Dual AC-Input Power System Architectures

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***Abstract* - Power systems for data-processing and communication equipment used in mission-critical applications that require high system availability must be implemented with fault-tolerant architectures. Generally, these fault-tolerant power architectures require that the power supplies built into data-processing/communication equipment are capable of operating from two different ac power sources. In this paper, a number of dual ac-input power system architectures are proposed and evaluated on a relative basis with respect to power density and cost.**

I. INTRODUCTION

High-availability power systems for data processing and communication equipment used in mission-critical applications must be implemented with enhanced reliability. Usually, increased power-system reliability is achieved by employing power system components with high intrinsic reliability and by implementing highly redundant power-system architectures that include the redundancy of the primary power source. Generally, these redundant power systems use passive back-up power sources such as UPSs or engine generators, or both [1]-[7]. The availability of redundant power systems with a passive back-up source can be maximized by providing multiple power paths [1]. Further increase of availability can be achieved by resorting to power system architectures with multiple power paths that are capable of operating from two independent ac electrical systems, i.e., by resorting to an active back-up source [1].

Generally, fault tolerant power systems that use two active power distribution paths require that the ac loads, i.e., the ac/dc power supplies built into the datacom equipment, are capable of accepting two ac inputs. As spelled out in [8], which defines the latest compliance requirements for these dual ac-input power systems, a dual ac-input fault-tolerant power system should operate properly from both power sources, as well as from either of the single sources in case the other source has failed or is out of tolerance. Furthermore, when both ac inputs are present, the load power should be shared between the two sources. Also, no internal or external switching devices are allowed to switch a dual-input power supply (ac load) from the failed line to the other line.

In this paper, a number of dual ac-input (or, dual-cord) ac/dc power supply architectures compliant with the specifications defined in [8] are proposed and evaluated on a relative basis with respect to power density and cost. The evaluations are performed assuming that for dual-line operation the power system is N+1 redundant.

II. HIGH-AVAILABILITY POWER SYSTEMS

Generally, power systems for data processing equipment used in mission-critical applications are expected to be available for at least 99.999% of the time [1], [3], [6]. This, so-called "five nines" availability, translates to a down time of not more than approximately 5 minutes per year. With a typical power grid availability of only 99.9% [4], i.e., "three nines" of availability, the ac power grid cannot come even close to meeting the expected uptime requirements.

It is well understood and documented that increasing the power system availability beyond the availability of the ac power grid requires the implementation of redundant power system architectures with multiple power and cooling distribution paths. The redundancy together with proper system monitoring enables on-line maintenance and repair of the system, which increases the fault tolerance of the system and, consequently, maximizes its availability. Recently, a number of fault-tolerant power system architectures with different degrees of redundancy and complexity have been proposed and/or analyzed for use in applications that require availability beyond "three nines" [1]-[7].

As an example, Fig. 1 shows a typical power system architecture used in some large data centers. The system primary power is always supplied from the ac line except during long ac-line failure periods when it is supplied from the engine/generator set (EG). The transfer between the ac line and the engine/generator set is done in a controlled fashion by the Automatic Transfer Switch (ATS). Before it is distributed to the ac/dc converters and other critical ac loads (not shown in Fig. 1), the primary power is conditioned by n+m UPSs connected in parallel. The parallel connection of the UPSs is usually configured to provide n+1 redundancy, i.e., typically m=1. The reliability of the individual UPSs is further enhanced by providing a bypass static switch that connects the input and the output of the UPS in case of a

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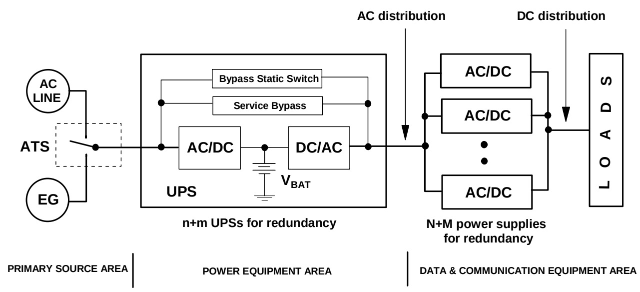

Fig. 1 Typical data center power system.

