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Energy Saving Drives New Approaches to Telecommunications Power System

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1. Introduction

Steady growth in the telecommunication industry providing data, voice and video is very likely to continue in the foreseeable future. This growth is supported by expansion into the new markets, especially in Asia, accelerated widespread of wireless and broadband technology, and strong demand for more efficient, power saving solutions. As the result of the growth, the telecommunication infrastructure becomes significant energy consumer and contributor to greenhouse emissions. Based on International Telecommunication Union estimation, the information and communication technology contributes 2-2.5 per cent into the worldwide greenhouse gas emissions (http://www.itu.int/themes/climate/index.html). To reduce the impact on global warming, more efficient distribution, conversion and use of electrical energy by telecommunication industry is required. Worldwide movements for energy saving and "Green power" generation and distribution, have resulted in number of voluntary initiatives and mandatory regulations by international and government organizations for increased efficiency of electronic equipment including data and telecommunication power systems. Examples of such organizations and initiatives are United States ENERGY STAR® program, German Blue Angel, Japan Environment Association, European Code of Conduct and others (http://www.energystar.gov/index.cfm?c=ent_servers.enterprise_servers; Mammano, 2006). The focus of this chapter is efficient and low power consumption DC power systems for a central office and base station of telecommunication infrastructure. According to (Fasullo et al., 2008) telecommunication industry consumes 160 Billion kWh each year, and majority of this electrical energy passes through DC power distribution system.

Telecommunication DC power systems have come long way from simple rectifier/battery system to complex switching power supplies, from centralized power to distributed architecture (Thorsell, 1990). At the same time, required tasks and functional complexity of power systems continue to grow. To effectively reduce the overall system power consumption per required functionality, all design levels from system architecture level down to each specific function and component must be optimized. This chapter limits its scope to energy saving considerations of power system at facility level, then down to power distribution in a rack, or cabinet, and finally focuses on the specific power conversion topologies and control algorithms implemented in power supplies.

At the facility level, intensive research and evaluation of 380-V DC distribution bus is reported to replace traditional 208 V (230 V) AC mains (Pratt et al., 2007; Akerlund et al., 2007). At the cabinet level, intermediate bus architecture (IBA) has become widespread to address increased requirements for supply voltage quality, accurate power sequencing, flexibility and availability of power system (Morrisson, 2002; White, 2003; Miftakhutdinov, 2008a). Currently, demand for high efficiency over wide output power range and low power consumption reshapes the telecom power distribution system once again. Typical cabinet level power system includes AC/DC front end power supply providing system bus voltage that can be –48 V, 24 V, 12 V or 130 V depending on specific system and application. The same power supply in most cases is used as a charger for the backup battery. Driven by government regulations and market demand, the telecom and server power supply is now required to be efficient over output power range from 10% (sometimes even 5%) up to 100% (http://www.energystar.gov/index.cfm?c=ent_servers.enterprise_servers).

Efficiency was always important for data and telecommunication power supply to achieve high power density and improve thermal performance. So far, only high efficiency at maximum load was required because it determines reliability, size and cost of equipment and cooling. Currently, the focus is shifted to energy saving and high efficiency over the entire output power range.

Overall, the design procedure includes power system architecture selection and identifying power conversion topologies and related control strategy. Use of the best in class components is also critical to meet the design goals. In the chapter, all these critical stages of telecom power system design are discussed in details including comparison of alternative solutions.

Optimal control algorithm is critical not only to meet static and dynamic requirements of telecom power system. It also opens new opportunities to increase the efficiency by transitioning into different optimal power saving modes depending on system conditions. Here, the flexibility, programmability and auto tuning capability of digital controllers must be weighted against the lower cost, simple, and usually faster analog control ICs. Promising control strategies along with the examples of advanced analog and digital controllers addressing new requirements for high efficiency will be provided in the chapter.

The interface between IC controller and power stage, that includes power switch drivers, current, voltage, and temperature sensing, auxiliary bias supply, has critical role and deserve careful consideration as well.

The chapter discusses requirements for telecom rectifiers and front-end server power supplies: the key functional parts of any data- and telecommunication power system.

Special attention is provided to intermediate bus converters (IBC) that are the enabling part of any IBA. The IBC requirements and parameters, popular topologies, design challengers are discussed in details. The design examples and test results of 600-W unregulated IBC converter with 48-V input and 5:1 transfer ratio are provided to illustrate and verify the recommended design approaches and solutions.

2. Strive for Efficiency and Power Saving

2.1 Energy Saving Trends and Regulations

High efficiency was always critical requirement for data and telecom power system as precondition to achieve high power density and improve thermal parameters. So far, only

the efficiency at maximum load was usually being taken into consideration. This is because the size, cost, temperature profile of components and their cooling selection is determined at the maximum output power, where power losses are the highest. However, currently the paradigm is shifted and the new requirements focus primarily on energy saving. Therefore, it is critical to have high efficiency even at mid and light loads, where, as it turned out, power system operates significant amount of time. Driven by government regulations and market demand, the data and telecommunication power supply efficiency is now specified from 10% (sometimes 5%) up to 100% of its output power range. At the same time, the power supply and entire system must not exceed the power consumption limits specified for idle operation modes. One example is ENERGY STAR®, which is a joint program of the U.S. Environmental Protection Agency and the U.S. Department of Energy. The program sets efficiency and power consumption recommendations and regulations for different types of electronic equipment. The version 1 of ENERGY STAR® Program Requirements for Computer Servers was effective starting May 15, 2009 (http://www.energystar.gov/ia/partners/product_specs/program_reqs/computer_server_prog_req.pdf). Table 1 below shows related efficiency requirements at 10%, 20%, 50% and 100% output power of single-output AC/DC and DC/DC converters.

