overshoot. Additional local bypass capacitance reduces the frequency of the high Q pole and the peak amplitude of the response. Additional power bus inductance increases the pole frequency and the peak amplitude of the response.

The first prototype of the Bricks-&-Buses architecture uses parallel plate copper bus bars to connect the Power Switching Bricks to the DC electrolytic capacitor of the Voltage Stiffening Bricks. The per unit length self inductance, L', of these bus bars can be approximated based on the permeability, μ, bus bar width, w, and bus bar separation, d, as follows in (1). This inductance is in addition to any series self inductance of the brick PCB itself.

$$L' = \mu \, d/w \qquad (1)$$

In the modular Bricks-&-Buses framework, increasing the power converter rating can be as simple as changing out the Power Switching Brick. For a given DC bus voltage, an increase in converter power capability requires a proportional increase in switch current. Consequently, for same device turn off time, this produces a proportionately faster current transition, di/dt. As a result the switching device voltage overshoot increases in proportion to power flow. From another perspective, additional local bypass capacitance must be added to achieve the same voltage overshoot with increased power rating.

Unfortunately this becomes more challenging as the converter power rating increases. If one assumes a uniform heat distribution on heatsink base, the heat sink surface area must scale in linear proportion to the power flow to maintain the same case temperatures. For a specific brick size class (fixed height and depth) the Power Switching Brick width will be approximately proportional to the power rating. The result is an increase in the parasitic power bus inductance, necessitating increased bypass capacitance.

A more comprehensive investigation of this trade-off will be the topic of further research. However, it is apparent that the current architecture, in which the electrical bus connections are located on an external edge, is only appropriate for a limited power range. As an alternative, a bus-centered architecture would reduce or eliminate this scaling problem by locating Voltage Stiffening Bricks immediately across the poles of a Power Switching Brick.

3.1.4 Radiated EMI

Mutual coupling between the Power Bus, Control Bus, and proposed Control Brick can result in disruption of low voltage analog sensing and control logic signals. This can affect the design and allowable proximity of the Control Brick to the Power Switching Bricks and the Power Bus.

In order to estimate the degree of induced voltage per signal trace area, a small voltage “sniffer” circuit was built. This circuit is comprised of a small flat inductive pick up coil on a circuit board, representing a typical loop in a control circuit board. The voltage output of the pick up coil is fed directly into a high bandwidth amplifier made by Mini-Circuits Corp [32]. A schematic of the circuit is presented in Figure 3-6. The properties of the sniffer coil amplifier circuit are summarized in Table I.

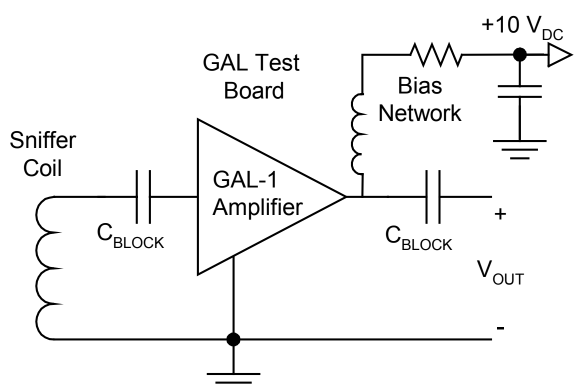

Figure 3-6 Sniffer coil amplifier circuit used for assessing the effect of radiated noise.

Table 3-1 Sniffer circuit properties.

Area per turn	1.1	cm^2
Number of turns	4	
Amplifier gain	20.8	dB
Net gain, G	0.0188	$(V/cm^2)/V$

The induced voltage was measured at specific positions around the converter, selected so as to be close to sensitive signal paths. The three locations are: at the Control Bus; within the converter volume adjacent to Power Switching Brick 2; directly adjacent to the screw terminals on the front of the Power Switching Brick 2. A solid model of the converter and three sniffer circuit locations is presented below in Figure 3-7.

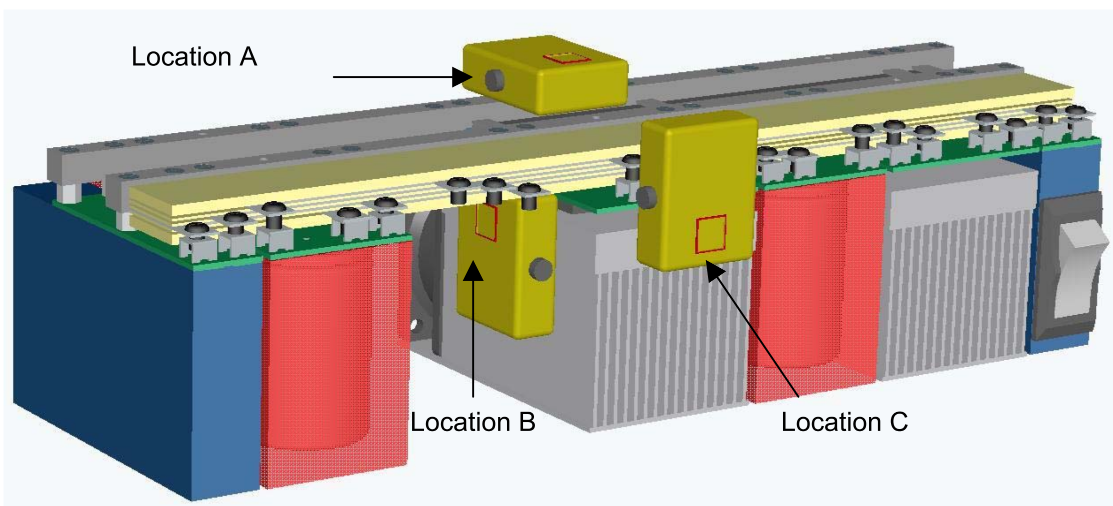

Figure 3-7 Solid model of the converter with 3 sniffer circuit measurement locations (converter shown upside-down).

The Bricks-&-Buses prototype was configured to operate as a buck converter as described in the following section. Measurements were taken while delivering 3.2 kW of power from a 400 V DC bus. The results from the measurements are collected in Table

II. A scope capture of a typical sniffer circuit voltage waveform at location C is presented below in Fig. 3-8.

Table 3-2 Induced voltage per unit area.

Measurement Location	V_{PK-PK} / Area (V/cm^2)
A	4.13E-02
B	2.63E-02
C	6.20E-02

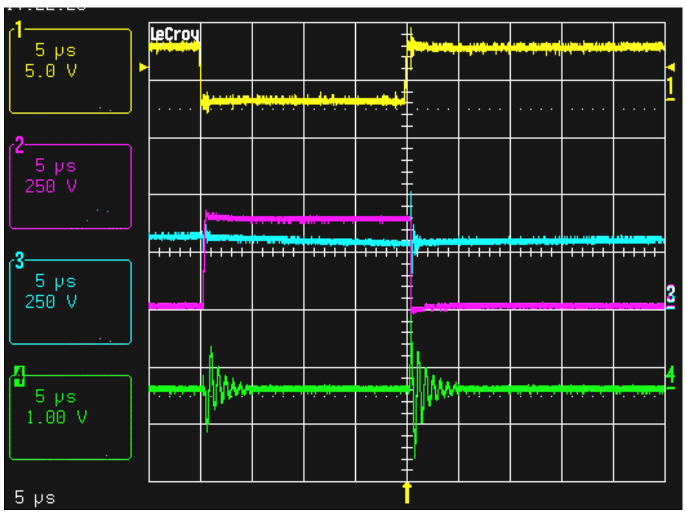

Figure 3-8 Induced voltage in sniffer circuit while delivering 3.2 kW to an R-L load: Ch1 (yellow) – gate control signal; Ch2 (purple) – IGBT VCE; Ch3 (blue) – load resistor voltage; Ch4 green) – sniffer circuit voltage (gain = 0.0188 (V/cm2)/V).

3.2 Prototype Operation

Initial tests of the converter demonstrated successful operation when configured as either a buck (AC/DC/DC) or inverter (AC/DC/AC), both fed from the diode bridge rectifier. Configuration properties for operation as a buck converter into an R-L series load are presented below in Table 3-3.

Table 3-3 Buck converter test configuration.

R_{LOAD}	30.0	Ω
L_{LOAD}	5.6	mH
C_{BUS}	2200.0	μF
C_{LOCAL}	0.4	μF
F_{SWITCH}	10.0	kHz
T_{AMB}	25.0	°C
IGBT	IRF: IRG4PC40F	
Diode	IXYS: DSEP30-06A	

Converter power flow and efficiency data were measured for DC bus voltages of 250 and 400 V. Plots of converter output power vs. duty ratio and efficiency vs. duty ratio are presented below in Figure 3-9 and Figure 3-10 respectively.

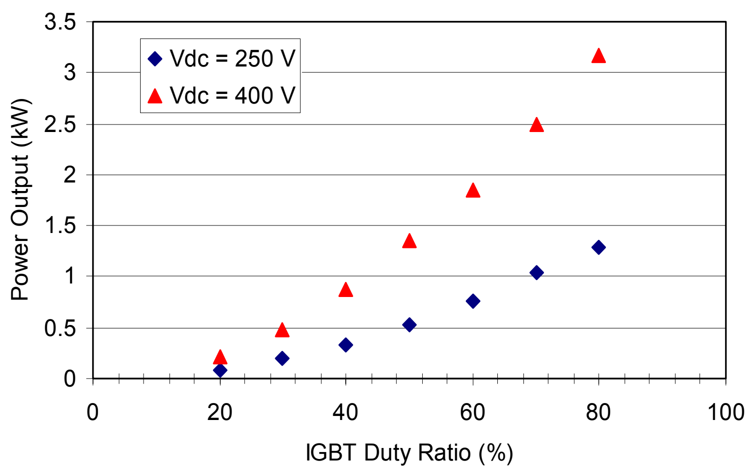

Figure 3-9 Buck converter power output vs. duty ratio for an R-L load.