UPS failure. In addition, optional internal back-up battery V_{BAT} fitted inside the UPSs can be used to supply energy during short line outages. Typically, the UPSs are also provided with a service bypass switch, which is used to manually shunt the UPS during schedule maintenance without significantly affecting the system reliability.

The ac power at the output of the UPSs in Fig. 1 is distributed to a redundant connection of ac/dc power supplies, typically, in N+1 configuration. Finally, the dc output power provided by the output(s) of the ac/dc converters is distributed via a dc distribution network to critical dc loads. It should be noted that for the sake of simplicity, the detailed structure of the ac and dc distribution networks that always employ protection devices such as electronic circuit breakers, is not shown in Fig. 1.

The calculated availability of the ac power at the output of the UPSs in the fault-tolerant power system as in Fig. 1, ranges from “five nines” [7] to “seven nines” [4], i.e., from 99.999% to 99.99999%, depending on the assumptions made about the failure rates of the system components and battery reserve time. However, since this number only includes electrical-system failures, i.e., it does not include the failures of the other systems such, for example, cooling system(s), the actual availability of the ac power at the ac-distribution bus is lower. In addition, accounting for failures of the downstream ac/dc converters, the system availability is further decreased. In the absence of reliable availability data for the entire system in Fig. 1, the extrapolation of data reported in [1] and [5] points to a site availability of not more than “four nines”, i.e., 99.99%.

The availability of datacom power systems can be further increased by using the dual ac-line power system architecture shown in Fig. 2. In this architecture, two independent sets of primary sources are used to provide power to two sets of redundant UPSs. The ac outputs of each set of UPSs is distributed by a separate ac-distribution bus to the corresponding redundant connection of the ac/dc converters that supply the load. When both ac-lines are present, the load power is supplied simultaneously from both ac sources so that each source provides approximately one-half of the required output power. When one of the ac lines fails, or it is out of the specified range, the load power is entirely provide by the other line without any load disruption. Generally,

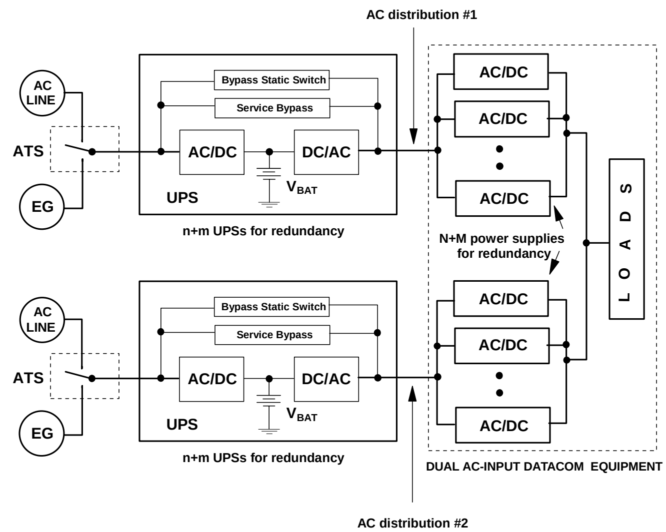

Fig. 2 Dual ac-input power system.

during the ac-line downtime, the redundancy of the system is lost, unless a back-up power source, i.e., either EG, or internal UPS battery, is activated. The availability of this System + System (S+S) redundant fault-tolerant architecture is expected to be more than “five nines,” or 99.999%, excluding “non-electrical” failures such as Emergency Power Offs due to human errors or fire alarms [1].

