1. Introduction

1.1 Power Electronics Building Blocks

The concept of the Power Electronics Building Block was initiated and promoted by the Office of Naval Research (ONR) with the objective of building large scale distributed power systems for the next generation of naval ships and other high power military applications. One of the purposes is to replace the conventional shipboard radial ac distribution system with a Zonal Electrical DC Distribution System (ZEDS) architecture which is intended to improve ship reliability and survivability and reduce ship acquisition and maintenance and service costs. [A1] The PEBB serves as building blocks in power generation, propulsion, power distribution, and integrated zonal level power conversion.

The PEBB approach has a very broad meaning. It is a concept of using standardized modules to integrate a large-scale system. Subsystems can be built upon small blocks; a large system can be constructed based on the subsystems. This involves a broad research of developing high power semiconductor devices, high power high density packaging, DSP and micro-controllers, motor drives, high frequency power conversion, and resolving issues related to power system architecture and system integration. The most important feature as a system building block is the commonality suitable to most applications. However, depending on the distributed power system structure and system power level, the building block itself may be defined differently. For a power level less than 50 kW, it is now possible to integrate a complete system, such as a three-phase inverter, into a single block as has been demonstrated by Satcon. For medium power applications between 50 kW and the Megawatt level, the basic system building block can be a half-bridge module, which is one of the circuit elements most widely used in power electronics systems for ac/dc, dc/dc, and dc/ac conversion. For very high power applications, each active semiconductor device or passive component, together with the power connection and thermal management element, is already very bulky and heavy. Integration of such devices becomes expensive because of limited applications. Probably they can be regarded as the basic element of a system. The second feature, as a system building block, is the common interface accessible by a computer. It requires the proper partition of the whole system into individual blocks and the definition of the interface between them [A4]. A standardized interface ensures the building blocks to interchange and plug and play.

Packaging of the power device and microelectronics embedded with the control logic and intelligence into a reliable PEBB module is one of the major research areas in the PEBB program. The operational temperature and thermal cycling strength of the high-density microelectronics is lower than power electronics, and the EMI generated by the power circuit can be disruptive to control electronics. Meanwhile, because the reduction of the passive component size and weight has been somehow not so significant in the past, increasing the switching frequency of the power circuit to replace the passive filtering with the active technique is regarded as one of the near future productive objectives [A2]. Therefore, in addition to many other power packaging challenges, such as thermal management and reliability, the reduction of possible EMI propagation and minimizing the parasitic effects in high power and high switching frequency operation are critical for PEBB integration.

If the half-bridge module with the associated gate drive is the basic switching element for the PEBB system, its input and output terminal characteristics are especially important while they are connected to form a power conversion system. The ideal terminal characteristics would have slower voltage and current slew rate for less EMI emission and less switching loss for high switching frequency. In reality, however, the power device switching transient waveforms also suffer from parasitic ringings resulting from the power connection layout and the semiconductor’s inherent properties, such as diode reverse recovery and IGBT turn-off current tail. The turn-on and turn-off loss depends on many factors, such as device brand, gate driver speed, operation temperature, and system layout. The incorporation of a soft-switching network into the PEBB module is one viable approach to slowing down the slew rate of the switching waveforms and reducing the switching loss and device switching stress. While taking all the power devices, soft-switching networks, integrated driver circuits, and the standard interface as a whole, there are other expectations from the module. Its input and output waveforms should be insensitive to system layout and application for easy system integration. From this point of view, some soft-switching techniques, which are indeed good for power switching devices, but may not good for the PEBB application [C5].

Among many power processing blocks, the passive filters are used to control inrush current, block EMI, buffer input output energy, and smooth line and load transients and disturbance. A standard and systematic design, integration, and packaging of passive components and filters would bring a significant contribution for PEBB system integration.