Rated Output Power	10% Load	20% Load	50% Load	100% Load
≤ 500 W	70%	82%	89%	85%
501 – 1000 W	75%	85%	89%	85%
> 1000 W	80%	88%	92%	88%

Table 1. Efficiency requirements for single output AC/DC or DC/DC server power supply

For AC/DC Server Power Supply the ENERGY STAR® Program also defines the minimum Power Factor Coefficient as 0.9 for loads from 50% to 100%. This practically means mandatory use of active power factor corrector block in power supply. The Program also limits maximum power dissipated at Idle State to 55 W for single processor based standard server. By definition, during the Idle Operational State, the operating system and other software have completed loading and the server is capable of completing workload transactions, but not processing of any useful work. Adding redundant power supplies to the system allows extra 20 W of power per each additional power supply. Another words only 20 W power can be consumed by the power supply at no load condition.
Similar power saving programs are currently implemented or under development worldwide by government organizations like German Blue Angel, Japan Environment Association, European Code of Conduct and others (Mammano, 2006). It becomes widespread practice that large data and telecommunication providers sometimes set even stronger efficiency and power saving requirements to power system manufactures in attempt to reduce the cost of service and stay competitive.

2.2 Power System Architecture at Facility Level

To meet new efficiency and power saving requirements all system and design levels must be reviewed and optimized. These levels include general power system architecture, power stage topologies for each power conversion, optimal power stage component selection and control algorithms providing optimal and efficient operation of the entire system.

Typical power system of data center at the facility level is shown in Figure 1. Such system generates uninterruptable 208 V AC line. There is double power conversion from DC to AC in UPS and from AC back to DC in the front-end power supply.

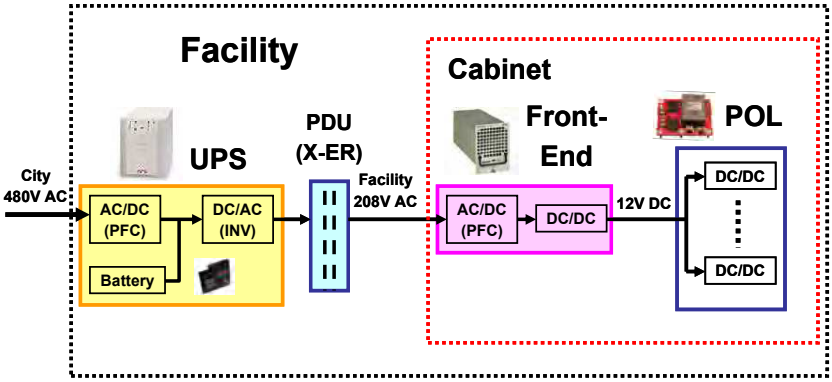


Fig. 1. Typical power system of data center

If to replace AC uninterruptable distribution power line at facility level by the DC line, as it is shown in Figure 2, more than 7% overall efficiency improvement (Pratt et al., 2007) and 10% to 30% saving in cost of operation (Akerlund et al., 2007) can be achieved.
Advantages of the power system with DC distribution bus at facility level are obvious from the power saving view however, some safety and technical questions must be resolved including certified DC power distribution units and availability of UPS with high voltage DC output. The European Standard EN 300 132-3 issued by ETSI includes DC bus up to 400 V as an option for powering telecommunication equipment, thus setting guidelines for development and use of such power architecture (ETSI, 2003).