It should be noted that in some of today’s high-end datacom equipment, dc-bus Distributed Power Systems (DPSs) are used to deliver power to the loads. In these DPSs, ac/dc converters in Figs. 1 and 2 are used to create a 12-V or 48-V dc-bus voltage, which is then distributed to dc/dc point-of-load converters (not shown in Figs. 1 and 2) that supply the dc loads [9].

Finally, the dual ac-input power systems can also be employed to provide a cost-effective powering solution for facilities where the convergence of data and voice transmission has brought about the collocation of datacom and telecom equipment [2]. Generally, the telecom equipment is powered from a –48-V dc-bus that is provided by ac/dc rectifiers connected directly to a primary source. Since the telecom power system does not use UPSs, the required load power during primary source outages is supplied from a battery plant. A battery plant provides a back-up time of several hours, typically, 3 to 6 hours. To deal with longer ac-line failure durations, the telecom power also employs an EG set. With dual ac-line input, datacom and telecom equipment can be reliably powered without the need of a battery plant, as shown in Fig. 3 [2]. In the power system in Fig. 3, each set of ac/dc rectifiers is used to create a 48-V dc bus. The two dc buses are connected to downstream dual-input dc/dc converters which supply the critical dc loads. It should be noted that other ac/dc converters for generating other dc voltages required by the datacom equipment (not shown in Fig. 3) may be connected to ac-distribution buses #1 and #2. With a reduced complexity, the fault tolerant power system in

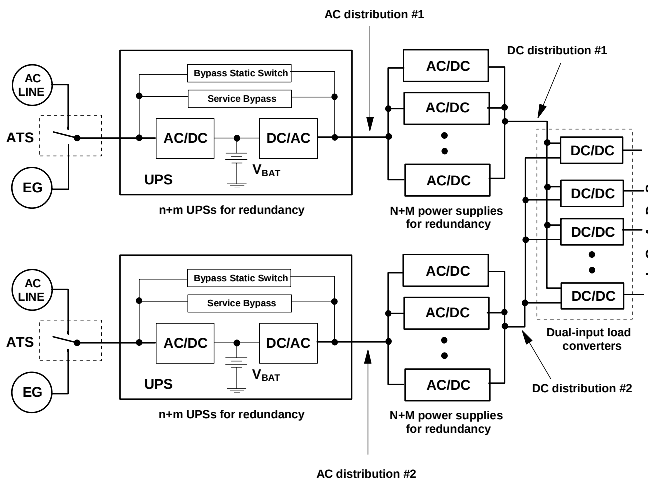

Fig. 3 Power system with dual-input ac/dc and dual-input dc/dc converters.

Fig. 3 seems to offer a high availability at a lower cost for sites with mixed ac-powered and dc-powered equipment [2].

III. Dual AC-Input Power Supply Architectures

The most obvious implementation of the dual ac-input power system is shown in Fig. 2. In this implementation, two identical N+1 redundant systems supplied from two independent electrical systems are used. In fact, this System + System (S+S) implementation employs conventional single-cable ac/dc power-supply modules to accommodate both ac-inputs. Each ac/dc power-supply module consists of a nonisolated front-end power-factor-correction (PFC) converter followed by an isolated dc/dc converter output stage, as shown in Fig. 4. Because this implementation of ac/dc power supplies is routinely used in power-supply industry, the approach of using the Single-Cable-Module Architecture (SCMA) to build a dual ac-input power system requires minimum design effort and time. However, the main drawback of the SCMA is poor utilization of components such as semiconductors, magnetics, energy-storage capacitors, and connectors, especially as the number of modules N increases.