1.2 Integration of PEBB Modules and PEBB-Based Distributed Power System

Pre-shaping the switching waveforms is one of the considerations of PEBB module design and packaging. The integration of the distributed power system is to connect many such PEBB modules onto the dc bus, group them together as a subsystem, and program the subsystem to perform a certain power conversion for different load and source. The system integration process can be divided into three stages: (1) development of PEBB modules- this includes not only the packaging of power devices, gate drivers, and the standardized interface into a module, but also the development of universal controllers, hierarchical control structure, and communications protocols between PEBB modules [A11]; (2) integration of PEBB modules, sensors, and digital controllers into a standalone system and programming the system to perform power conversion; and (3) integration of individual systems, filters, and central control into a distributed power system. Integration of a distributed power system has many considerations, such as module/subsystem parallel, dc bus regulation, system stability, and unbalanced and nonlinear loading effect. The distributed power system testbed is developed for system integration. The testbed serves dual purposes. One is to demonstrate the utility and effectiveness of PEBBs in the design and construction of a large-scale distributions system. The other objective is to investigate interface and compatibility of PEBB modules, system integration and system stability. The system integration process and the structure of the test-bed system are shown in Figure 1. There are many system components integrated into the test-bed system. For the purpose of redundancy, the system has two generators. The generators are connected to ac/dc PWM rectifiers to feed a common dc bus. The rectifiers perform two functions: one is the power factor correction, and the other is the dc bus voltage regulation [D9]. Meanwhile, PEBB systems can be packaged further and paralleled to increase system power level and the current carrying capability or reduce the input current and output voltage ripple. Motor load is one of the typical loads on the dc bus with the voltage source inverter to convert the dc voltage into a modulated variable frequency ac voltage for speed regulation. Another load is the four-leg inverter for utility power supply. Because many end-user loads, such as personal computers, air-conditioners, fans, and lighting are connected to the utility bus, both the dc and utility bus have to support unbalanced and nonlinear loads.

Interactions might take place between the subsystems in system integration because when new connections are made the system order increases, other new loops are formed, and new system eigenvalues appear, whereas the local controllers generally are designed to meet the specifications of the individual subsystems. There exist three system integration protocols. The first is the system input and output specification: power electronic equipment is specified by the manufacturers to operate under given input/output and voltage/current ranges. This protocol is for the steady state operation. The second protocol is the small signal impedance criteria: the system building blocks are treated as a black box with input and output ports. Each box is characterized by the small signal input and output impedance at the ports. In order to prevent possible oscillations after the interconnection, the minor loop gain, which is defined as the ratio of output impedance of the source box and the input impedance of the load box, should not encircle minus one point [F1]. This is the Nyquist stability criterion for an interconnected system. Because the small signal impedance is developed upon the averaged PWM concept of switching model power converters, this protocol is only valid in the same frequency range of the average model. It covers the middle frequency range, which is less than half of the switching frequency. The third protocol is the EMI specifications: this specification is designed to reduce the conducted and radiated electro-magnetic interference between the interconnected and surrounding systems. This protocol addresses a wide frequency range below 30 MHz. However, compared to the complexities of the power electronics system, the existing system integration protocols only cover limited cases. The system interaction could take place in many forms in the full frequency spectrum. Prediction of the interactions in an interconnected system is not as easy as that in a simple circuit. The purpose of the system integration is to explore the possible interactions between the system building blocks, investigate the PEBB interface compatibility, and develop system level controls and system structures for easy integration.