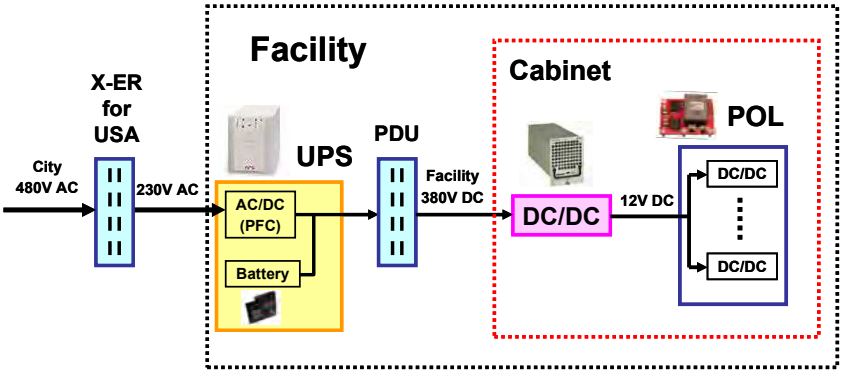


Fig. 2. Power system with 380 V DC distribution bus at facility

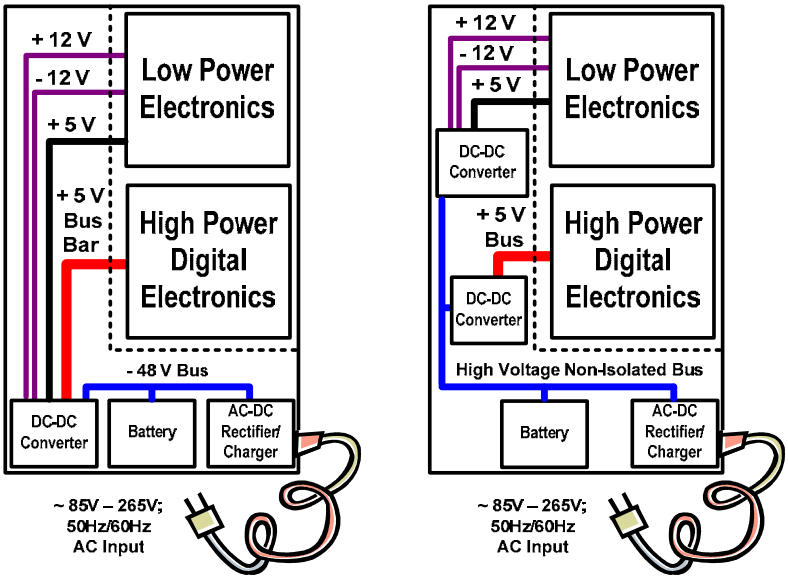
3. Evolution of Telecommunication Power System at Cabinet Level

Power distribution systems for tele- and data-communication equipment at cabinet level have undergone dramatic changes within last two decades because of fast progress of

modern digital-processing technology, requiring high quality supply voltages with specific power sequencing. significant increase in economic losses in case of service interruption was another key factor demanding highly reliable, flexible and available power system. And the most recent changes are driven by push for the efficient, "green" power with the reduced cost of ownership. The evolution of cabinet power system from centralized power to distributed power architecture (DPA) and then to the intermediate bus architecture (IBA) as subset of DPA is the focus of this section.

3.1 Centralized Power System

Originally, the only voltage needed for telecommunication electromechanical switching systems was –48 V provided by AC/DC rectifiers and back up batteries. Since 1960s, the transition from electromechanical relays to electronic semiconductor switchers added to power system the DC/DC converters generating +5 V and ±12 V from –48V supply. These centralized power supplies, typically located in the bottom of a rack or cabinet, included AC/DC front-end rectifier/charger, a power backup battery and DC/DC converter. Large and costly supply bus bars routed the required voltages to each shelf inside the cabinet, which contained replaceable line cards with switching, diagnostic and monitoring equipment. Figure 3 shows typical configuration of centralized power systems that were dominant till mid 1980s (Thorsell, 1990, Ericsson Inc., 1996)



(a) Centralized power system (b) Multilocation centralized power system

Fig. 3. Different types of centralized power system with battery backup

In multilocation centralized power systems, the DC/DC converters were physically located in different places, thus requiring safety shielding because of the presence of the high-voltage bus. The centralized power system is still used in "silver" box power supplies for

low end desktop and server computers, but it has become obsolete in relatively large telecommunication power distribution systems because of the following reasons:

- Centralized, custom power supplies require longer time to market and lack flexibility for quick modification.
- Failure of any part of the power system means failure for the electronic equipment in the whole cabinet.
- Custom, bulky power-delivery bus bars are expensive.
- Static and dynamic regulation of the supply voltage is poor and varies from shelf to shelf

3.2 Distributed Power Architecture

A dramatic step happened in early 1990s when the market largely adopted distributed power architecture (Tabisz et al., 1992; Lindman & Thorsell, 1996). The bulky centralized power supplies were replaced by AC/DC rectifier/charges providing –48-V backplane voltage to each shelf and line card. The line cards allow hot-swap replacement to reduce failure downtime. Each line card includes a number of –48-V input isolated DC/DC modules, that provide all required voltages to the electronic functional blocks (Figure 4).

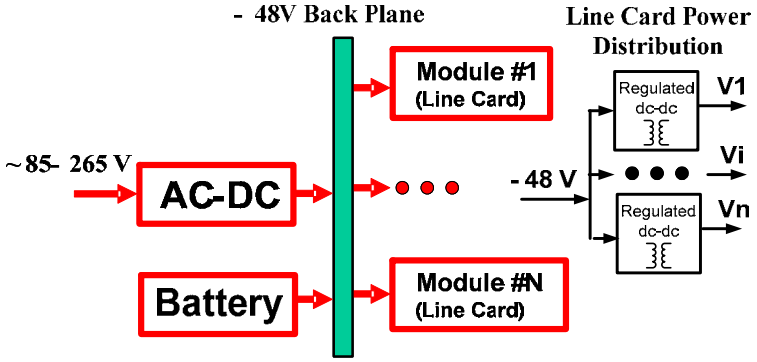


Fig. 4. Example of distributed power architecture

The introduction of distributed power architecture (DPA) was driven by the following:

- A trend towards digital processing blocks with increased power consumption, lower voltages, and specific power sequencing
- A broad market introduction of modular, high density, and reliable isolated DC/DC converters at a reasonable cost
- A demand for a more flexible, shorter design cycle power distribution systems allowing quick changes and updates
- A need for systems with high reliability and availability that supported hot swapping and had lower maintenance costs

3.3 Hybrid Power System

DPA-based systems addressed new power requirements, but the system cost remained relatively high. When the required number of supply voltages per line card exceeded the

initial four to five, the excessive number of isolated DC/DC converters was questioned (Narveson, 1996). In this paper there was suggestion to use only one isolated DC/DC converter. This converter provides most power demanding supply voltage in the system and also supplies non-isolated point-of-load (POL) regulators, which provide the remaining supply voltages to electronic blocks. This architecture, commonly called hybrid power system (Figure 5), was the first step towards the IBA. The hybrid power system reduces power distribution costs and allows placing POLs right next to the related load, thus reducing the impact of supply plane parasitics and improving high di/dt transient response. If power sequencing is needed, an additional switch can be added between the isolated converter output and the electronic load (Figure 5).