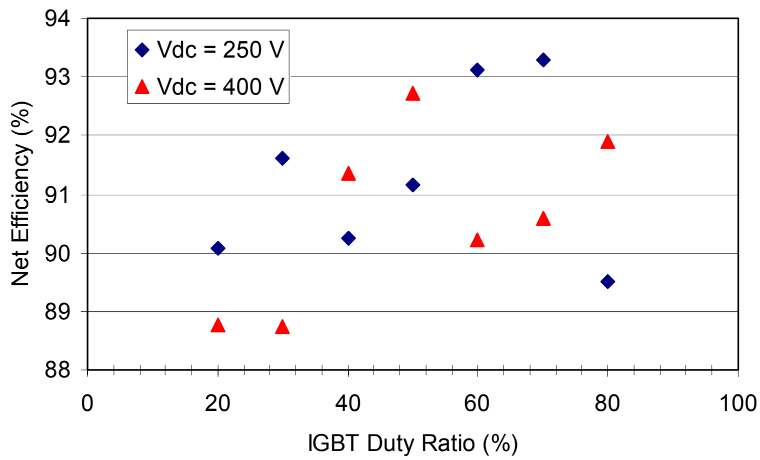

Figure 3-10 Buck converter efficiency vs. duty ratio for an R-L load.

The IGBT case temperature remained within 25 °C of ambient while delivering 3.2 kW to the load. This modest temperature rise indicates that there is thermal headroom for higher power throughput from the power switching bricks. A scope capture of the gate control signal, IGBT V_{CE} and load resistor voltage for 3.2 kW operation is presented in Figure 3-11.

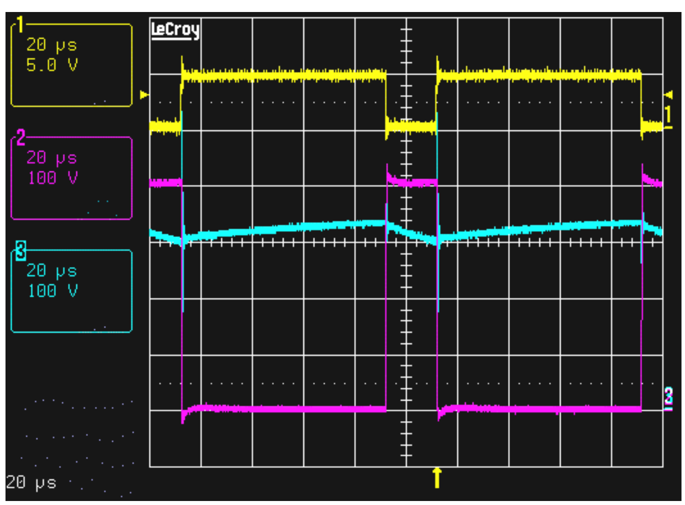

Figure 3-11 Buck converter operation delivering 3.2 kW to an R-L load: Ch1 (yellow) – gate control signal; Ch2 (purple) – IGBT VCE; Ch3 (blue) – load resistor voltage.

Chapter 4 Design Issues of Power Converter Components

Any power converter consists of power semiconductors, capacitors, inductors and transformers for realizing their electrical function and cooling systems to maintain adequate operating temperature margins for the electrical components. This chapter provides a discussion of detailed design considerations used for selecting and sizing the constituent components of a generic power converter. These considerations would form the basis for architectural design of power converters in continuing investigations.

4.1 Power semiconductors

Semiconductor switching devices may be considered to be the muscle of any power conversion system. The choice of power semiconductors directly affects the performance of power conversion and power transfer process. Key parameters considered in sizing power semiconductor devices include their blocking voltage capability, current carrying capability determined by the conduction power loss, switching speeds affecting their switching loss, and effective thermal resistance for the device package.

The main dc bus voltage for the central electric drive train is about 700V. This immediately points to a blocking voltage requirement for the accessory power converter to be above this level leading to the choice of IGBTs as the choice active switching device. At voltage levels of several 100 V, MOSFETs do not feature competitive properties in terms of current carrying capacity [35] The use of IGBTs places limits on the range of switching frequency attainable due to increased transition intervals during switching. In addition, power device's conduction and switching performance affect the system's overall efficiency and cooling requirement. Thus in order to select and size switching devices properly, it is important to obtain an accurate estimate of power loss in the device as described further.

The average conduction loss through a power semiconductor (IGBT or a diode) during a switching period can be estimated as

$$P_{cond} = V_{on} \times I_{on} \times D \tag{2}$$

where V_{on} is the device voltage drop during on-state, I_{on} is the current flowing through the device and D is the duty ratio of the device during the switching period.

Switching loss can represent a significant portion of the total device loss, especially when the switching frequency is selected to be high. Switching loss for an IGBT includes turn-on loss and turn-off loss. The turn-on and turn-off loss can be estimated respectively as

$$P_{on} = \frac{1}{2} \cdot (I_{on} + I_{rrm}) \cdot (t_r + t_{rr}) \cdot V_{off} \cdot f_{sw} \tag{3}$$

$$P_{off} = \frac{1}{2} \cdot I \cdot t_f \cdot V_{off} \cdot f_{sw} \tag{4}$$

where I_{on} is the magnitude of current flowing through IGBT during on-state; I_{rrm} is the diode reverse recovery current; t_r is the rise time; t_{rr} is diode's reverse recovery time; t_f is the fall time for turn-off; V_{off} is the voltage across the IGBT during the off state, f_{sw} is the switching frequency. The two equations above show that the switching loss is approximately proportional to the off-state blocking voltage and on-state conduction current. Technical datasheet from device manufacturers may provide the turn-on energy loss, E_{on} and turn-off energy loss, E_{off} directly in mJ or μJ, at specified testing conditions of device junction temperature, blocking voltage, V_{off_rated} and conduction current, I_{on_rated}. In this case, the turn-on and turn-off power loss calculations can be estimated by scaling the manufactures' test data to match the voltage and current levels at particular design conditions as illustrated below:

$$P_{on} = E_{on} \cdot \frac{V_{off}}{V_{off\_rated}} \cdot \frac{I_{on}}{I_{on\_rated}} \cdot f_{sw} \tag{5}$$

$$P_{off} = E_{off} \cdot \frac{V_{off}}{V_{off\_rated}} \cdot \frac{I_{on}}{I_{on\_rated}} \cdot f_{sw} \tag{6}$$

The ambient temperature for the power converter system is generally provided as one of the overall project specifications. Therefore, if the power semiconductor devices with a maximum allowable junction temperature T_{jmax}, a low thermal impedance heat removal path is critical to maintain the switching device's junction temperature from being too close to T_{jmax}. Furthermore, higher device junction temperatures lead to a shorter device life expectancy. Thus, a careful choice of the power device package format is necessary, as the device junction to case thermal resistance may be a significant part of the overall thermal resistance.

Power semiconductor's reliability/failure rate can be described by the bathtub curve as shown in Figure 4-1. In the first stage of power devices life, the failure rate is high but decreasing. The second stage is the useful life span, which is the characterized by a relatively constant and low failure rate. The third phase sees an increasing failure rate, due to parts being worn out. Most reliability analysis is concerned with the failure rate during the second stage [36]-[39].

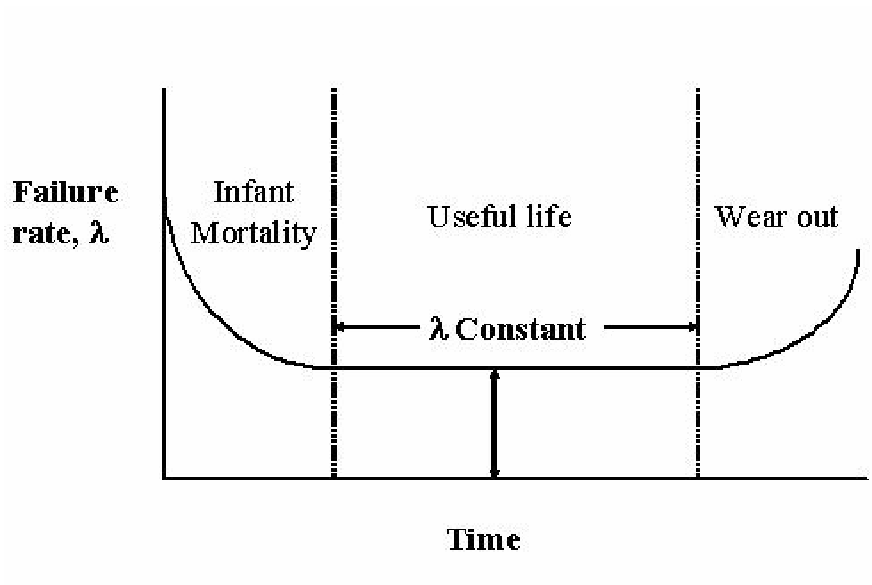

Figure 4-1: Bathtub-shaped failure rate curve for electronic devices and systems

There are different failure mechanisms causing a power semiconductor device to fail in function. In general, most failure mechanism can be modeled by using the Arrhenius equations shown below.

$$TTF = C \cdot e^{\frac{E_a}{K_b \cdot T}} \tag{7}$$

where *TTF* is the time to failure, in hours; *C* is a constant, in hours, E_a is activation energy; K_b is Boltzmann's constant 8.616×10^{-5} eV/K; *T* is absolute temperature in the unit of K. For a specific failure mechanism, there is a corresponding activation energy, e.g. for failure under high temperature reverse bias, E_a =1 eV; for high temperature gate bais failure $E_a =0.4$ eV. A more useful term is acceleration factor (AF), defined as

$$AF = \frac{TTF_{rate}}{TTF_{oper}} = e^{\frac{E_a}{K_b} \cdot (\frac{1}{T_{rate}} - \frac{1}{T_{oper}})} \tag{8}$$

where TTF_{rate} is the manufacture predicted device time-to-failure under testing/rated condition and TTF_{oper} is the expected time-to-failure under real operating condition. T_{rate} is the junction temperature under testing condition and T_{oper} is the junction temperature in real operation condition. With the information of $TTF_{rate,}$ E_a *and* T_{rate} provided by the device manufacturer, the acceleration factor can be estimated based on device junction temperature, which depends on the total device loss and cooling conditions.

