PRESENT AND FUTURE OF DISTRIBUTED POWER SYSTEMS

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Abstract – **The current stage of development of distributed power systems is presented. Various dc-bus and ac-bus distributed power system architectures are discussed. System integration issues related to paralleling and cascading of dc/dc converters are explained. Benefits and challenges of distributed power systems in various applications are summarized.**

1 Introduction

Continuous advances in semiconductor technology result in ever-increasing functional densities and processing speeds of electronic systems. To allow higher processing speeds and to minimize power consumption, supply voltages are being reduced in new logic families. With the simultaneous increase in power demand and decrease in supply voltage level, new challenges arise for the power system. Traditional centralized power systems often fail to provide adequate performance for new generations of electronic equipment. As a result, the distributed power system (DPS) approach is gaining increased acceptance in many applications [1-6]. This paper summarizes the recent developments in DPS technology, discusses benefits and challenges of DPS architectures, and attempts to identify future trends and directions in DPS design.

2 DPS Structures

In a centralized power system all power processing is performed in one bulky power supply which provides the final voltage(s) required by the load(s). A DPS is characterized by distribution of the power processing functions among many power processing units (PPUs). Several basic DPS structures can be identified according to the way the power processing functions are distributed among several different PPUs. These basic DPS structures are illustrated in Fig. 1.

2.1 Paralleling

Paralleling, shown schematically in Fig. 1(a), has been used successfully in many power systems. The parallel modules can be centrally located to replace a centralized power supply. Such a configuration is often referred to as a modular power supply system. In a DPS with an intermediate bus, parallel modules can be used for the front-end and/or load converters. In either case, paralleling is used to achieve the following characteristics:

Thermal Management: In the parallel configuration, each PPU handles only a part of the total power. Since less power is dissipated in each unit, thermal design is simplified.

Reliability: Paralleling reduces electrical and thermal stresses on semiconductor devices. Although the number of components in a parallel structure is increased, overall system reliability is increased.

Redundancy: An important characteristic of parallel operation is the possibility of configuring a redundant system using more modules than the minimum required by the load. Usually n+1 modules are used, where n is the minimum number of modules required to deliver the load power. Redundancy is desirable in many high-reliability applications, including mainframe computer, avionic, space and military applications.

Modularity: The parallel structure is very suitable for modular system design. The advantages of modular design include ease of system reconfiguration and flexibility. For example, if power demand is increased, additional modules can be added to provide the required power. Since only standard modules need to be designed, system development time as well as engineering and manufacturing costs are reduced, and safety approvals can be obtained more quickly.

Maintainability: A properly designed parallel configuration allows the on-line replacement (hot-swapping) of defective modules. This provides means for non-interrupting maintenance and repair, a very desirable

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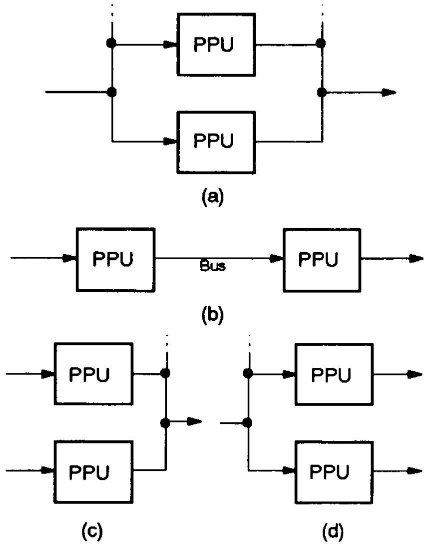

Fig. 1: Basic DPS structures: (a) Paralleling. (b) Cascading. (c) Source splitting. (d) Load splitting.

feature in high-reliability systems operating in a continuous fashion.

Size reduction: Modular design can provide increased power density because lower power modules can operate at higher frequencies with reduced filter component size. Interleaving (phase-shifting of clock signals) of parallel modules increases the ripple frequency, leading to reduction of the overall filter size.

2.2 Cascading

Cascading of power processors is necessary in most DPS configurations to introduce an intermediate bus in the power system, as shown in Fig. 1(b). This approach to power system design is dictated by the following considerations:

Point-of-Load Regulation: The cascade configuration facilitates placement of a power supply in close vicinity to the load for improved voltage regulation and dynamic response. If the load converter can be fabricated with sufficiently high power density, it can be placed directly on a logic board next to the load (on-board converters).