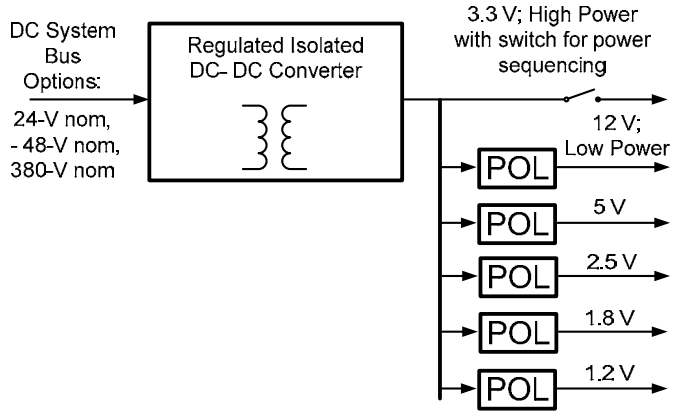


Fig. 5. Hybrid power system

The hybrid power system is preferable solution when one of the output voltages requires relatively high power. In this case, a single regulated isolated converter improves the efficiency of the whole system when the converter's output voltage is 3.3 V or higher. With the 3.3-V bus voltage, the hybrid system's overall output power might be limited to about 200 W. This limit is suggested because high currents circulating through the power and ground planes can cause significant losses and EMI issues as the system power increases.

3.4 Intermediate Bus Architecture

Driven by digital- and analog-IC industry demands for the low-level supply voltages in the 0.5-V to 3.3-V range and for the low-cost POLs, since early 2000s the market adopted the IBA (Morrison, 2002; White, 2003, Mills, 2004). In many applications, the IBA-based power system includes a front-end AC/DC power supply with a typical output of –48 V, 24 V, 12 V or 130 V. In some data-communication and medical equipment the input DC voltage can be 380 V taken directly from a power factor corrector output (Zhu & Dou, 2006) This voltage is supplied to an input of intermediate bus converter, that provides isolation and conversion to the lower level intermediate bus voltage, typically within 5 to 14 V. This intermediate bus voltage is supplied to non-isolated, POL regulators that provide high quality voltages for a variety of digital and analog electronic functional blocks (Figure 6).

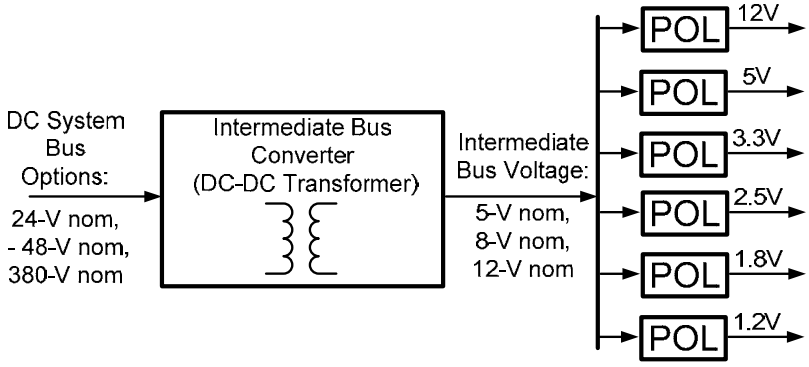


Fig. 6. Example of intermediate bus architecture

The following are advantages of IBA:

- System cost is reduced because only one isolated converter is needed and low cost, standardized, non-isolated POL regulators are available in the market.
- IBC circuit can be made simple because typically intermediate bus voltage variation is relaxed.
- Quality of supply voltages is increased because non-isolated POLs are located next to the electronic functional blocks.
- System is flexible for modifications and updates.
- Overall system reliability is higher.
- Housekeeping, power sequencing, diagnostics, optimized power saving modes are easier to implement because all major control signals are on the secondary side.

The following are challengers that IBA needs to address:

- The IBC must have highest efficiency and power density to provide a competitive edge for IBA versus DPA.
- The overall line card power can be limited because of high currents circulating through ground and bus-voltage planes.
- Parallel operation of highly efficient unregulated bus converters can be difficult.
- Specialized IBC controller ICs are needed to address specific IBC requirements.

3.5 Comparison and Trade-Offs of IBA versus DPA

IBA is a continuation of DPA at the line card level. An optimal choice between IBA and standard DPA for each specific case depends on many factors, including the number of supply voltages, the required voltage and power levels, the system-bus input voltage range, and the specified static and dynamic regulation for supply voltages. It is obvious that cost and efficiency are the most significant trade-off. Table 2 shows the pros and cons between IBA- and DPA-based systems in very general terms. A detailed analytical comparison is needed to make the right design decision. Examples of such analysis can be found in literature (Sayani & Wanes, 2003).

System Requirement		IBA	DPA
Input Voltage Range	Wide	–	Best
	Narrow	Best	–
Number of Outputs	<4	–	Best
	≥4	Best	–
One Regulated Output Demands Most of the Power		–	Good
		Hybrid system could be the best in such case	
Cost		Best	–
Efficiency		Better	Best
Load Supply Voltage Quality		Best	Good
Power Density		Best	Good

Table 2. Comparison of IBA versus DPA for different system requirements

3.6 Selection of Optimal Bus Voltage

Optimal selection of intermediate bus voltage is critical for the overall performance and lowest cost of IBA based power distribution system. For higher bus voltages, IBC is more efficient; however, POL regulators perform more efficiently at lower bus voltages. A lower bus voltage means higher currents circulating through the power and ground planes, thus adding additional losses. Obviously, there are some trade-offs to consider when defining a bus voltage optimized for the lowest overall power losses.