Such design considerations of semiconductor devices are integrated along with cooling considerations, reactive component sizing considerations, etc. to develop an architectural scaling approach to power electronics design.

4.2 Capacitors

Capacitors form a critical component of power conversion system by providing energy storage at the intermediate dc bus or to absorb ripple current at input and output terminals of the converter.

The operating life of capacitors is critical to ensure adequate reliability levels for power conversion system. In order to guarantee a desired life-time for the capacitor, both capacitor ripple current and its equivalent series resistance (ESR) have to be considered in rating of capacitor. While other types of capacitor have their advantages over electrolytic capacitors, electrolytic capacitors still is most widely used in the power conversion field. With a careful design, electrolytic capacitors can also achieve desirable life-time [40]-[44]. An electrolytic capacitor's ESR depends on both ripple frequency and operating temperature. The capacitor's ESR decreases as the operating frequency and the temperature increase. The equation below shows a typical relationship between the ESR and frequency.

$$ESR_f = ESR_{120} - 39800 \cdot \frac{f_{sw} - 120}{f_{sw} \cdot C} \qquad (9)$$

where f_{sw} is the ripple frequency; ESR_f and ESR_{120} are the capacitor's *ESR* at frequency of f_{sw} and 120Hz respectively in mΩ; C is the capacitance in μF. Figure 4-2 shows this relationship graphically. At the low frequency range, ESR drops significantly with the frequency, while at higher frequencies, the dependency is weak.

Typical values of the capacitor's ESR at certain frequency, e.g. 120 Hz are generally provided by the manufacturer's specifications sheet. This data may be fit a mathematical curve so that they may be conveniently used for analytical designs as illustrated Figure 4-3 [45]-[46]. On a log-log scale, it may be noted that the capacitor ESR decreases linearly with increasing capacitance, while capacitor size and maximum ripple current increase linearly with capacitance.

The product of the ESR and square of ripple current gives the maximum power dissipation the capacitor can tolerate, under specified cooling conditions. Since the ESR of the capacitor depends on the operating frequency, the ripple current flowing through the capacitor can be decomposed into different frequency components. Then the heat dissipation is calculated at each ripple current frequency, using the corresponding ESR at that frequency. The sum of the heat dissipation at different frequencies gives the total heat generated in the capacitor. Often, a reasonable estimate of the total heat dissipation can be obtained by considering only those frequencies where the major ripple components exist.

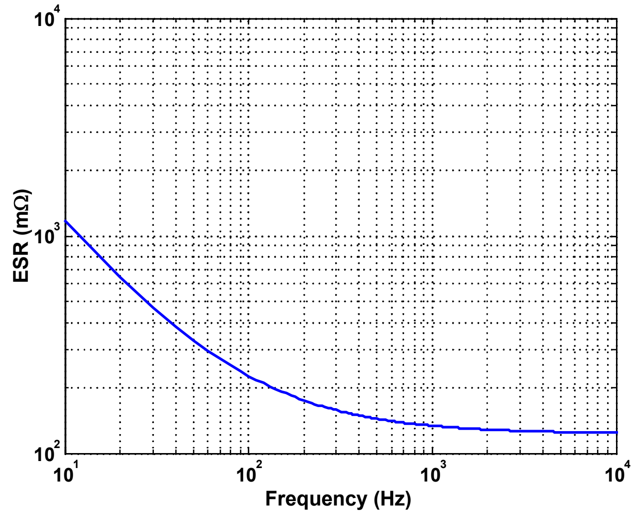

Figure 4-2: A plot of the variation of a capacitor's ESR as a function of ripple current frequency

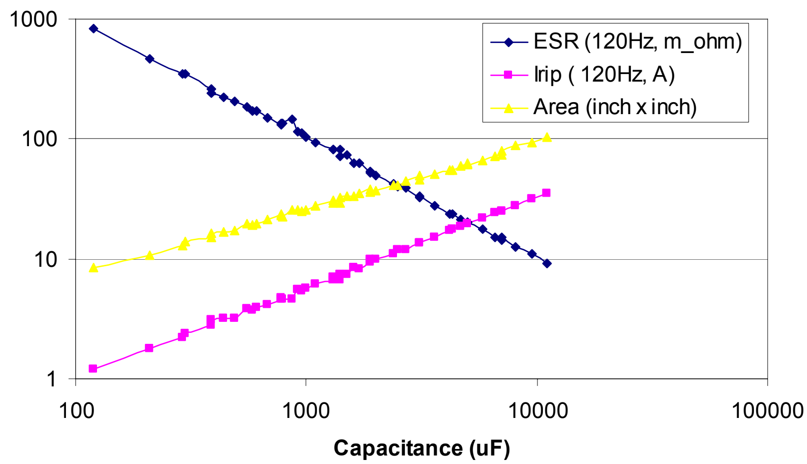

Figure 4-3: Typical variation of capacitor's ESR, ripple current and cross sectional area (diameter X height) as a function of capacitance

For instance, the current flowing through the dc bus capacitor bank fed by a diode bridge rectifier, which in turn feeds a step down converter is dominated by components related to the ac line frequency and the PWM switching frequency. Thus, two separate ESR loss calculations carried out for the ac line frequency ripple and PWM frequency ripple current provide an accurate estimate of the total capacitor heat dissipation.

Once the total power dissipation in the capacitor is known, its core temperature can be estimated using the manufacturer-provided data for the thermal resistance for capacitor internal structure. The electrolytic capacitor's life expectancy may be readily determined from the core temperature and operating voltage stress as

$$Life = Life_{base} \cdot Mv \cdot 2^{\frac{T_{base} - T_c}{10}} \qquad (10)$$

where $Life_{base}$ is the manufacture predicted capacitor life expectation at specified temperature T_{base}; T_c is the core temperature at real operation conditions. Mv is the voltage stress factor define as

$$Mv = 4.3 - 3.3 \cdot \frac{V_{cap\_a}}{V_{cap\_rate}} \qquad (11)$$

where V_{cap_a} and V_{cap_rate} are capacitor voltage levels at operating conditions and specified test conditions respectively.

These considerations from the basis for sizing capacitors that form a significant part of power converters.

4.3 Thermal management elements

Good thermal management is critical in maximizing the utilization of power semiconductors' electric power processing capability. Better thermal management allows higher heat removal rate from the semiconductor devices, leading to a higher power throughput and/or increased reliability through extended lifetime.

High ambient temperatures pose significant thermal management challenges. Cooling can be realized using natural air convection, forced convection using air or liquids. Among these, the liquid cooling system is being considered most suitable for high performance systems, and hence the discussion here will focus on them. However, similar thermal design relationships can be developed for other forms of cooling as well.

With the assumption of a preexisting liquid coolant loop, the thermal management system design is reduced the selection and application of an appropriate cold plates. Figure 4-4 illustrates the structure of the cold plate being considered in the evaluation study [47].

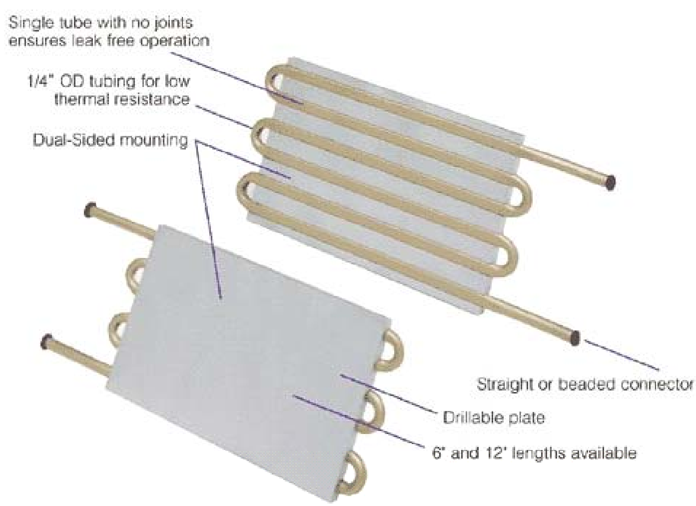

Figure 4-4: Schematic of the cold plate used for cooling semiconductors

The cold plate consists of an aluminum base plate with embedded tubes. The power devices can be amounted on either side of the cold plate, and the heat generated by the power devices passes through the device package and reaches the cold plate surface, then it spreads to the tubes arranged evenly on the cold plate surface. After reaching tubes, the heat is transferred to the coolant inside the tubes through convection mechanism. The thermal system performance may be evaluated using the equivalent thermal resistance model for the cold plate shown in Figure 4-5 [47]. The total thermal resistance for the cold plate may be divided into three parts, including thermal resistance $R_{\theta SD}$, $R_{\theta DB}$ and $R_{\theta BA}$.