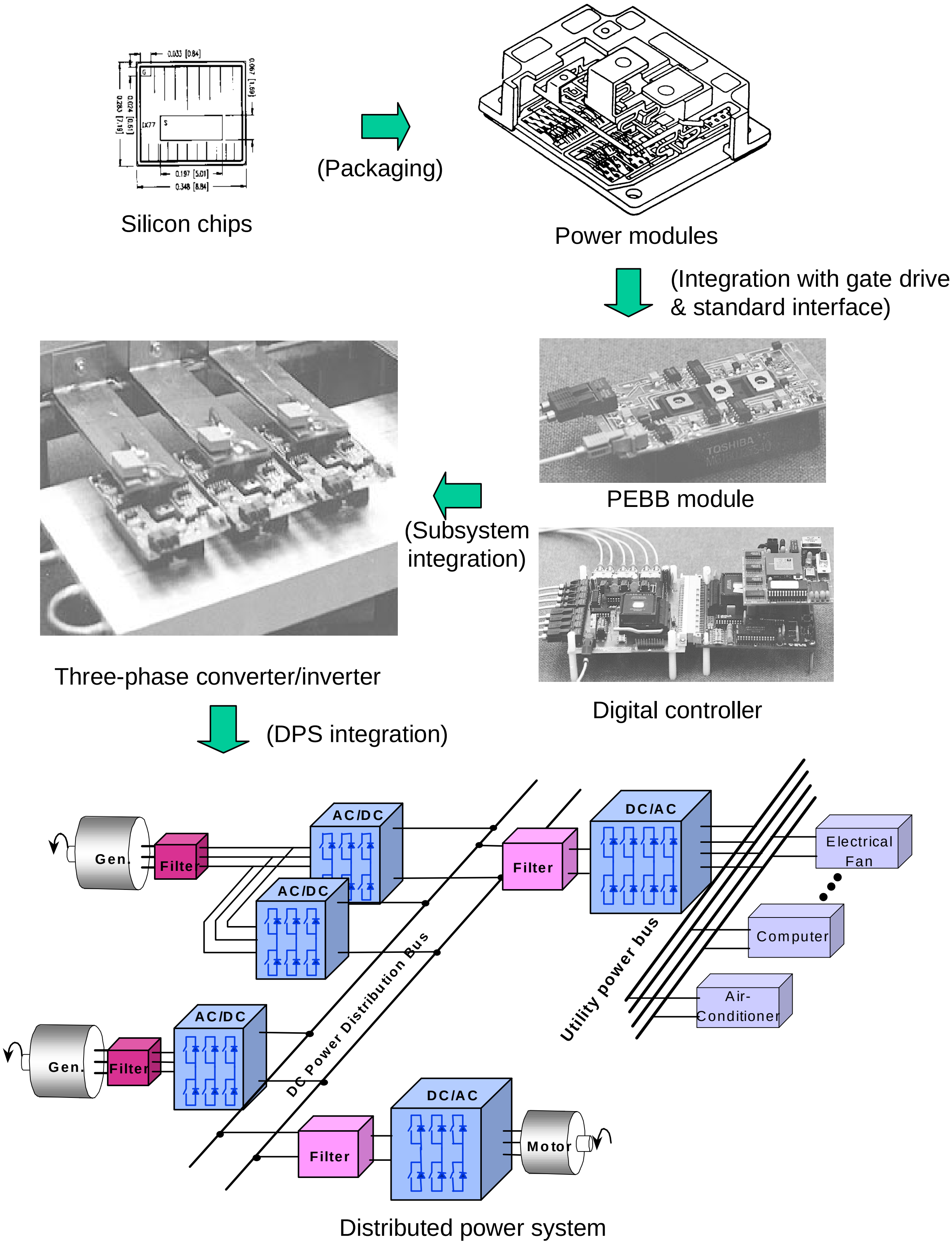

Figure 1.1 The process of system integration and the distributed power system structure

1.3 Dissertation Outline and Major Results

Chapter 2 deals with the development, packaging, and design considerations of the PEBB module. The half-bridge module was identified as the basic switching cell for the PEBB structure. Integrated with the driver circuit and common interface, the conceptual PEBB modules were built and tested. The discrete PEBB module shows a strong parasitic oscillation at the turn-on and turn-off waveforms. Concerning the system integration issues, a commercial high-power wire-bond IGBT module was modeled rigorously by extracting the parasitic inductance associated with packaging layout, bonding wires, and terminal connectors. This process maps a physical device into an equivalent circuit with the direct correlation between the conductor traces and circuit elements. The dominant packaging inductance is identified. The simulations show there are complicated electrical, magnetic, and mechanical interactions inside the wire-bond module. The closely bonded aluminum wires on top of the IGBT chips introduce a proximity effect at switching transients, which causes the non-uniform current distribution between IGBT chips and bonding wires and the mechanical stress on bonding joints. This modeling process and the simulation results provide the microscopic views about the layout parasitics and the electrical effects. It facilitates the advanced PEBB packaging design for better switching performance based on the current packaging technology. An alternative way to smooth the switching transient waveform and improve switching characteristics is to use soft-switching techniques. The zero-current transition (ZCT) soft-switching technique is proved better for PEBB application after the comparative analysis with the zero-voltage transition (ZVT), because the parasitics along the power flow path are absorbed into the resonant soft-switching operation. This makes the PEBB modules insensitive to integration.