In general, the power losses, *Ptot,* associated with any switching power conversion can be expressed as

$$Ptot = Pconst + Kv \times V^2 + \mathrm{Re}\, q \times I^2 \tag{1}$$

where *Pconst* is nearly-constant power losses consumed by the control and housekeeping circuits; $Kv \times V^2$ is the power losses associated with the switching process (a function of switching voltage, frequency and in some cases, the load current); *Kv* is a coefficient measured in W/V^2 that reflects module losses dependence on the switching voltage; $\mathrm{Re}\, q \times I^2$ is the conduction power losses that are dependent on load current, *I,* and equivalent resistances, *Req,* of the components and traces. It is assumed that the switching frequency is constant.

The optimal bus voltage has to be analyzed for each design case because the selected IBC converter and POL regulators differ in terms of their power losses dependence from the bus voltage and current. The following example of bus-voltage optimization is for a DPA consisting of an unregulated IBC converter and POLs providing five different output voltages. It is assumed that for the bus voltage ranges from 5 V up to 15 V, the MOSFET switches for the selected IBC converter and POL modules remain the same. The key optimization parameters are shown in Table 3. These data is taken from the IBC converter and the POL modules available in the market. The parameters *Req* and *Kv* are specific for the selected modules and might be different for other practical examples.

Module	Vout, V	Iout, A	Pout, W	Pconst, W	Req, mΩ	Ploss(I), W	Kv, W/V^2
POL #1	0.7	60	42	0.46	2.5	9	0.038
POL #2	1.0	120	120	0.92	1.25	18	0.076
POL #3	1.5	60	90	0.46	2.5	9	0.038
POL #4	2.5	60	150	0.46	2.5	9	0.038
POL #5	3.3	30	99	0.23	5	4.5	0.019
Total	-	-	501	2.53	-	49.5	0.209
Bus Plane	-	-	-	-	2	Pplane(Vbus)	-
IBC	Vbus	Ibus	Pbus(Vbus)	0.5	4	Req x $Ibus^2$	0.056

Table 3. IBA power system parameters for optimal bus voltage analysis

The sum of the constant losses of each POL module (2.53W) and the sum of the output-current related losses (49.5W), can be used to define the total losses in the POLs as function of *Vbus*:

$$Ppol(Vbus) = 2.53W + 0.209\frac{W}{V^2} \times Vbus^2 + 49.5W \tag{2}$$

The bus-voltage power and ground planes have a resistance, *Rbus,* equal to 2mΩ, and the overall output power, *Pout total,* is equal to 501 W. Thus, the plane losses are defined as function of *Vbus*:

$$Pbus(Vbus) = Rbus \times \left(\frac{Ppol(Vbus) + Pouttotal}{Vbus} \right)^2 \tag{3}$$

IBC converter *Vbus*-dependent losses, *Pibc(Vbus)*, are shown in Equation (4) after substituting the related parameters from Table 3 and the Equations (2) and (3):

$$Pibc(Vbus) = 0.5W + 0.056\frac{W}{V^2} \times Vbus^2 + 4m\Omega \times \left(\frac{Pbus(Vbus) + Ppol(Vbus) + Pouttotal}{Vbus} \right)^2 \tag{4}$$

Therefore, total IBA-based power system losses can be defined as:

$$Ptotal(Vbus) = Ppol(Vbus) + Pbus(Vbus) + Pibc(Vbus) \tag{5}$$

Figure 7 shows power losses plots as a function of bus voltage. The optimal bus voltage for minimal overall power losses can be chosen from the plot. In this particular case, the curve showing total power losses is relatively flat in the region of minimum losses for bus-voltages between 8 and 10.5 V. With this wide optimal bus-voltage range, the unregulated IBC converter can be good fit depending on its input voltage range.

The optimal bus voltage is usually lower for the higher switching frequencies of POLs and the lower total system power. This trend supports a balance between the voltage-dependent losses like switching losses and the current-dependent losses like conduction losses.

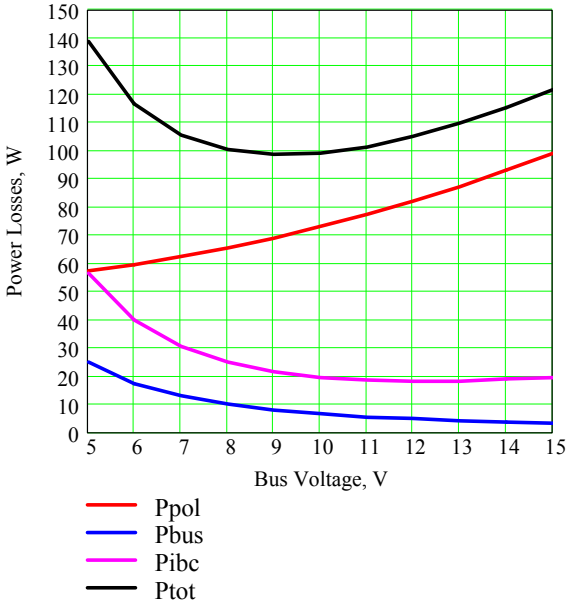


Fig. 7. Power losses over bus voltage

4. Telecom Rectifier and Front-End Server Power Supply

Practically every telecom rectifier, or server power supply have the following key functional blocks, which are usually associated with any over 500 W AC/DC power supply:

- EMI filter
- Power factor corrector (PFC) with hold up capacitor
- Isolated post-PFC DC/DC converter
- Auxiliary bias or standby power supply
- Fan and its regulator

Regulations and specifications define the overall efficiency of AC/DC power supply. It is the responsibility of designer, based on previous designs and future forecast, identify the efficiency and power losses of each functional block to meet the total efficiency goals.