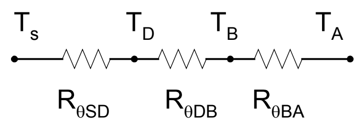

Figure 4-5: Equivalent thermal resistance circuit for the cold plate illustrated in Figure 4-4

$R_{\theta SD}$ represents the thermal resistance consisting of conduction of heat from surface of the cold plate to the inner surface of the liquid channels. It can be estimated as

$$R_{\theta SD} = \frac{1}{k_{al} \cdot (4 \cdot s_{coef}) \cdot Len \cdot N_p} \tag{12}$$

where k_{al} is the thermal conductivity of the cold plate base material; s_{coef} is a shape factor affected by the relative dimension of the cold plate and coolant channel, *Len* is the length of the coolant channel; and N_p is the number of channels in parallel. Shape factor is to chosen to be 1.52 as the optimum value [47].

$R_{\theta DB}$ represents the thermal resistance between the inner surface of the coolant channels and the coolant flowing through the channel. It measures the convection heat transfer efficiency between tubes and the coolant at the boundary layer. It may be estimated using,

$$R_{\theta SD} = \frac{1}{h_{DB} \cdot A_s} \tag{13}$$

where A_s is the total heat exchange area which can be calculated as

$$A_s = \pi \cdot D \cdot Len \cdot N_p \tag{14}$$

D being the diameter of the coolant flow channel. The heat transfer coefficient h_{DB} is defined as

$$h_{DB} = 0.023 \cdot \mathrm{Re}_D^{\ 0.8} \cdot \mathrm{Pr}_f^{\ 0.4} \cdot \frac{k_f}{D_h} \tag{15}$$

where Pr_f is coolant's Prandtl number; k_f is coolant's thermal conductivity; D_h is the hydraulic diameter of the coolant channel; Re_D is the coolant's Reynolds number defined as

$$\mathrm{Re}_D = \frac{\rho_f \cdot V_{c\_mean} \cdot D}{\mu_f} \tag{16}$$

where ρ_f is the mass density of the coolant; μ_f is viscosity of the coolant; and V_{c_mean} is the coolant mean velocity. It is a function of coolant volume flow rate (VFR), and is defined as

$$V_{c\_mean} = \frac{VFR \cdot 4}{\pi \cdot D^2 \cdot N_p} \tag{17}$$

$R_{\theta BA}$ represents the temperature rise of the coolant as it collects heat as it flows through the channel. It can be estimated using

$$R_{\theta BA} = \frac{1}{2 \cdot \rho_f \cdot VFR \cdot C_p} \tag{18}$$

where C_p is the specific heat of the coolant.

Among the three thermal resistances, $R_{\theta DB}$ is the most dominant element. The pressure drop of the coolant for flowing through the channels can be estimated by

$$\Delta P = f_{coef} \frac{\rho_f \cdot V_{c\_mean}^{\;2}}{2 \cdot D} \cdot Len \tag{19}$$

where, f_{coef} is defined as

$$f_{coef} = 0.316 \cdot \mathrm{Re}_D^{-\frac{1}{4}} \tag{20}$$

These relationships form the basis for obtaining scaling properties of thermal management elements used for maintaining adequate temperature margins for power semiconductors.

4.4 Magnetic elements

In many power conversion applications, magnetic elements including inductors and transformers are generally custom-designed. The major components for an inductor include both core and windings/wires, which conducts flux and current separately. Core designs can be either cut-core with discrete air gap or powder core with distributed air gap. Sometimes, a combination of powder core with discrete air gap is also applicable [48], [49].

For cut-core based design, with the information of the operating range of the flux density and electrical current, size/volume of the core can be estimated. To be more specific, area product of the core can be estimated. The area product A_p is defined as the product of core cross section area and core window area [48]. The core cross-sectional area measure how 'wide' the flux path is and the core window area measures how much room is available to fit in wires.

$$A_p = \frac{L_{out} \cdot I_{out} \cdot I_{out\_pk}}{k_w \cdot J_w \cdot B_m} \times 10^8 \quad (21)$$

The area product gives the size/volume information of a core. The shape of the core determines how the area product is distributed into window area and section area. Too much window area yields either a large air gap to maintain flux density below the maximum allowable value, or a less efficient usage of the window area, which leads to unnecessary core weight and hence additional core losses.

4.4.1 Inductor design considerations

DC filter inductor acts as a short-term energy storage element. Energy is stored in the air gap of a cut-core inductor. The following equation describes the relationship between inductor's inductance, inductor current, core cross-sectional area, air-gap length and flux density in the core.

$$\frac{1}{2} L_{ind} \cdot I_{pk}{}^2 = \frac{1}{2} \frac{B_m{}^2}{\mu_o} \cdot S_m \cdot l_g \quad (22)$$

Iron powder core is widely used in the DC output filter application. Iron powder core has the property of distributed air gap, thus the energy storage is distributed among the whole core volume, instead of only the air gap as in the case of cut-core inductor design. Equation above can be modified as

$$\frac{1}{2} L_{ind} \cdot I_{pk}{}^2 = \frac{1}{2} \frac{B_m{}^2}{\mu_o \mu_r} \cdot V_{core} = \frac{1}{2} \mu_o \mu_r H_m{}^2 \cdot V_{core} \quad (23)$$

It can be seen from equation above that, the higher the permeability, higher the effective inductance. For a powder core, core material permeability has a significant influence on inductor's ability of energy storage. The core material sees a decrease in its effective permeability with an increase in the DC current level. This causes change in the inductance of the filter inductor when the load current level changes. Careful design consideration is thus necessary to make sure that the required inductance is maintained at all load conditions.

Core manufacturers normally provide data on the initial core permeability, and curve for per unit of initial permeability Vs DC magnetization force. A typical curve is shown in Figure 4-6, which can be used for appropriate designs.

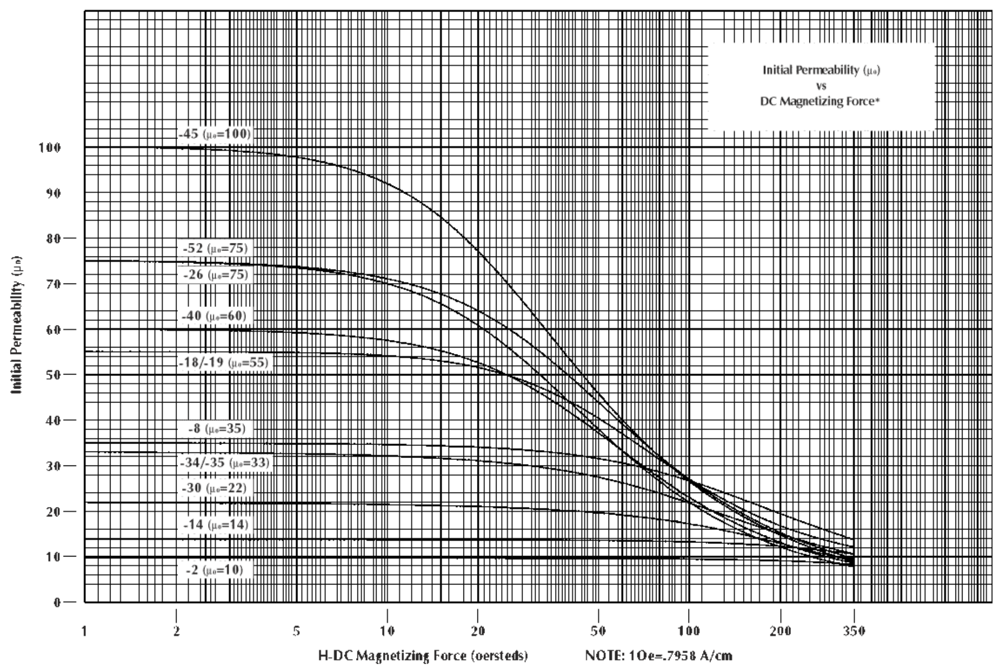

Figure 4-6: Initial permeability vs. DC magnetization force graph

For the DC output filter application, the load current is primarily a DC current with a relatively small high frequency ripple component. Thus, the DC current primarily determines the effects of DC magnetization. With the specified the inductance value and DC load current, the total energy to be stored by the inductor can be calculated.

Considering the DC magnetization effects, an appropriate volume/size of powder core can be determined.

4.4.2 Transformer design considerations

Isolation transformer's duty ratio is chosen in a way that the nominal duty ratio for the bridge converter is around 0.5 so that it has enough room to change to accommodate the possible swing of input voltage. Consideration is also given to the fact that with high primary/secondary turns ratio, the transformer primary side current has a lower magnitude and it helps lower conduction and switching losses.

A similar concept of area product as used in inductors design can be developed for transformer core design. The area product is defined as

$$A_p = \frac{V_{in}}{4B_m \cdot f_{sw}} \cdot \frac{I_{out}}{J_w \cdot k_w} \cdot Turn\_ratio \qquad (24)$$

With the information of area product, appropriate core can be selected. Number of turns of winding then can be determined based on the effective window area and the maximum current requirement for the windings.

These design relationships for magnetic elements may be incorporated in developing unified scaling properties for the power converter system.

In addition to the power converter primary elements such as semiconductors, capacitors, inductors, transformers and heatsinks, several auxiliary devices such as controllers, switchgear, and sensors also need to be incorporated in the unified architecture. The integration of all these considerations into a unified framework is the subject of ongoing investigations.

Chapter 5 Framework Issues and Directions

This chapter attempts to identify and provide an initial discussion of the issues to be addressed for a complete evaluation of the Bricks-&-Buses framework. The framework presented attempts to be comprehensive in describing both the physical realization and design and manufacturing processes of power electronic converters. As such, a comprehensive analysis of this framework is beyond the scope of work presented here. Many of the issues raised will require dedicated research efforts to address completely. Nonetheless, this section intends to introduce and discuss the most important points and provide direction for future research.