Figure 5 shows another dual ac-input architecture, which uses dual-cable modules. In the Dual-Cable-Module Architecture (DCMA) shown in Fig. 5, two isolated PFC converters connected in parallel are used to accept the two ac-inputs. The paralleled PFC stages are followed by a common dc/dc converter output stage. When both ac-inputs are present, the load power is supplied simultaneously by both isolated PFC converters so that the PFCs share the power. Since in case of a line failure the total output power of a module needs to be supplied from the remaining line, each isolated PFC converter front-end needs to be rated at the full output power of the module. Generally, packaging of two isolated PFC converters that can individually support the

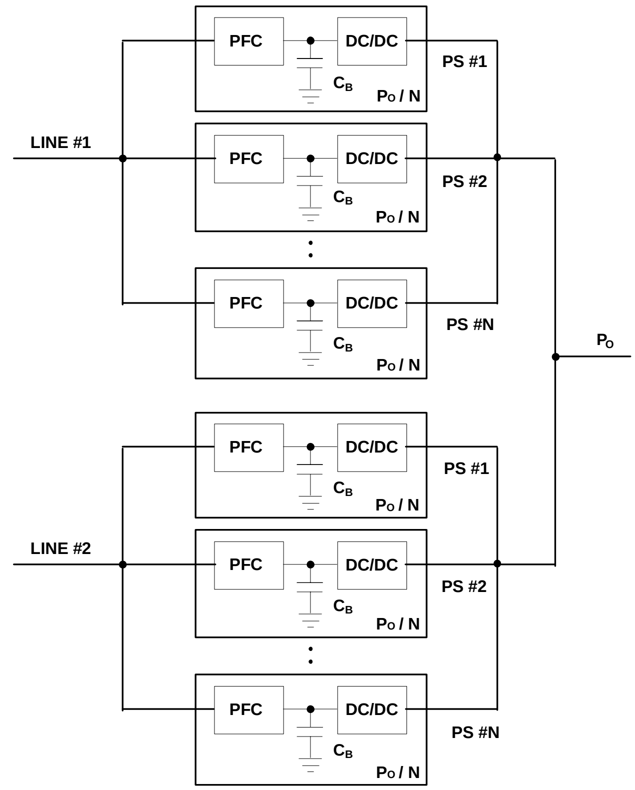

Fig. 4 Single-Cable-Module Architecture (SCMA).

module's output power requires more space than a single nonisolated PFC converter in the SCMA in Fig. 4. As a result, the size of a dual-cable module is expected to be larger than the size of a single-cable module rated at the same power.

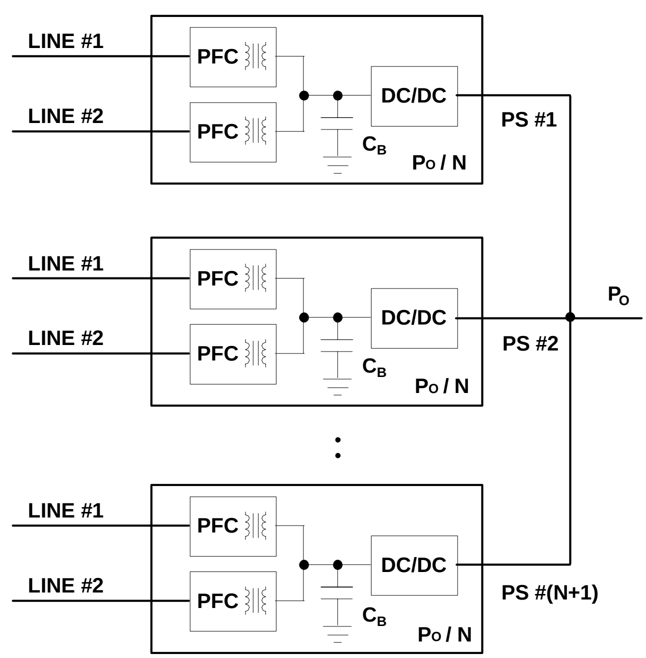

Fig. 5 Dual-Cable-Module Architecture (DCMA).

A dual ac-line power system can also be implemented using mixed single-cable and dual-cable modules, as shown in Fig. 6. Generally, this Mixed Single/Dual-Cable-Module Architecture (MSDCMA) approach requires 2 single-cable modules (SCM) and N-1 dual-cable modules (DCM). Since the size of DCMs is larger than the size of SCMs because the DCMs are implemented with a pair of isolated PFCs, the MSDCMA requires modules with different form factors. This may not be desirable from the maintenance and procurement point of view since it would involve two part numbers.