Once the highly integrated PEBB modules with the driver circuit and the standard interface are available, the design effort will be shifted to program the controllers instead of making customized designs such as gate resistor selection and power connector design. The initial step of the control design is to establish models of the system. Chapter 3 provides a methodology of modeling high-power large-scale systems based on modularized concepts. Three level models are presented: the discrete model, the large signal average model, and the small signal model. A novel modeling technique is developed for the large signal average model. The half-bridge

PEBB module is modeled as a duty cycle controlled voltage and current source based on two-port network theory. In addition to calculate the averaged the duty cycles, the averaged space vector modulation (SVM) is incorporated with the switching clock signal. Even though the simulation step varies, it calculates the duty cycles at least once at the beginning of each switching cycle. Therefore, it captures the discontinuity existing in SVM. Based on the averaged half-bridge and SVM model, a multi-phase system can be built in the computer the same as the hardware. There are no back and forth abc/dq transformations as in the conventional large signal dq model. It also reserves the common mode component inherently, which is very important in system-level analysis. The time domain simulation results are verified with discrete switching and dq models. Using the Saber built-in functions, it is shown that these models can be used for small signal analysis as well. The open and closed loop small signal transfer functions are verified with dq models.

Chapter 4 demonstrates the system-level interactions using the models developed in Chapter 3 and the experiments in the PEBB system test-bed. Three interaction scenarios are presented. The first is the zero-sequence circulation current in paralleled three-phase rectifiers caused by the interleaved discontinuous SVM. At the discontinuous point of the SVM, the intended switching frequency interleaving produces an excitation on the zero-axis. The conventional control of a single three-phase system only controls the dq components. Therefore, a beat frequency circulation current is developed between the paralleled system. The SVM without using the zero vectors is used to mitigated the circulation current, which is analyzed in comparison with the 60-degree clamping SVM and implemented on the test-bed hardware. The second interaction scenario is the load and source interactions caused by unbalanced load and/or impedance overlap. In order to get utility power from the dc distribution bus, the ac/dc inverter, either single or multiple phase, is needed. Unlike other loads, the inverter load can draw 2ω ripple current from the dc bus, which is a low frequency large signal current component containing a high energy spectrum. If the dc bus has to accommodate the regular dc current and the extra ac current, the bus capacitor has to very large or the source rectifier has to respond. Secondly, if the output impedance of the source rectifier and input impedance of the load inverter approach each other, the transient response of the dc bus becomes oscillatory, which threatens the dc bus stability. The third interaction scenario is the combined common mode noise caused by both front-end PWM rectifiers and load inverters. The common mode voltage appeared at the neutral point of an inverter load was reported to cause leakage current, insulation breakdown, and motor bearing damage in industry applications. The common mode voltage is introduced by the PWM modulation and the dv/dt related to fast switching speed of the semiconductor devices. In the distributed power system with a PWM rectifier as the front-end converter, neutral voltage shift becomes more severe because the common mode voltage modulated by the front-end converters rides onto the dc bus and propagates to downstream loads. The SVM effect and other system structures with less common mode voltage shift are analyzed.

In order to ensure the stability of the interconnected systems in the distributed power system, small signal impedance specifications have to be given to the equipment venders. The impedance specification can cause too many penalties or be too costly in a specific design. The fifth chapter proposed a new concept of the dc bus conditioning for the distributed power system. The bus conditioner is a bi-directional dc/dc converter. It has a band pass filter which senses only the ac current on the dc bus. This signal is used as the reference signal of the current loop. By a proper design of the controller, the bus conditioner operates as a current amplifier tracking the given reference with an opposite polarity. The ac current in the load is shunted into an isolated energy storage component, which buffers the unbalanced loading effect from the dc bus. It actively increases the input impedance of the regulated converter, decreases the output impedance of the source converter, and provides more stability margins to distribution systems.