Toward this end, the following principal questions are posed of the Bricks-&-Buses framework:

- Can Bricks-&-Buses converters achieve performance comparable to custom converter designs? Where are the performance limitations of this framework, and where are the regions of high relative performance?
- How effective is this approach with regards to converter packaging, manufacturing and assembly?
- How will the Bricks-&-Buses technical specifications be created?
- Will these specifications be flexible enough to allow for custom designs and organic growth with changes in constitutive technologies?
- Will it be possible to easily construct all conventional topologies?

- Will it be easy to implement new topologies?
- How likely is it that the Bricks-&-Buses framework will yield the proposed design – manufacturing, servicing and economic benefits?

These questions seem best answered through analysis of the Bricks-&-Buses framework from two general perspectives: technical issues, and implementation and acceptance.

5.1 Technical Issues

The Bricks-&-Buses approach to packaging of the elements and connective systems of a power converter has several technical benefits and drawbacks. These will be discussed from the perspectives of modularity, aspect ratios, and scalability.

5.1.1 Modularity

The modularity of the Bricks-&-Buses approach to converter packaging yields several benefits. First, the modular components, along with the connective architecture, form the foundation of the high level design environment. They allow straightforward integration of the elements of a converter into designs that are electrically, thermally, and volumetrically compact. The standardization of the component packages allows components and subsystems to be replaced or upgraded more easily. Assuming the component packaging (brick) standard is flexible, one component design can be suitable for multiple converter applications. As a result, they can be produced in higher production volumes yield lower unit costs.

Unfortunately this modular approach is not without its drawbacks. Most notably of these is the volumetric and cost overhead associated with a physically modular system. An unavoidable byproduct of the flexibility of the Bricks-&-Buses is that it is non-optimum for any one particular application. The financial cost and power density penalty for this flexibility is believed to be modest for medium to high power converter (roughly 10 kW and up). But, these penalties will be rather cumbersome for smaller converters. However, the other benefits of the Bricks-&-Buses framework should outweigh these drawbacks for converters that are not both small in physical size and produced in very large volume.

In addition, unlike the microprocessor design process, the technical specifications for the Bricks-&-Buses framework cannot be continuous in nature. Because of the varied technologies and sources for the elements of a typical converter, and the complexity of the interconnection, the framework must be indexed. This results in another layer of cost inefficiency when performance requirements are far from the framework indexing points.

5.1.2 Aspect Ratio

The term *aspect ratio* refers to the basic relationship between two characteristic lengths. In the case of power converters, this is most relevant to the packaging of different elements of a converter into volumes that have comparable characteristic length. This challenge is best illustrated by an example. The converter shown below in Figure 5-1 has a Structural Bus, Power Bus, and Control Bus located in the center of two rows of bricks.

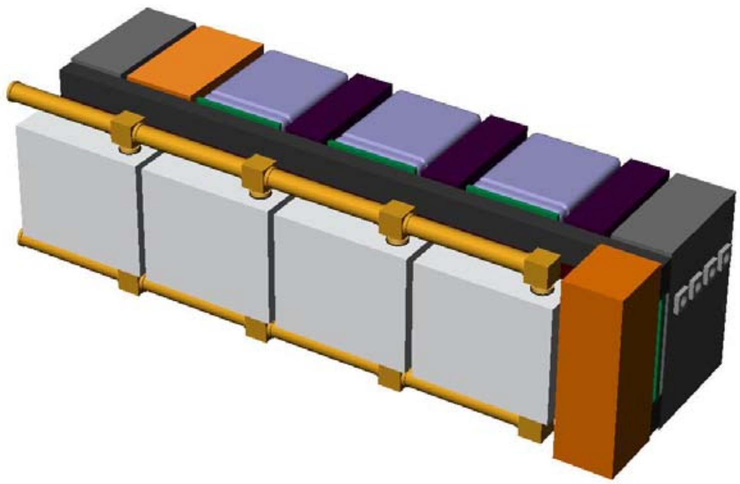

Figure 5-1 Water-cooled 3-phase AC/DC/AC converter for illustration of aspect ratio.

The 1st side of the converter has four Power Switching Bricks and one Auxiliary Utility Brick. The 2nd side of the converter has three Voltage Stiffening Bricks, three Current Stiffening Bricks, Control Brick and Input Output Brick. The converter is divided in this manner to allow the Voltage Stiffening Bricks to be located directly across from the throws of the respective Power Switching Bricks. All of the bricks in this converter have the same length (in the direction from the bottom to the top of the page).

A particular converter design will call for certain value of bus capacitance, rated for a particular voltage and ripple current. Given a particular capacitor technology this will require a certain capacitor volume. In order for the Bricks-&-Buses converter to efficiently use the total converter volume, the components on the same side of the converter as the capacitors must have roughly the same height. This dictates that the capacitors must increase in size along the direction of the long direction of the converter. Difficulty occurs if or when the required capacitor size displaces some of the other bricks (Control Brick, Current Stiffening Bricks, Input Output Brick) to the 1st side of the converter. For efficient use of volume, these bricks must have roughly the same height as the Power Switching Bricks.

This can be problematic because capacitor technology at a certain application rating dictates one preferred height to mitigate internal inductance. On the other hand Power Switching Brick technology at the same application rating may dictate a different preferred height for optimum heat extraction.

The interaction of these two components is only one example of this possible conflict. If this is not properly addressed, aspect ratio mismatch can produce inefficient use of the converter volume, or other complications due to displaced components and large current path lengths (see following sections on Parasitic Inductance and Cross Coupling). While not necessarily a critical problem, this issue must be investigated thoroughly as a preliminary step of defining the Bricks-&-Buses technical specifications.

5.1.3 Parasitic Inductance

Parasitics are unintended physical properties of the connective bus structure and modular components. These properties can act to limit the practicality and performance of the Bricks-&-Buses approach to power converter realization.

One of the most common and problematic examples is parasitic inductance between semiconductor switching devices and decoupling capacitance on a DC voltage bus. Coupled with fast current turn off, parasitic inductance can induce device damaging voltage spikes, resonance, and increased switching losses [33,34] Some degree of parasitic inductance is unavoidable in any converter layout.

The question of the Bricks-&-Buses architecture is whether the parasitic inductance of the standard Power Bus architectures and the will be comparable to that of a custom converter layout. As described in the previous section, the bus-centered converter configuration is preferred for reducing unnecessary conduction path length between the Voltage Stiffening Brick and Power Switching Brick. This bus-centered approach is consistent with currently accepted industry practices [33,34].

Nonetheless, two prominent issues regarding parasitic inductance remain. The first is whether the Bricks-&-Buses automated converter layout engine will be able to position the Voltage Stiffening Bricks and Power Switching Bricks so as minimize the parasitic inductance. The second issue is tied to the question of aspect ratios. Given a restrained converter height, can all of the Voltage Stiffening Bricks can be located in sufficient proximity to the Power Switching Bricks so as to keep the parasitic Power Bus inductance to an acceptable level. In other words, for a design requiring a specific capacitance, the Bricks-&-Buses geometry must be so constraining in one direction so as to require the Voltage Stiffening Bricks to be spread an unacceptably long distance along the length of the converter.

5.1.4 Cross Coupling and Loading

The buses of the proposed framework are intended to separate the connective networks of a power converter along function lines. These connective networks service multiple bricks within the converter. The interaction of the bricks and buses is intended to proceed in a manner such that there is no unintentional cross coupling or loading between any combination of bricks and buses. That is, any one brick should not be adversely affected by the operation of any other brick, and likewise between the bricks and buses, and any two buses themselves.

There are, however, several physical mechanisms by which one brick or bus could be unintentionally influenced by its neighbors. The most likely of these are related to electromagnetic and thermal interference. They are described as follows along with possible remedies.

Electromagnetic Interference

This would likely occur as a result of radiated electromagnetic energy from the Power Switching Bricks or Power Bus. This radiated energy could corrupt or distort the digital or analog signals of the following: Control Bricks, Sensor Bricks and Control Bus. Remedies for this depend on the power level of the converter and the degree of likely interaction. Remedies include: tight electromagnetic design rules for the Power Bus and Power Switching Bricks (i.e. small enclosed loops, closed electric fields); minimum distances between the Power Bus and Control Bus; minimum distances between the Power Switching Brick and Control Brick and Sensor Brick; electromagnetic shielding of sensitive bricks and buses.

Thermal Interference

This effect would likely be from the Thermal Bus or Power Switching Bricks to the Voltage Stiffening Brick or other temperature sensitive components. Likewise a closed loop Thermal Bus could be loaded as a result of services multiple Power Switching Bricks on one line. If the Thermal Bus technical specifications are poorly defined, the first Power Switching Brick can consume a significant fraction of the cooling capacity, resulting in uneven cooling in the converter. Likewise, an ambient air-based Thermal Bus is susceptible significant fluctuations in heat extraction. One possible solution is regulation of device temperatures through feedback control of the coolant throttle.

5.2 Implementation and Acceptance

This section introduces some of the implementation and industrially oriented issues facing the Bricks-&-Buses framework. These include the establishment of open standards, indexing the design continuum, achieving industrial acceptance and determining economic performance.

5.2.1 Open Standards

The success of the Bricks-&-Buses framework hinges tightly on the quality of the technical specifications. Standards that are poorly defined, overly restrictive, do not allow for adaptation, or do not address the needs of industry will quickly become an unused relic. Likewise, the interdependent nature of contemporary power converter design draws on many technical disciplines.