IV. ARCHITECTURE COMPARISONS

To evaluate the SCMA, DCMA, and MSDCMA on a relative bases with respect to the power density and component count, it is assumed that when both ac lines are present, the ac/dc converter system is N+1 redundant. The same approach can be easily extended to any other redundancy order.

It should be noted that the minimum redundancy of the SCMA architecture is N+N since the SCMA requires at least 2N modules. The other two architectures, require N+1 modules to implement N+1 redundancy. It is also interesting to note that even for single ac-line operation, the DCMA still retains N+1 redundancy. However, the SCMA and MSDCMA lose redundancy when one of the ac lines is down. Finally, it should be noted that the MSDCMA degenerates into the SCMA for 1+1 redundant implementation.

The key characteristics of the three dual ac-input

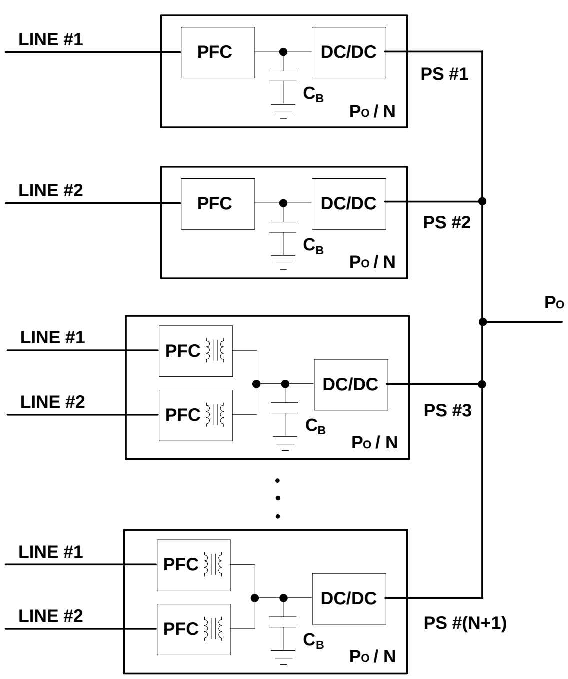

Fig. 6 Mixed Single/Dual-Cable-Module Architecture (MSDCMA).

architectures are summarized in Table I. The number of the semiconductor devices, magnetics, energy-storage (bulk) capacitors, and connectors is estimated based on the total number of the PFC circuits and dc/dc converter output stages. Specifically, the number of semiconductor devices is proportional to the number of PFC circuits plus the number of dc/dc stages since at least one switch is necessary for the implementation of each circuit. Similarly, the number of magnetics is proportional to the number of nonisolated PFC circuits plus twice the number of isolated PFC converters plus twice the number of dc/dc stages, because the nonisolated PFC circuits require at least one magnetic piece (a boost inductor), the isolated PFC circuits require at least two magnetic pieces (a boost inductor and a transformer), and the dc/dc output stages require also at least two magnetic components (a transformer and an output filter). Finally, the number of energy-storage capacitors is proportional to the number of modules, whereas the number of connectors is equal to the number of modules. As can be seen from Table I, the SCMA requires the largest number of components, whereas the MSDCMA requires the fewest.

The component utilization of each of the architecture can be assessed on a relative basis by defining the Component Utilization Factor (CUF) as

$$CUF = \frac{\text{minimum \# of required components}}{\text{actual \# of components}}.$$

For example, for an N+1 redundant system, the minimum number of output connectors is N+1. However, the SCMA implementation requires 2N connectors, so that $CUF_{con}^{SCMA} = (N+1)/2N < 1$, as shown in Table II. Since the overall CUF of the MSDCMA is the best, the MSDCMA is expected to have the lowest cost.