4.1 Power and Efficiency Distribution

For a power and efficiency distribution analysis between the key functional blocks of AC/DC power supply the following approach can be used. Usually the EMI filter and PFC are considered together because it is convenient from the test procedure as well. The output of the PFC (typically 400 V) supplies the main isolated DC/DC converter and the standby power supply. The typical standby power-supply output-power range Can be from 5 W up to 30 W depending on application. It is much lower than the output power of main DC/DC converter. But, the efficiency and power consumption of standby power supply can not be neglected, because the regulations specify the efficiency down to 10% or even 5% of

maximum output power. The fan regulator is usually supplied from the output of DC/DC converter and thus, it is included into the efficiency of converter. Table 4 below is an example of power and efficiency distribution analysis between the PFC, main DC/DC converter and standby power supply. It is fulfilled for 12-V, 660-W output server power supply.

Rated Output Power	10% Load	20% Load	50% Load	100% Load
Efficiency from Table 1	75%	85%	89%	85%
Overall Power Consumption	89 W	158 W	376 W	788 W
PFC Efficiency	95.3%	96.4%	97.6%	97.7%
PFC Output Power	85 W	152 W	367 W	770 W
Standby Power	6 W	7 W	10 W	10 W
Standby Power Efficiency	80%	82%	85%	85%
Standby Power Consumption	7.5 W	8.5 W	12 W	12 W
DC/DC Input Power	77.5 W	143.5 W	355 W	758 W
DC/DC Output Power	66 W	132 W	330 W	660 W
DC/DC Efficiency Goal	85.2%	92.7%	93%	87.1%

Table 4. Power and efficiency analysis of 660-W server power supply

4.2 Power Factor Corrector

Efficiency of power factor corrector (PFC) depends significantly on input AC line range (Cohen & Lu, 2008). Typically, for the more than 500-W PFC, the boost converter based power stage remains the most popular option. The boost converter achieves its highest efficiency at high input line, and the efficiency gradually degrades at lower input voltages. The efficiency and power factor specified by ENERRGY STAR® test procedure for the single output server power supplies has to be confirmed by measurements at 230 Vrms AC line (http://www.energystar.gov/ia/partners/product_specs/program_reqs/computer_server_prog_req.pdf). However, if the design targets the 85 to 265 Vrms universal range, all critical thermal and electrical parameters of PFC have to be verified in the whole operating range. Usually, the output power capability rated at 230-Vrms input voltage, for the same front-end AC/DC power supply is de-rated for the 115-Vrms AC line.

Currently the interleaved PFC and bridgeless PFC are two major directions where most of the research and development is focused. The interleaved PFC is already established solution in mass production supported by available in the market controllers from different vendors (see in http://focus.ti.com/docs/prod/folders/print/ucc28070.html). Typical application diagram of the two-phase interleaved, continuous current mode PFC using UCC28070 from Texas Instruments is shown in Figure 8.

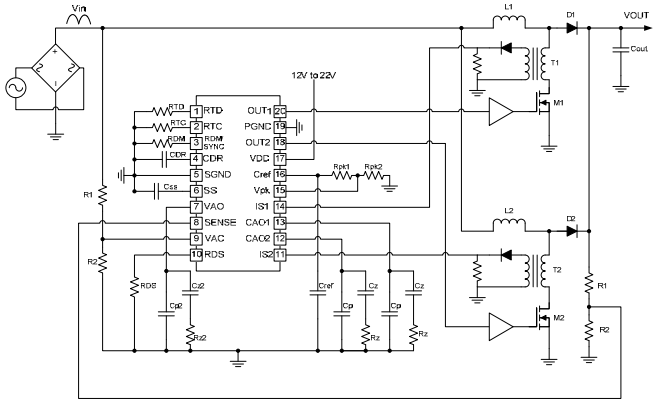


Fig. 8. Two-phase interleaved PFC converter using UCC28070 controller

Advantages of interleaved PFC include:

- Reduced input current ripple because of ripple cancellation effect caused by 180^{O} phase shifted operation;
- Reduced EMI filter because of lower input current ripple;
- Lower RMS current through the output capacitor because of ripple cancellation effect. This means less number of capacitors is needed, or increased reliability when the output capacitance can not be reduced because of required hold up time;
- Better, equalized temperature profile because the power dissipated components are spread between phases. This also results in the higher overall efficiency.

The first bridgeless PFC circuit has been patented as far as in 1983 (Mitchell, 1983), but the concept is still mostly at the research stage. The practical implementation has been limited by the high voltage MOSFET and diode performance, EMI issues, difficulties of voltage and current sensing. Latest achievements in components technology, especially availability of CoolMOS™ transistors and Silicon Carbide diodes, renewed interest to the bridgeless PFC (Hancock, 2008). The analytical and experimental comparison of few different bridgeless PFC topologies is provided in (Huber et al., 2008). The analysis claims that the bridgeless PFC with two boost circuits (Souza & Barbi, 1999) shown in Figure 9 has the efficiency advantages and less EMI issues versus other bridgeless PFC topologies. In general, publications claim up to 1% efficiency improvement when using the bridgeless PFC versus standard approach.