As such, it is believed that the best approach to defining the Bricks-&-Buses framework is through the development of open standards. These would likely be the result of an on-going industry consortium or committee of the IEEE and/or other Power Electronics societies. Care must be taken when establishing committee design and decision procedures to prevent industrial biases, personal preferences and politics from unduly affecting the process of creating and maintaining the Bricks-&-Buses framework standards.

It is believed that this group would periodically produce a set of technical definitions for the bricks and buses as well as the associated library files. This could be akin to the ANSI standards for the C programming language. These standards would be used by all aspects of the power electronics industry – from brick production by component manufacturers, to the software environment, to converter assembly. Custom and non-standard elements would be integrated into this system as appropriate.

5.2.2 Industrial Acceptance

Beyond the definition of the standards, the success of this framework depends on the degree to which it is accepted and adopted by those working in industry. In this respect the Bricks-&-Buses framework faces a few challenges. Undoubtedly, many in the industry will be skeptical for very genuine reasons – i.e. "Is the Bricks-&-Buses approach to power converter realization a genuinely better (cheaper, faster, higher performance) way to produce power converters?"

However, many will be skeptical for reasons beyond the framework itself. These challenges are as related to industrial inertia and cultural issues, as technical ones. Industrial motivation for the Bricks-&-Buses framework may be lacking for two reasons. First, engineering may have difficulty envisioning their new role in the context of this framework. Some may feel that the nature of their jobs will be disrupted, or their job security threatened.

Second, corporate adoption will be slow. This framework changes the nature of the value-added process. The benefits from the Bricks-&-Buses framework will be seen industry-wide in the long term. However, most companies will react in response to short term ends, to protect proprietary technologies in the current value-added design – manufacturing structure. This may be overcome by establishing the benefits of the Bricks-&-Buses framework in fledgling markets that are not so entrenched.

Chapter 6 Conclusions

A new framework for realization of power converter has been presented called Bricks-&-Buses. This framework requires three elements: modular components or bricks, from which any practical converter topology can be constituted; buses, or connective architectures, for interconnection of the bricks; a software environment in which to describe the converter at an abstracted level and automatically generate engineering and design files.

The results of the prototype demonstration phase indicate that the proposed framework has the potential to significantly improve the power electronics design and manufacturing process. Some of the expected benefits include reduced costs, increased serviceability, accelerated performance improvements, and a cleaner design, manufacturing and assembly cycle.

Three parallel tracks of planned activities are being planned to carry this concept further. (1) Development of a design environment to develop next generation power electronics systems; (2) Development of a manufacturing process coupled with the design environment that allows mass customizable production; (3) Development of plug-and-play control approaches operating on suitable platforms that is compatible with the physical power conversion process. Industrial partnership has been identified for continued development along all these tracks.

References

[1] Venkataramanan G., "An Integrated Architectural Framework for Power Conversion Systems", IEEE International Workshop on Integrated Power Packaging, Waltam-Boston, MA July 14-15, 2000.

[,2] Venkataramanan G., "Integration of Distributed Technologies Standard Power Electronic Interfaces", Concept/Design Review Meeting Presentation, WEMPEC Annual Meeting, May 23, 2002 (Appendix of this report).

[3] Lee, F., Peng D., "Power Electronics Building Block and System Integration" Power Electronics and Motion Control Conference, 2000. Proceedings , vol. 1 , Aug. 15-18, 2000.

[4] Patterson D., Hennessy J., *Computer Organization & Design*, Morgan Kaufmann Publishers, Inc., San Francisco, CA, 1997.

[5] Mead C., Conway L., *Introduction to VLSI Systems,* Addison-Wesley Publishing Company, Reading, MA, 1980.

[6] Panint Electronic Limited, Website: www.panint.com (8/23/2003)

[7] Mankikar M., *Update – A Quarterly Newsletter for the Power Source Manufactures Association,* Third Quarter 2003. Website: www.psma.com

[8] Fishbein J., "Integrated power packaging: trends, driving forces, and restraints" Power Electronics in Transportation, 1994. Proceedings , 20-21 Oct. 1994.

[9] Semikron, Website: www.semikron.com (8/23/2003)

[10] Infineon Technologies, Website: www.infineon.com (8/23/2003)

[11] International Recifier, Website: www.irf.com (8/23/2003)

[12] Meinhardt M., Alderman A., Flannery J., Cheasty P., Eckert S., Mathuna C., "STATPEP – Current Status of Power Electronics Packaging for Power Supplies – Methodology", Applied Power Electronics Conference and Exposition, vol.1, March 14-18, 1999.

[13] Chen R., Canales F., Bo Y., van Wyk J.D., "Volumetric Optimal Design of Passive Integrated Power Electronic Module (IPEM) for Distributed Power System (DPS) Front-end DC/DC Converter", Industry Applications Conference, vol. 3, Oct. 13-18, 2002.

[14] Ericsen T., "Power Electronic Building Blocks-a Systematic Approach to Power Electronics", IEEE Power Engineering Society Summer Meeting, vol. 2 , July 16-20, 2000.

[15] Office of Naval Research Advance Electrical Power Systems PEBB Website: https://aeps.onr.navy.mil/ (8/23/2003)

[16] Kehl D., Beihoff B., "The Future of Electronic Packaging for Solid State Power Technology: The Transition of E-packaging to Electromechanical Engineering", IEEE Power Engineering Society Summer Meeting, vol. 2 , July 16-20, 2000.

[17] Wang F., Rosado S., Boroyevich D., "Open Modular Power Electronics Building Blocks for Utility Power System Controller Applications", IEEE Power Electronics Specialist Conference, vol. 4, June 15-19, 2003.

[18] Beihoff B., "Power Cell Concepts for the Next Generation of Appliances", IEEE International Electric Machines and Drives Conference, vol.1, June 1-4, 2003.

[19] Hudgins J., Mookken J., Beker B., Dougal R., "The New Paradigm in Power Electronics Design", IEEE Power Electronics and Drive Systems Conference, vol. 1 , July 27-29, 1999.

[20] Jinghong G., Celanovic I., Borojevic D., "Distributed Software Architecture of PEBB-Based Plug and Play Power Electronics Systems" IEEE Applied Power Electronics Conference and Exposition, vol. 2, March 4-8, 2001.

[21] Kelley A., Harris M., Hartzell D., Darcy D., "Coordinated Interconnect: a Philosophical Change in the Design and Construction of Power Electronic Converters", IEEE Industry Applications Conference, vol. 2 , Oct. 12-15, 1998.

[22] Hopkins D., Mathuna S., Alderman, A., Flannery J., "A Framework for Developing Power Electronics Packaging", Proc. of the Applied Power Electronics Conference and Exposition, vol.1, Feb. 15-19, 1998.

[23] Jacobsen J., Hopkins D., "Optimally Selecting Packaging Technologies and Circuit Partitions Based on Cost and Performance", Proc. of the Applied Power Electronics Conference and Exposition, vol.1, Feb. 6-10, 2000.

[24] Omrane, B.; Mariun, N.; Aris, I.B.; Bashi, S.M.; Taib, S.; "Expert System-Based Approach to Automate the Design Process of Power Electronics Converters" Asia Pacific. IEEE/PES Transmission and Distribution Conference and Exhibition, vol.3, Oct. 6-10, 2002.

[25] Van Wyk J.D., Lee F., "Power Electronics Technology at the Dawn of the New Millenium – Status and Future", Power Electronics Specialists Conference, vol.1, 27 June 27 – July 1, 1999.

[26] Venkataramanan G., "Integration of Distributed Technologies – Standard Power Electronic Interfaces", Report for California Energy Commission, Prepared by Power System Engineering Research Center-Wisconsin (PSerc), Wisconsin Power Electronics Research Center (WisPERC), Sept. 2001.

[27]. Planar Magnetics Ltd. Website: http://www.planarmagnetics.com/ (8/26/2003)

[28]. Payton Group International Website: http://www.paytongroup.com/ (8/26/2003)

[29] Bussco, A division of Circuit Components LLC Website: www.bussco.com/. (8/26/2003)

[30] Eldre Corporation Website: www.busbar.com/ (8/26/2003)

[31] G. Venkataramanan, "Characterization and Comparison of Capacitors for Decoupling Applications", Conference record of the IEEE IAS Annual Meeting, St. Louis, Oct. 1998.

[32] MiniCircuits Website: http://www.minicircuits.com/ (8/26/2003)

[33] Skibinski G., Divan D., "Design Methodology and Modeling of Low Inductance Planar Bus Structures", European Conference on Power Electronics and Appliactions, vol.3, Sept. 13-16, 1993.

[34] Beukes H., Enslin J., Spee R., "Busbar Design Considerations for High Power IGBT Converters", Power Electronics Specialist Conference, vol. 2, June 22-27, 1997.

[35] Baliga,B.J., "The future of power semiconductor device technology", proceedings of the IEEE , Volume: 89 Issue: 6 , June 2001 , Page(s): 822 –832.