Distribution Efficiency: Low supply voltages and high power levels typical for modern high-performance data-processing systems make power distribution at the logic-level voltage very inefficient and bulky. In a cascade configuration, the intermediate bus voltage can be increased to a convenient level to reduce the distribution currents. As a result, distribution losses in the bus conductors are reduced, and overall system efficiency is improved.

Simplification of Bus Harness: Distribution of power at higher voltages results in simpler, smaller, lighter, and less expensive distribution harnesses.

Handling of Wide Line Variations: Due to the two-stage power conversion, cascade connection can easier accommodate wide input voltage variations (*e.g.*, more than 4:1 in military systems).

2.3 Source splitting

Source splitting, illustrated in Fig. 1(c), allows the use of separate power sources to supply a common load. Source splitting is typically associated with the following system configurations:

Battery Backup: Many systems require uninterrupted power supply operation. Battery backup is the technique most commonly used to provide a temporary power supply in the case of a primary power failure. Since a separate PPU is required for each power source, the split-source configuration arises naturally in systems with battery backups. The PPU associated with the battery can be as simple as an isolation diode or as complex as a bidirectional battery charger/discharger.

Separate Phases: Another form of power source redundancy can be achieved by supplying power to the equipment from separate utility phases. In such a case redundancy is achieved by using a separate PPU for each phase.

Multiple Buses: An additional level of system redundancy can be achieved by using multiple power distribution buses and using a separate load converter for each bus.

2.4 Load splitting

Load splitting is a configuration where separate load converters are used to supply different loads, as shown in Fig. 1(d). This structure is used due to the following considerations:

Distributed Load: In many large-scale systems (spacecraft, mainframe computer, *etc.*), loads are physically distributed over substantial distances. Power distribution at logic-level voltages is not practical due to high conduction losses and complexity of the distribution hardware required for multiple supply voltages. A DPS with an intermediate bus is a natural solution to this problem. In such system, each load is equipped with a separate converter to provide the required supply voltage(s).

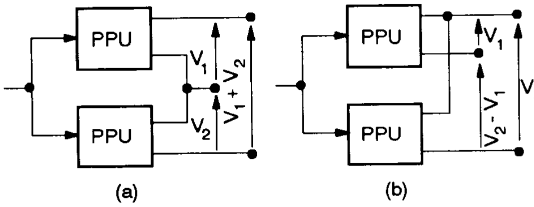

Fig. 2: Stacked DPS structures: (a) Additive stacking. (b) Subtractive stacking.

Regulation: In systems with distributed loads, centralized power supply often cannot provide adequate regulation at the point of load due to the bus impedance. This problem is eliminated by using a DPS with separate load converters located in close proximity to each load.

Noise Decoupling: When several loads are connected to a common power distribution bus, noise interference may occur between the loads. The load-splitting technique minimizes this problem by introducing *two* load converters between any two loads. The load converters and associated filters can virtually eliminate the noise interactions between modules.

Selective Battery Backup: In some applications it is desirable to provide a battery backup only for a critical part of the system, without unnecessary oversizing the battery and associated power processors. Splitting the load and providing separate load converters for different parts of the system allow implementation of the selective battery backup.

2.5 Stacking

Stacking of PPUs (usually dc/dc converters) allows combining the outputs of individual PPUs to obtain supply voltages different than the nominal voltage of each individual PPU. This technique can be used to obtain nonstandard output voltages using standardized converter modules. For high voltage applications, the stacked configuration of Fig. 2(a) provides output voltage equal to the sum of the nominal voltages of the stacked PPUs. For very low-voltage applications, the stacked configuration of Fig. 2(b) provides output voltage equal to the difference between the voltages of the individual PPUs, thus providing an improved overall efficiency in some applications [14].

3 DPS Architectures

The basic DPS structures discussed in Sec. 2 are used to construct various DPS architectures. Most DPS architectures include an intermediate distribution bus and are configured using various combinations of cascading and load splitting. The bus voltage can be either dc or ac, and thus two fundamentally different DPS architectures can be identified – *dc-bus* and *ac-bus*. Selection of the dc-bus or ac-bus architecture has a profound impact on the entire DPS design and performance.