Finally, Fig. 7 shows the normalized power-density of the three dual ac-line power system architectures as a function of module number N, where the normalization is done with respect to the power density of the SCMA. The power-density comparisons presented in Fig. 7 are obtained by assuming that the volume of the DCMs that employ a pair of isolated PFCs is 35% larger than the volume of the SCMs that are implemented with a non-isolated PFC. As can be seen from Fig. 7, for systems with 1+1 redundancy, the SCMA architecture offers the highest power density, whereas for N>1, the MSDCMA exhibits the highest power density in addition to the best component utilization. The power density of DCMA is the lowest for 1+1 redundant systems. However, for higher N, the power density of the DCMA is approaching that of the MSDCMA, which implies that the size and cost of the DCMA and MSDCMA are similar for N>3.

TABLE I

ARCHITECTURE COMPARISONS OF DUAL-AC LINE N+1 REDUNDANT POWER SYSTEMS

number of	SCMA	DCMA	MSDCMA
MODULES	2N	N+1	N+1
Single-Cable Modules	2N	0	2
Dual-Cable Modules	0	N+1	N-1
PFC CIRCUITS	2N	2(N+1)	2N
Non-isolated PFCs	2N	0	2
Isolated PFCs	0	2(N+1)	2(N-1)
DC/DC STAGES	2N	N+1	N+1
SEMICONDUCTORS	~4N	~3(N+1)	~3N+1
MAGNETICS	~6N	~6(N+1)	~6N
BULK CAPACITORS	~2N	~N+1	~N+1
CONNECTORS	2N	N+1	N+1

TABLE II

COMPONENT UTILIZATION FACTOR (CUF) COMPARISONS

CUF	SCMA	DCMA	MSDCMA
Semiconductors	$\frac{3N+1}{4N}$	$\frac{3N+1}{3(N+1)}$	1
Magnetics	1	$\frac{6N}{6(N+1)}$	1
Bulk Capacitors	$\frac{N+1}{2N}$	1	1
Connectors	$\frac{N+1}{2N}$	1	1
TOTAL	Lowest (Worst)	Fair	Highest (Best)

V. SUMMARY

Three architectures for dual ac-input fault-tolerant power systems are presented and evaluated with respect to power density and component utilization. Specifically, Single-Cable-Module Architecture (SCMA), Dual-Cable-Module Architecture (DCMA), and Mixed Single/Dual-Cable-Module Architecture (MSDCMA) were considered assuming N+1 redundancy when both ac-lines are present.

It was found that for systems with 1+1 redundancy, the SCMA and MSDCMA offer identical volumes and component utilization since for 1+1 implementation the MSDCMA degenerates into the SCMA. For redundancies 5+1 and higher the MSDCMA and DCMA exhibit similar volumes and component utilization, whereas in the redundancy range from 2+1 to 4+1, the MSDCMA gives the smallest volume and has the best component utilization.

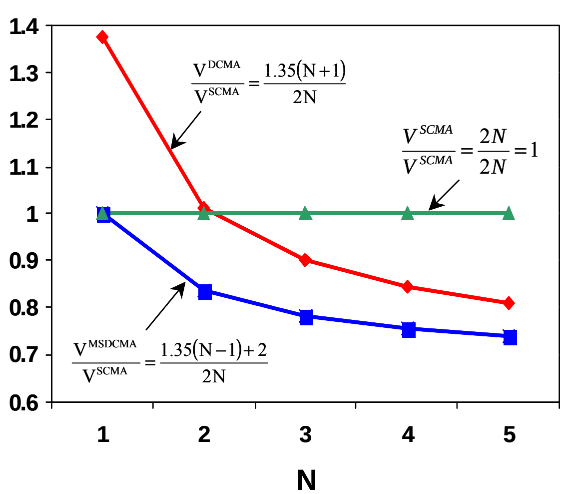

Fig. 7 System power-density comparisons.

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