[36] Assessing Product Reliability, handbook by NIST, http://www.itl.nist.gov/div898/handbook/apr/section1/apr124.htm

[37] Switch reliability report, International Rectifier, http://www.irf.com/product-info/reliability/

[38] William J. Vigrass, "Calculation_of_semiconductor_failure_rates", http://rel.intersil.com/docs/rel/calculation_of_semiconductor_failure_rates.pdf

[39] http://www.weibull.com/LifeDataWeb/a_brief_introduction_to_reliability.htm

[40] M.N.Anwar, Mehrdad Teimor, ' An Analytical Method for Selecting DC-Link-Capacitor of a Voltage Stiff Inverter', 2002, IEEE

[41] Michel Bramoulle, 'Electrolytic or Film Capacitors?', 1998, IEEE

[42] Ian W. Clelland , Rick A. Price, 'Current Handling and Non-Shorting Feature of Multilayer Polymer (Film) Capacitors', 1999, IEEE

[43] Ron Anderson, 'Select the Right Plastic Film Capacitors for Your Power Electronic Application', 1996, IEEE

[44] M.H. El-Hussenni, P. Venet, G.Rojat, C.Joubert, ' Thermal Optimization of Metalized Polypropylene Film Capacitors', 2000, IEEE

[45] Aluminum-Electrolytic Capacitor Application Guide, http://www.cornell-dubilier.com/appguide.pdf

[46] Sam G. Parler, Jr. "Selecting and Applying Aluminum Electrolytic Capacitors for Inverter Applications", white paper, Cornell Dubilier

[47] http://www.r-theta.com/products/aquasink/aquasink.pdf

[48] Power conversion and line filter applications, Micrometals iron powder cores catalog

[49] Micrometals iron powder cores, http://www.micrometals.com/parts_index.html

[50] ECE412 class notes, University of Wisconsin – Madison

Appendix I. Design Review Meeting Comments

Integration of Distributed Technologies –

Standard Power Electronic Interfaces

Concept/Design Review Meeting

1:15 p.m., Thursday, 23th May, 2002

1610 Engineering Hall

University of Wisconsin-Madison

Industry Participant General Comments

- There may be more overhead in the interconnection of power electronics components than functional components of a computer.
- Success of modular architecture for power electronics depends on commitment by major manufacturers.
- Modular architecture will add significant cost for enclosure and interconnection.
- Modular power converters may be applicable in the same manner as flexible controllers for industrial drives.
- Evolving modern packaging concepts for variable frequency drives is similar to Bricks & Buses prototype.

- It is necessary to get automotive industry on board early because they will drive quantity. However, some auto manufacturers, like Toyota, do everything in house. Consequently, they are not likely to adopt industry standard approach.
- From several kW up to automotive range, power electronics is an afterthought and has application-specific sizes and shapes, and hence control concepts may be more suitable.
- Computer interfaces are not totally standardized for complete compatibility (i.e. between different PC manufacturers).
- If power electronics standardization came from the top down, then large manufacturers would be more accepting.
- Inroads could be made in markets like UPS systems.
- Telecom is a good market for concept demonstration because a modular approach is already used for integration of other system components.
- A modular architecture for power electronics is a good concept.
- It would be more applicable to UPS, utility and distributed generation.
- It may not be most suitable for established markets like industrial drives.
- A modular architecture is easier to apply to new and emerging markets.
- Architecture standards must be flexible and extensible enough to survive for a long time.

Technical Hurdles

- Integration of systems requires clear specification of control and hierarchy.

- Multiple components must work together upon integration; may need external control.
- Who services components from various manufacturers?
- There is not complete exchangeability in PCs.
- Individual component standards would incorporate modularity specifications.
- Value is added in integration.
- Standards must be published.
- Different components have unique properties making it hard to standardize.
- Definition of power and control interfaces is fundamental.

Appendix II. Design Review Meeting Participants

Integration of Distributed Technologies –

Standard Power Electronic Interfaces

Concept/Design Review Meeting

1:15 p.m., Thursday, 23th May, 2002

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Appendix III. Design Review Meeting Presentation Slides

The objective of the meeting is to review standardized interface concepts for power electronics system realization and identify future activities for the approach

Agenda

1:15	Concept Presentation
1:45	Open Discussion
2:15	Action Plan
2:30	Adjourn

All are welcome

Integration of Distributed Technologies

Standard Power Electronic Interfaces

Concept/Design Review Meeting
1:15 p.m., Thursday, 24th May, 2002
1610 Engineering Hall

A project sponsored by the California Energy Commission (CEC) through the Consortium for Energy Reliability Technologies and Solutions (CERTS) with additional support from the NSF Center For Power Electronics Systems (CPES)

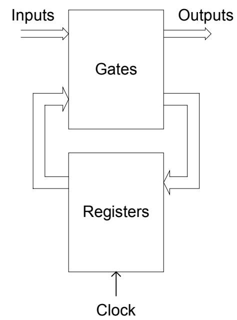
Paper bag revolution

Square bottomed paper bag in standard sizes

- Snazzy high tech products get the buzz, but it's the little things that create real wealth
  – Paul Krugman

Digital Computer

State machine

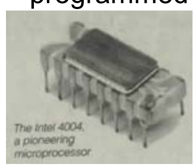


Digital Logic Industry

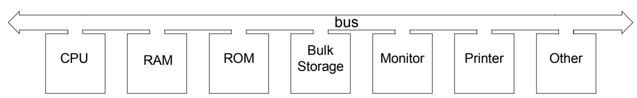
- Early 1970s
- IC manufacturers design logic circuits
- System designers use circuits to implement products
- Fragmented design effort
- Secretive design environment

MITS Altair

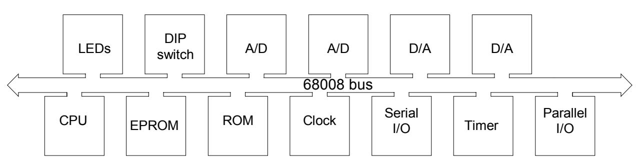
- First inexpensive general purpose microcomputer
- Used a microprocessor
  - programmed to do all manner of tasks



Micro Computer



Address Bus, Data Bus, Control Bus, Memory Addressing



Altair – first real PC

- Mr Roberts wanted the Altair to be expandable, so more memory and other hardware could be added. To make that possible, he and a colleague, William Yates designed the machine's "Bus" – Altair bus/S100
- MITS created the "open" hardware standards enabling independent component suppliers to sell add on equipment…
- … established software as a separate business in personal computing.

VLSI Design

- First microprocessor based systems were lower performance compared to "classical" systems
- But evolution was rapid because of the open and versatile architecture

VLSI Developments

- Xerox-PARC, Intel, Caltech, MIT, Berkeley, etc.
- Multidisciplinary teams
- System oriented design
- Standardized design rules
- Integrated manufacturing

VLSI Design

- Made system design accessible
- VLSI is more than physical integration
- Integrated environment for concepts, simulation, processing, manufacturing, testing, etc.

Moore's Law

What was the revolution that led to Moore's Law?

Old fashioned way: a little bit at a time

Moore's law driver

- An open and versatile architecture for systems
- Realize a simple, but highly integrated system
- Push the technology envelope to make systems have higher performance
- Self-fulfilling prophesy

Digital Vs. Power Electronics

- Consume less power
- Process more information
- Reduce cost
- Find more applications

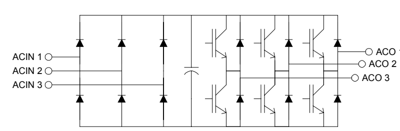
- Process more power
- Take up less space
- Reduce cost
- Find more applications

Power Electronics Today

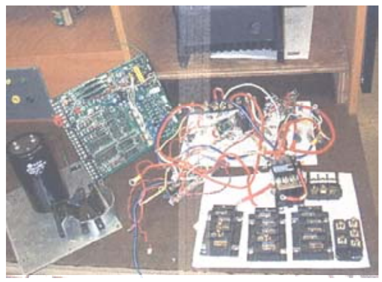
- Concerns
  - High cost
  - Low reliability
  - High complexity
  - Custom design
  - Long design cycle
  - Large manufacturing cost
  - Low volume

Should we look at a general purpose power processing system architecturally?

3 phase ac-dc-ac converter



State of the art
Packaging and realization



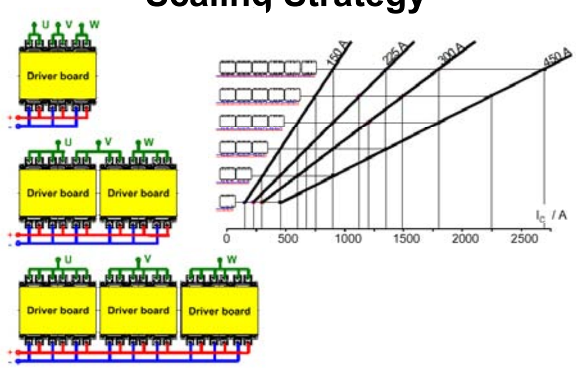
Upcoming Concepts

- Integrated Power Electronic Modules
- Integrated gate driver and protection
- Reactive components – external
- Thermal issues – external
- BOS components – external

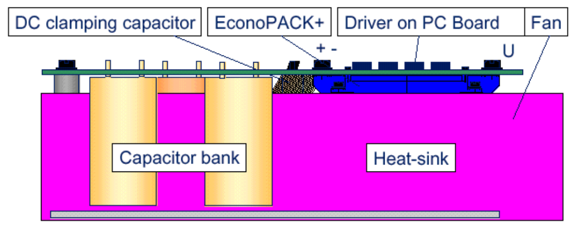
Power Switch Module

Eupec Semicondcutors

Scalinq Strategy

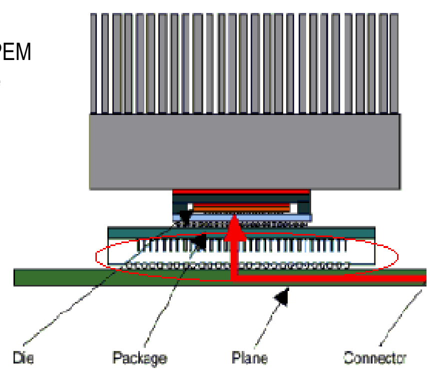


Compact Inverter



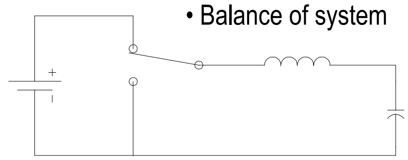
Power Switch Module

CPES IPEM
Package
Concept



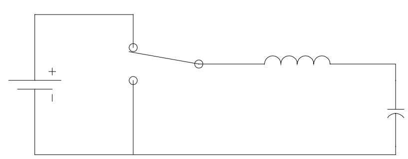
Integrated Approach

- Single pole double throw switches
- Inductors
- Capacitors
- Control circuits
- Balance of system