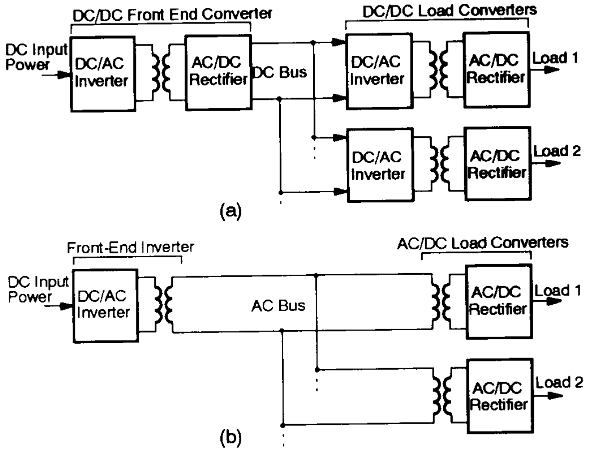

Fig. 3: Distributed power systems: (a) DC bus. (b) AC bus.

The dc-bus and ac-bus architectures are illustrated in Fig. 3. For both systems it is assumed that a rectified line voltage is used as an input to the front-end converter.

In the dc-bus architecture there are two dc/dc conversion steps: the front-end converter and the load converters. Consequently, two inversions and two rectifications must be performed. Since each conversion step introduces power losses, the overall efficiency is not optimal.

The ac-bus DPS is potentially more efficient than the dc-bus DPS, since the conversion is achieved using only one inversion and one rectification. Similar to the dc distribution scheme, some means of regulation is usually required for the ac DPS to compensate for line and load variations [7]. The low-frequency (50 or 60 Hz) ac power distribution has been used for decades in utility systems where efficiency is critical. The high-frequency ac power distribution has been investigated in recent years, primarily for avionic and space applications [9, 10]. A 20 kHz ac distribution system has been proposed for distributing power between loads and sources operating at 3-phase ac, single-phase ac, or dc [8]. In this system, the high-frequency ac bus voltage can be converted to low-frequency ac voltage using a pulse density modulation, or to a dc voltage using a simple rectification.

Advantages of ac bus DPS include: high efficiency, ease of voltage and current transformation, effective ground noise isolation, simplified arc quenching at higher voltages [1], and the possibility of connectorless distribution via a distributed transformer [11].

However, ac-bus DPSs have not been widely accepted in power supply applications due to several potential problems. Since the EM noise radiated from the bus may interfere with sensitive equipment, special (shielded or flat) cables must be used for the bus to minimize the noise. The special bus cabling increases the cost and complexity of the DPS. In addition, the skin-effect increases the bus resistance at high-frequencies. To keep the bus losses down, the practical maximum bus frequency is limited to a 20-100 kHz range. As a result, filtering of the rectified bus voltage requires relatively large filters [10]. The rectification of the ac voltage in the load converters may cause serious problem due to the harmonic currents injected in the bus. To avoid this problem, each load converter should be designed for high power factor and low harmonic distortion of the input current. It might be possible to achieve this by using a simple resonant rectifier scheme [12], but active PFC might be required in some applications. Finally, paralleling of converter modules in the ac bus environment may be rather difficult due to the requirement of precise synchronization and impedance matching.

3.1 DC Bus Architectures

Dc-bus architectures have been gaining increased popularity and are becoming a mature technology due to the inherently low noise and low conduction loss of the dc bus and due to the availability of standard dc/dc converter modules. These considerations outweigh the problems related to the double dc/dc conversion, the possibility of a sustained arc above 32 V [1], and the relatively high cost in volume production.

3.2 Examples of DC-Bus Systems

A number of DPSs with dc bus voltages ranging from 12 V to 360 V [13-16] have been proposed. The applications range from small personal computers [16], through 1 kW military VHSIC systems, to 100 kW mainframe computers. The two latter systems are discussed in the following sections to illustrate the principles of DPS architectures.

3.2.1 DPS for Mainframe Computers

Unique power system requirements exist in high-performance VLSI mainframe computers. The high functional density of VLSI circuits, high power consumption, and low supply voltages (0.7-3.6 V) [14] result in extreme demands on the power supply system. A distributed architecture can meet these challenges, and in addition, provide enhanced reliability, repairability, and ease of maintenance through the use of redundant modules.

Figure 4 shows the architecture of a DPS for a mainframe computer [13]. The system operates from a three phase input and uses parallel modules, each containing a rectifier with a power-factor-correction (PFC) circuit and filters. The front-end converters operate in parallel to provide the required power. The full-bridge zero-voltage-switched (ZVS) PWM converter topology [18] is used for the front-end converter. A 360 V bus is used to reduce distribution losses. The load converters are connected in parallel to handle high load currents. A stacked power system architecture is employed for each load converter to improve the conversion efficiency and to reduce the number of converters required for several low output voltages.