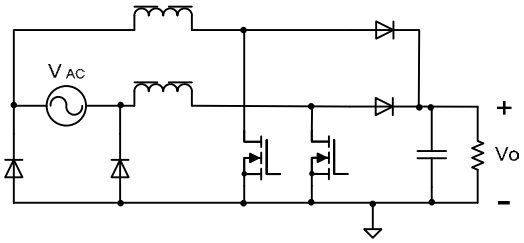


Fig. 9. Bridgeless PFC with two boost circuits (Souza & Barbi, 1999)

4.3 Isolated DC/DC Converter for Front-End Power Supply

The isolated DC/DC converter topology selection is critical for total efficiency of front-end power supply. Zero voltage switching (ZVS) enabling topologies are preferable in such applications because of the relatively high input voltage usually, from 350 to 420-V range. Attractive solutions include phase shifted full-bridge, asymmetrical half-bridge, LLC resonant converter and variations of these topologies (Zhang et al., 2004; Miftakhutdinov et al., 1999; Fu et al., 2007).

For the interleaved topology, the asymmetrical half-bridge converter suits best because of its relative simplicity (Miftakhutdinov et al., 1999). One possible example of interleaving with four phases is shown in Figure 10.

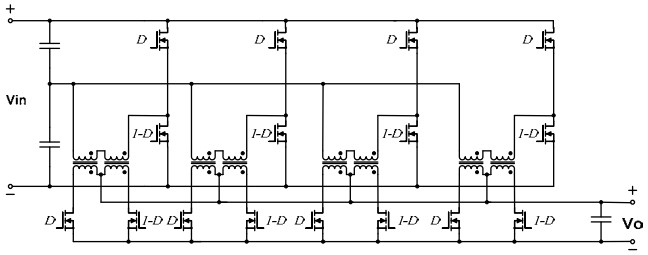


Fig. 10. Four phases interleaved asymmetrical half-bridge.

The LLC resonant topology is recently gaining popularity as post-PFC isolated DC/DC converter (Figure 11).

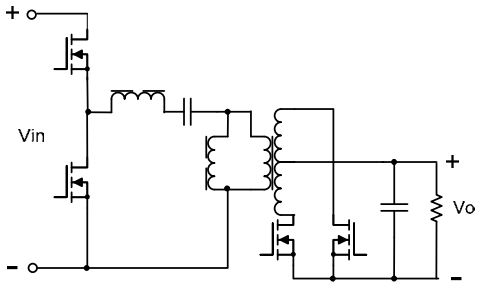


Fig. 11. LLC resonant converter power stage

Its main advantage is ZVS for the primary side switches and zero current switching (ZCS) for the secondary side synchronous rectifier MOSFETs (Fu et al., 2007). Variable switching frequency, special attention to light load operation and difficulties with interleaving limit this topology to sub-kW range.

One implementation of classical phase shifted bridge topology using specialized analog controller is shown in Figure 12. The efficiency improvement of this circuit is achieved by using synchronous rectification, adaptive control algorithm providing ZVS condition over wide operating range, accurate adaptive timing of control signals for primary and secondary power FETs and light load management block providing the highest efficiency and power savings at low output power conditions.

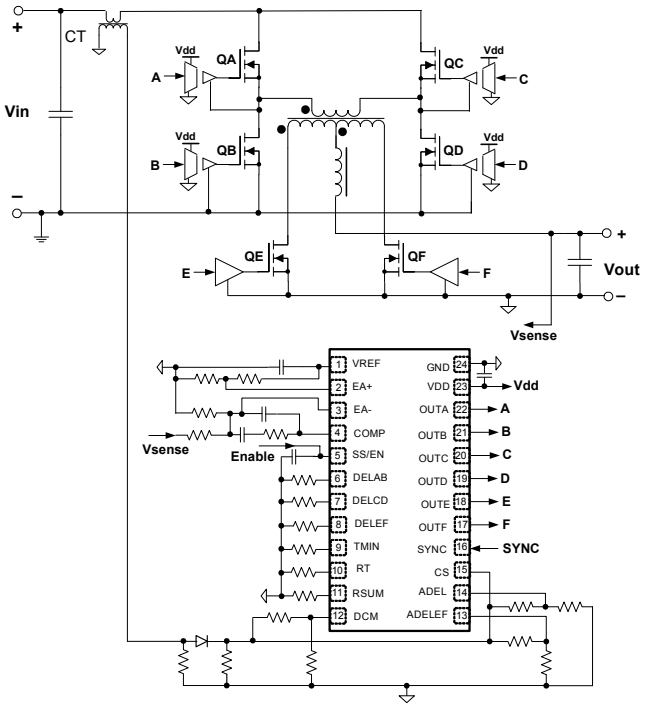


Fig. 12. Phase shifted full-bridge converter with advanced analog controller

4.4 Control Algorithms for High Efficiency

Optimal control algorithm is critical not only to meet static and dynamic requirements of telecom power system, but it also opens new opportunities to increase efficiency by transitioning into optimal power saving modes depending on system conditions. When selecting the controller, the flexibility, programmability and auto tuning capability of digital controllers have to be weighted versus lower cost, simple and generally faster analog control ICs. The list of most popular power saving control strategies is provided below.