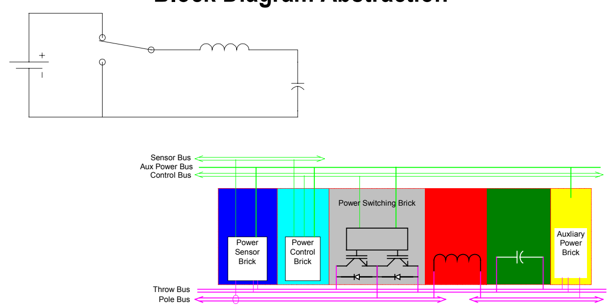
Complexity of Realization

- Non uniform scaling of device size
- Thermal management
- Interconnections



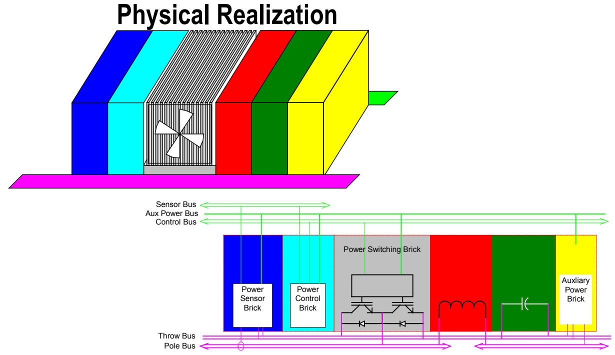
Modular Bricks & Buses Concept

Block Diagram Abstraction



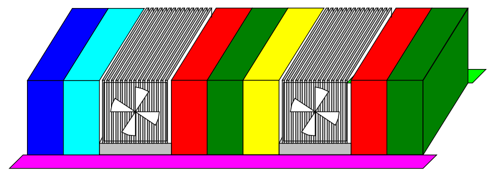
Modular Bricks & Buses Concept

Physical Realization

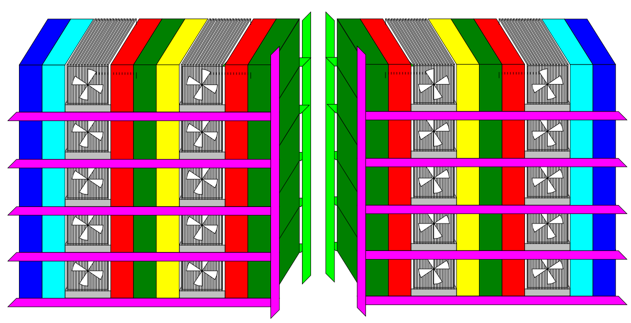


Bricks and Buses

Modular Integration



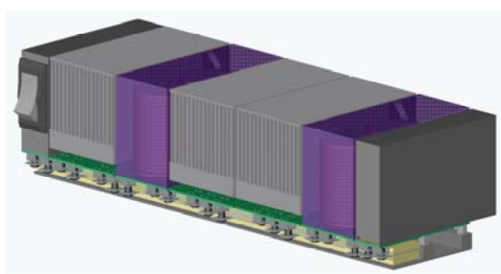
Scaling Up



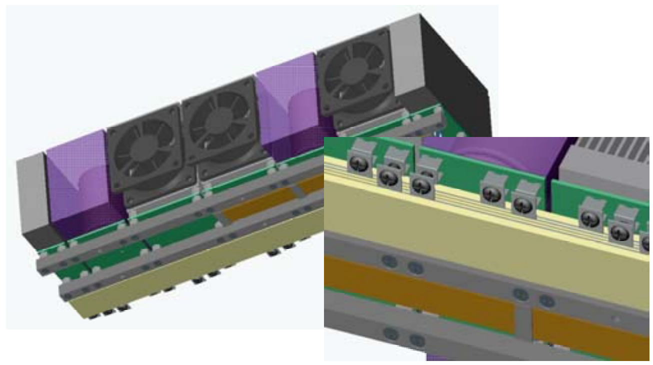
Bricks & Buses

- Two of the dimensions fixed – depth and height
- Width of the bricks variable
- Each brick thermally self managed through restricted faces
- Accommodates variable volume to scale size
- Proportional scaling of available surface area
- Power bus and signal bus on different faces to minimize coupling
- Single bundle power bus contains interconnect EMI

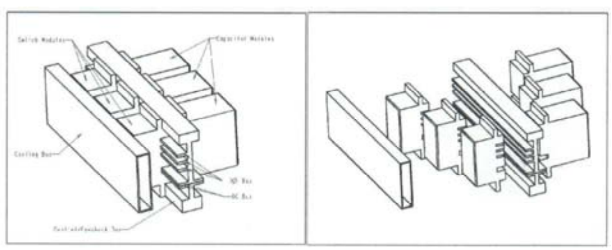
Bricks and Buses Converter



Bricks and Buses Converter

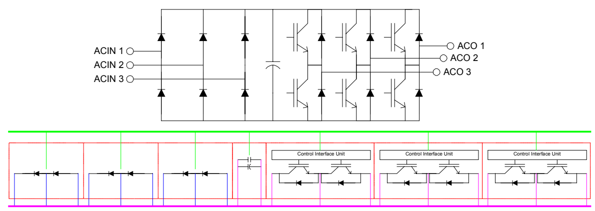


Bus Centered Assembly Concept



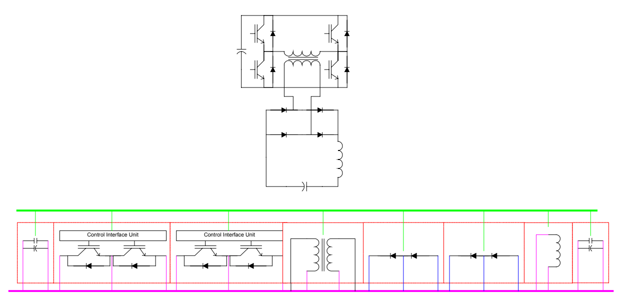
Realizations

3 phase ac-dc-ac converter



Realizations

Isolated dc-dc converter



Components

- Power Switching Brick (PSB)
- Power Control Brick (PCB)
- Current Stiffening Brick (CSB)
- Voltage Stiffening Brick (VSB)
- Sensor Device Brick (SDB)
- Auxiliary Power Brick (APB)
- Input Output Brick (IOB)
- Auxiliary Utility Brick (AUB)
- Power Bus Assembly (PBA)
- Control Bus Assembly (CBA)
- Power Processing Software (PPS)

Components

Power Switching Brick (PSB)

- Single Pole Double Throw (SPDT)
- Unique address
- Integrated gate drives
- Isolated power supply
- Isolated signal interface
- Protection
- Thermal management functions
- Address decoding
- Decoupling bus capacitors
- Snubbers
- Soft-switching networks

Components

Power Bus Assembly (PBA)

- Stiff current
- Stiff voltage
- Multilayer bus bar
- Bus connection tabs at specified intervals

Components

Voltage Stiffening Brick (VSB)

- Capacitive filters
- Throw bus lines
- Absorption of harmonic currents
- Π section filter

Components

Current Stiffening Brick (CSB)

• Inductive filters
• Pole bus lines
• Absorption of harmonic voltages
• T section filter

Components

Power Control Brick (PCB)

• programmable device
• coordinating and channeling power flow
• communicating to various PSBs through the control bus.
• embedded software executes the switching functions
• feedback and feed-forward information

Components

Sensor Device Brick (SDB)

- Current, voltage, temperature, speed, etc.
- Smart sensors
- May be observers/estimator
- Will have digital data readily available for broadcast when called for
- PSB may have integrated smart sensors for throw voltage and pole currents

Components

- Auxiliary Power Brick (APB)
- Housekeeping Power Bus (HPB)
- Auxiliary Utility Brick (AUB)
- Input Output Brick

- Power Processing Software
    - High level programming
    - Instructions for common power conversion functions
    - HTML development environment

Technology elements

- Primary scaling parameters
  - Power throughput
  - Switching frequency
- Secondary issues
  - device transition periods
  - parasitic inductance and capacitances,
  - Power loss, cooling technology
  - capacitor, inductor technology

Technology elements

- Multilayer bus
  - Technology exists and potentially low cost
- Power Switching Brick
  - Integrated Power Electronic Module (IPEM), power overlay, flip-chip, packaging technologies.
- Capacitors
  - Aspect ratio rectangular
- Control and auxiliary elements
  - Readily packageable

Design Environment

- HDL type of environment
- Should be graphically oriented
- Geometrically driven
- Electrical, mechanical and thermal properties extracted
- Coupled - performance prediction and validation
- Directly interface with the manufacturing process

Object Oriented Design Flow

- Define power processing function
- Input throughput specifications
- Select architecture
- Brick selection (objects) and interconnect definition
- Control development
- Electrical simulation
- Thermal verification
- Mechanical verification
- EMI verification
- Brick manufacturing
- System assembly
- System testing

What next?

- Scaling analysis – electrical, thermal, interconnect, emi, structural
- Architectural studies
- Object oriented design
- Object oriented control
- Protocols for various layers of communication
- Concept demonstrations
- Standard development
- Design rules development
- Manufacturing process development