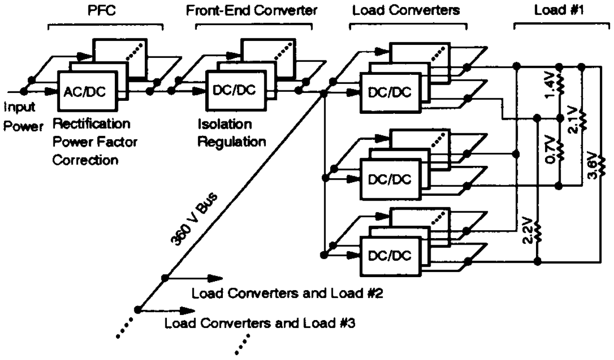

Fig. 4: Distributed power system for VLSI mainframe computer.

The system shown in Fig. 4 is formed using almost all of the DPS structures described in Sec. 2: three-level cascading, paralleling, load splitting, and stacking. The system is completely protected from any single-point failure, with the exception of a failure of a distribution bus.

3.2.2 DPS for Military VHSIC Systems

Due to very high switching speeds, VHSIC systems represent extremely dynamic loads. As a result, the power supply system must be designed to meet stringent dynamic regulation requirements. To achieve the required regulation, a DPS architecture with on-board load converters was proposed [13].

Figure 5(a) shows the typical architecture of a DPS for a military VHSIC system. The power system is designed using single-level cascading and load splitting. The 1 kW front-end converter (backplane power supply) accepts the raw input power and provides a regulated 50 V bus. The backplane power supply is built on a single standard-electronic-module format 'E' (SEM-E) card and provides power to a number of logic SEM cards, as shown in Fig. 5(b). This design simplifies the maintenance procedures, since the plug-in power supply can be replaced just like any other card in the system. The bus voltage of 50 V has been selected due to the personnel and equipment safety requirements, functional partitioning constraints, electrical performance considerations, and EMI considerations [13]. High-density load converters are placed on the logic cards to provide the required regulation.

4 Design Considerations for DPS

Design of a dc bus DPS involves a number of trade-offs and choices related to the selection of distribution bus

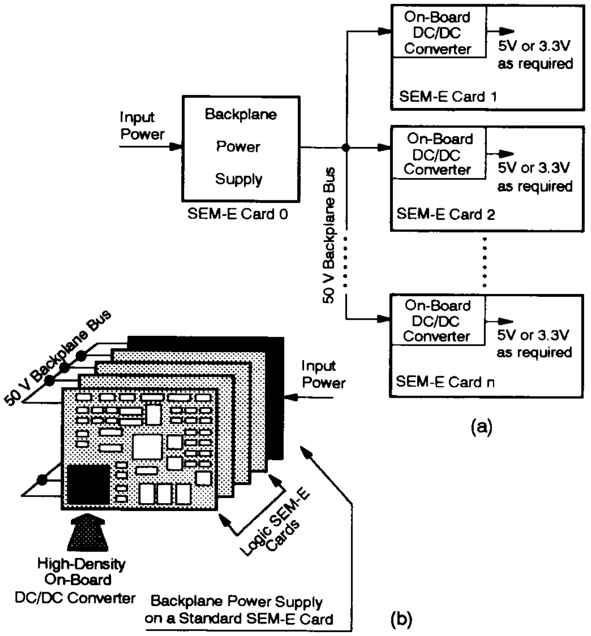

Fig. 5: Typical distributed VHSIC power system: (a) Block diagram. (b) Physical system layout.

voltage, optimization of the front-end and load converters, and integration of the system.

4.1 Bus Voltage Selection

Selection of the bus characteristics is an important step in DPS design since it affects all power system components. The level of bus voltage and degree of bus voltage regulation are the main characteristics of the dc bus.

The major considerations in the selection of the dc-bus voltage are:

Power level: To minimize distribution losses, bus voltage must be sufficiently high to reduce distribution currents to acceptable levels. This implies higher bus voltages for higher power systems.

Safety considerations: If safety is an important consideration, bus voltage must be within safety-defined levels. In most cases this means a bus voltage below 60 V dc. To avoid possibility of a sustained arc, a bus voltage below 32 V must be selected [1].

Battery backup requirement: In many systems with a battery backup, bus voltage must be compatible with the battery voltage to eliminate the battery discharger unit. In some applications (*e.g.*, telecom) this single item determines the bus voltage level.