- Interleaving of few phases for better current and temperature distribution at maximum output power and gradual phase shedding when the load is reduced (Figure 10);
- Synchronous rectification using MOSFETs with the diode emulation technique at light load to avoid current circulation. It could be beneficiary to switch off the drive circuit of rectifier MOSFETs at very light load where the drive losses exceed the conduction losses. Performance of synchronous rectifier significantly depends on accurate timing between primary and secondary side switches (Figure 12);
- Proper use of zero voltage (ZVS) and zero current (ZCS) switching technique to reduce switching losses in power MOFETs. This requires optimal adaptive or predictable set of delays between switching events depending on operation conditions (Figs. 10 - 12);

- Optimal adjustment of intermediate bus voltage, drive voltage and other system parameters to maintain highest efficiency at different operation conditions;
- Smooth transition between operation modes to maintain highest efficiency depending on operating conditions, for example from continuous mode to discontinuous, from fixed frequency to frequency foldback etc (Figure 12);
- Proper use of pulse skipping or burst mode at light load or no load to reduce the power consumption (Figure 12)

This list shows benefits of wide use of digital controllers to address power saving technique because of their programmability and flexibility. The digital controllers for power supplies are available from few vendors at reduced cost that make these devices competitive with analog controllers, even for relatively low power applications in sub-kW range (see in http://focus.ti.com/docs/prod/folders/print/tms320f28023.html). Specifically designed for these applications high end analog controllers also have their niche. Analog controller ICs remain popular in mature, high volume applications where the operating conditions are well known and established, and thus, cost is more critical than programmability and flexibility (Figure 12).

4.5 Design Considerations and Component Selection

Optimal selection of power stage components provides foundation for high efficiency power system design. Magnetics and power switches are major contributors into the total power losses budget. In this chapter the main focus is on power MOSFETs and high voltage diodes where the significant progress has been achieved lately. The new super junction technology for high voltage MOSFETs significantly reduces Rdson, drain-source and gate-source capacitances providing lower conduction losses and switching losses (Bjoerk et al., 2007). Still accurate ZVS condition analysis over operating conditions remains critical to ensure the highest efficiency. Because of significant non-linear behavior of drain-source capacitance, the super junction MOSFETs, like CoolMOS™, require new analytical model to estimate switching losses and determine ZVS conditions. The following Equation (6) is adequate for energy calculation stored in the output capacitance of high-voltage regular MOSFETs (Miftakhutdinov, 2008a)

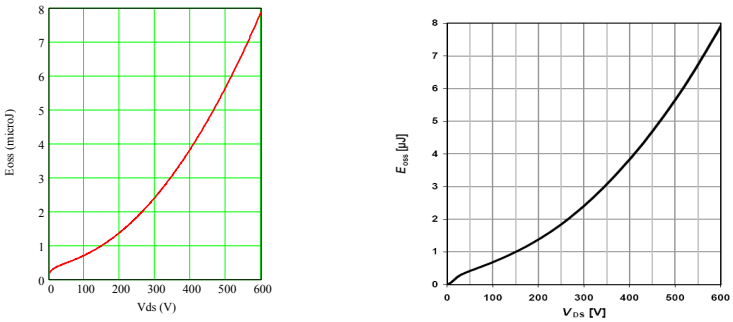
$$Ecds = \frac{2}{3} \cdot Coss \cdot \sqrt{Vdsoss} \cdot Vds^{\frac{3}{2}} \tag{6}$$

Here, *Ecds* is the energy, *Coss* is the output capacitance at *Vdsoss* = 25V from datasheet, and *Vds* is the voltage where the energy should be calculated. The new super junction MOSFETs require different model because of significant non-linear behavior of drain-source capacitance. The following approximated Equation (7) provides good practical results for super junction FETs:

$$Ecds = \frac{Coss}{Kc} \cdot (Vdsoss)^2 \cdot \ln(\frac{Vds + 5V}{V}) + \frac{Cinit \cdot (Vds)^2}{2} \tag{7}$$

where Kc = 2.2 and Cinit = 40 pF for SPA11N60FCD type MOSFET from Infineon.

The plots in Figure 13 compare calculated energy using Equation (7) with the plot provided in the datasheet.



a) analytically derived plot b) experimental plot from datasheet

Fig. 13. Energy Ecds over Vds for SPA11N60FCD type MOSFET

The pairing of super junction MOSFETs with silicon carbide diodes in PFC applications results in significant power losses reduction (Miesner et al., 2001). The use of silicon carbide diodes practically eliminated the need for complicated snubbers in PFC boost power stage. This is because these Schottky type diodes have very fast recovery time versus the p-n junction silicon diodes. Regardless of the extra cost of such diode, the industry widely accepts silicon carbide diodes for PFC applications because the overall efficiency gain could be 3% or higher.

5. Intermediate Bus Converter

This section discusses major requirements to IBC converters, compares key parameters of the available in the market products, considers preferable topologies and focuses on design challengers that must be taken into account. An example of practical implementation based on the IBC controller UCC28230 is also provided and supported by test results. Additional analysis and design information related to IBC as part of IBA can be found in publications (Barry, 2004; Miftakhutdinov & Sheng, 2007; Miftakhutdinov et al., 2008; Miftakhutdinov, 2008a; Miftakhutdinov, 2008b)

5.1 Major Requirements and Parameters of Modern IBCs

IBA includes an additional DC/DC conversion stage provided by IBC to supply intermediate bus voltage. It is important for the IBC to be highly efficient with high power density at the lowest possible cost. The first bus converters in the market were slightly modified versions of fully regulated DC/DC modules. However, the IBC's strict requirements in a short time have made it a stand-alone, specialized product in module manufacturer' portfolios. A list of major IBC parameters follows:

- Efficiency: 96% to 97% typical
- Power density: >250 W/inch^3
- Cost: $0.1 to $0.2 per watt