The regulation of bus voltage has a serious impact on the power system components. A tightly regulated bus allows optimization of the load converters for maximum efficiency. To provide a tightly regulated bus voltage, however, the front-end section must include a regulating stage, typically a dc/dc converter. As a result, the efficiency of the front-end section is reduced. Hence the bus voltage regulation must be specified based on the overall system performance after careful consideration of the involved trade-offs.

4.2 Front-End PPUs

The front-end PPU performs one or all of the following functions:

- Line rectification and filtering.
- Power factor correction and input line current harmonic reduction.
- Dc/dc conversion.
- Energy storage for hold-up.

In the simplest DPS, the filter and rectifier are the only parts of the front-end PPU. Bus voltage is unregulated, and the load converters must be designed to accept a relatively wide input voltage range. If a PFC is required, the front-end PPU may also include a PFC circuit.

In applications where the input voltage has a very wide range (*e.g.*, military systems), the front-end PPU must include a dc/dc converter to regulate the bus voltage. The dc/dc converter in this application has been referred to as a front-end converter [17], line conditioner [28], backplane power supply, primary power converter [15], or preprocessor [22]. A complete front-end PPU, including a rectifier and a dc/dc converter, is sometimes referred to as a line conditioner [13] or a prime power converter [1, 2]. In this paper, the dc/dc converter feeding a dc bus in a DPS is referred to as a front-end converter.

Most front-end converter designs evolve around the full-bridge (FB) topology due to the high power requirement of 1 kW or more. Conventional PWM designs operating at 500 kHz have been considered, but the more advanced FB ZVS-PWM [17, 18, 19] and resonant FB-ZVS converters [20] provide better performance in some applications.

In high-reliability systems it is necessary to use parallel front-end dc/dc converter modules. To provide optimum performance, current sharing between the modules must be assured. Most current-sharing techniques use a current-sharing bus to provide a common voltage to control the current supplied by each module. "Democratic" current-sharing techniques are preferred to the "master-slave" configuration. One possible implementation of a "democratic" current sharing uses the "trim" inputs provided on some dc/dc converter modules [21]. Integrated control circuits providing this type of current sharing are becoming available commercially. The "common error voltage" technique in conjunction with current-mode control provides good current sharing but also requires a current sharing bus. The current-sharing bus can be eliminated by allowing the output voltage of the front-end converter modules to drop in a controlled manner with increasing load current [2]. There seems to be a limit, however, on the number of modules that can be reliably paralleled in this manner [13].

Parallel front-end converter modules should be synchronized to eliminate the beat-frequency noises [13]. In a DPS, the synchronization should be a result of cooperation among all modules connected to a common synchronization bus [2].

To reduce the system noise, modules can be operated with fixed phase shift (interleaving, phase staggering). This technique, however, is difficult to use in an expandable system, where the number of modules is not predetermined, and no control circuitry outside the modules is allowed. A desirable synchronization scheme would be included inside identical modules, and would automatically change the phase shift according to the number of operational modules connected to the bus.

4.3 Load Converters

The success of the DPS concept depends largely on the availability of small, efficient, low-noise, and low cost load converters. Substantial research efforts have been devoted recently to the development of new circuit techniques suitable for high-density load converter modules. Several state-of-the-art designs have been developed for on-board converter applications, including a high-frequency fully-resonant converter [22], an interleaved soft-switched forward converter [23], an integrated-magnetics converter [24], and a forward ZVS multi-resonant converter [25]. All mentioned circuits were developed for a military VHSIC application and typically achieve power density of 50 W/in^3, efficiency of 82%, and a low profile of 0.25 in.

These research efforts suggest that major improvements are necessary in the power semiconductor devices and magnetic materials to achieve the desirable density and high efficiency. In particular, low-voltage MOSFETs designed specifically for synchronous rectifier applications could dramatically improve efficiency of low-voltage load converters [26]. To make the DPS concept truly practical in VHSIC applications, power density and efficiency of on-board power converters must be increased to 100 W/in^3 and 90%, respectively. In commercial applications, cost and efficiency of the load converter modules are the most critical factors.

4.4 System Integration and Dynamic Interactions

One of the primary concerns associated with the application of DPSs is the system integration and interactions between the components of the DPS. This issue has been often ignored in the development stage. The potential sources of the dynamic interactions in a DPS are related to paralleling and cascading of converter modules. In most applications, an EMI filter is necessary for each dc/dc converter in the DPS which drastically increases system complexity and potential for interactions among the system components.

Recent studies [27-32] improved the understanding of the nature of these interactions and provided design guidelines for integration of DPSs.

4.4.1 Paralleled dc/dc converters

When identical dc/dc converter modules are paralleled, system stability is not affected, provided each module has its own output-filter capacitor. In such case, the overall loop-gain transfer function of paralleled modules is identical to that of a single module, provided the load is changed in proportion to the number of modules [28]. As a result, each converter module can be optimized separately, and an arbitrary number of identical modules can be paralleled without detrimentally affecting the overall loop-gain characteristic. However, if the modules share a common filter capacitor, paralleling modules will degrade the stability margin as the number of modules is increased [27]. It has been also suggested [2] that when non-identical modules are paralleled, the stability of the system may be compromised.

4.4.2 Cascaded dc/dc converters

One possible cause of DPS instability is the effect of loading the front-end converter with load converters. The input impedance of a load converter can be modeled by a negative resistance up to the crossover frequency of its loop-gain transfer function [28]. This negative resistance can destabilize a line conditioner optimized for a resistive load.

It has been shown [28, 31] that for buck-derived circuits the front-end converter must have a high crossover frequency and a sufficiently high feedback gain to maintain stability. Conventional design techniques can be used to optimize the front-end converter design, but the design should be verified using the actual load input impedance or at least its negative-resistance approximation.

For converters with RHP zeros in their control-to-output voltage transfer functions, however, it may be difficult to obtain satisfactory performance in front-end converter applications. For example, a boost front-end converter optimized for resistive load may become unstable when loaded with dc/dc converters. Only a relatively low integrator gain offers a reasonable phase margin [31], and the overall system performance may be compromised.

4.4.3 EMI filter design considerations

To minimize noise on the distribution lines, adequate filtering must be provided in a DPS. The addition of EMI filters at the input of the front-end converter and at the input of each load converter may result in undesirable interactions. Proper design techniques must be used to minimize the interactions and to ensure adequate system performance. The intermediate-bus filter for each module can be properly designed by finding a compromise between low output impedance and high input impedance of the filter [29, 30].

The system input filter provided at the input of the front-end converter implemented by paralleling several modules is usually divided in two stages. The first stage is common to all modules, and the second stage is provided for each module independently. The separate secondary filters minimize ripple currents on the distribution line feeding the modules. Conventional two-stage filter design techniques can be used for the system input filter, but additional damping must be introduced in the secondary filter to avoid interactions [29, 30].

5 Future of DPSs

There is no doubt that DPSs will eventually replace centralized architectures in most large, many medium, and some small electronic systems. To make the DPS approach more viable and attractive, however, many issues still need to be addressed. The following challenges can be currently identified:

Packaging: New packaging techniques need to be developed to allow increase of power density of on-board converters to 100 W/in^3 and above. High-voltage integrated circuit technology must be employed to improve electrical performance and power density. Hybrid thick-film technology or similar techniques will be necessary to achieve the required density and provide adequate thermal management.

On-Board Efficiency: High efficiency is required for load converters to minimize power dissipation on the card containing the load. Presently, the on-board dc/dc converters can only achieve efficiency around 80%. Improvements must be made to increase the efficiency to 90% range. Synchronous rectification should substantially increase the efficiency once suitable semiconductor devices and circuit techniques are developed. To achieve small size of point-of-load converters, high-frequency dc/dc converter designs must be employed. New converter technologies should be explored to combine low switching losses with low device voltage and current stresses. Semiconductor and magnetic devices should be improved to meet challenges of high-frequency, high-density on-board converters.

Noise: Placement of a high-frequency on-board converter in a close proximity to noise-sensitive electronic circuits may cause EMI problems. Extensive research is necessary in this area to provide better understanding of the problem and develop appropriate design tools and techniques. New circuit techniques must be sought to minimize the EMI generated by the load converters. Innovative packaging and shielding techniques will be necessary to reduce the EMI problem.

Cost: Manufacturing costs (measured in dollars per watt) for distributed-power modules are currently higher than those for centralized power supplies [4]. This may cause an economical barrier in some applications where DPS architecture is desired, but economical considerations are an overriding factor. To make DPS approach attractive for these applications, the manufacturing costs must be reduced. This can be achieved by extensive standardization of the DPS subsystems and full utilization of the surface-mount technology.

System Integration: Although much has been already done to explain dynamic interactions in DPSs, the system study must be continued, and computer-aided tools must be developed to provide systematic design techniques capable of addressing the DPS in its entirety.

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