Rack-Level DC Power Solution for Volume Servers

Won-Ok Kwon, Hae-Moon Seo, and Pyung Choi

Rack-level DC power supply is the optimal technology for providing DC power to a volume server without any power infrastructure changes in an existing AC data center. In this paper, we propose a smartly controllable and monitorable DC rack power system. The proposed system improves power efficiency by changing the power distribution architecture of a conventional method in the rack. We developed an optimal power control method in multipower modules to provide high efficiency at low loads. In addition, the proposed system provides real-time web monitoring of the rack power and environment around a rack. In our experiments, the proposed system improved the power efficiency by over 10% compared to an AC power system providing *N*+1 redundant power and power monitoring.

Keywords: Rack-level DC power supply, power monitoring, power distribution.

I. Introduction

Ever since the appearance of Google's server farm, low cost x86 platform-based servers have been extensively used in search and cluster fields. Servers costing less than $6,000 occupy 88% of server shipments and consume 68% of the electricity used in data centers [1], [2]. The power efficiency and stability of low-cost volume servers are generally very low. Also, it is difficult to analyze their power consumption since power monitoring is not supported.

Several computer enterprises formed the Green Grid Association and are working to provide industry-wide recommendations and best practices on metrics and technologies that will improve energy efficiency in data centers around the world [3]. Research on changing existing AC data centers to DC data centers as a means to improve power efficiency is actively in progress. Google no longer uses an ATX standard power supply and has changed to a +12 V single DC power supply to improve energy efficiency [4]. In 2006, researchers at the Department of Energy at Lawrence Berkeley National Laboratory teamed with about 20 companies to demonstrate technologies that can save energy-related costs for data centers. Instead of converting back and forth from AC to DC in powering equipment, they demonstrated that using DC entirely throughout a data center will save 10% to 20% in power costs and improve reliability [5], [6]. Nevertheless, DC power distribution makes sense if a company is building a petabyte-scale data center from the ground up. However, there are many problems, such as compatibility with existing computer equipment and cable standardizations [7]. Some blade systems support DC distribution using dynamic load-sharing methods to improve power efficiency [8], [9]. However, these blade systems are expensive and do not provide compatibility with low-cost commodity volume servers or PC system power.

Therefore, a rack-level DC distribution in which there are no

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Manuscript received Mar. 9, 2010; revised July 28, 2010; accepted Sept. 6, 2010.

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doi:10.4218/etrij.10.1510.0060

structural changes of the electric system in existing data centers has been proposed by several companies and papers [10]-[12]. The AC power flowing in the rack is changed into DC power through a rectifier and distributed to each server through busbars mounted on the rack. Each server has a power distribution part that changes single DC power into standard ATX power. Since this kind of method removes the low efficiency of an AC power supply and uses a high-efficiency rack rectifier, it brings about efficiency improvements and heat reduction [12]. However, server compatibility decreases due to the insufficient standardization of DC servers. The rack's compatibility also decreases due to busbars in the rack for DC distribution. Also, the power efficiency of this system is not much better than in an AC system. Power control and monitoring through a network are also not supported.

This paper proposes a rack-level DC rectifier, the rack power supply unit (RPSU), that helps negate these disadvantages. The RPSU system improves power efficiency by changing the rack distribution voltage and using an optimal control algorithm in multipower modules. The principle of the optimal control algorithm is that it turns the power module on or off within the range of guaranteed power redundancy through the use of real-time load sensing. The RPSU system also improves compatibility by removing bars in the rack and by providing a power distribution board (PDB) in which DC is converted to ATX power. Finally, the RPSU gives rich information to a data center manager through network monitoring of rack power consumption and the temperature and humidity around the rack.

The outline for the rest of the paper is as follows. We deal with the power problems of volume servers and find a solution in section II. Then, we describe the design and model the RPSU system in section III. We prove the advantage of the RPSU power system and compare it with the AC system of power efficiency through experimentation in sections IV and V. We conclude in section VI.

II. Problems and Solutions of Volume Server Power

Because of their cost-effective performance, x86-based low-cost, low-power volume servers are widely used in the market. However, these volume servers have some power problems. The first problem is related to power efficiency. Most 1U volume servers in the market have an average of 70% PSU power efficiency. Therefore, 30% energy loss occurs when changing from AC to DC. Although PSUs are designed to handle the maximum rated load, servers very rarely operate at full load, and therefore many PSUs operate below average power efficiency since the power efficiency of PSUs drops significantly at low loads [13], [14].

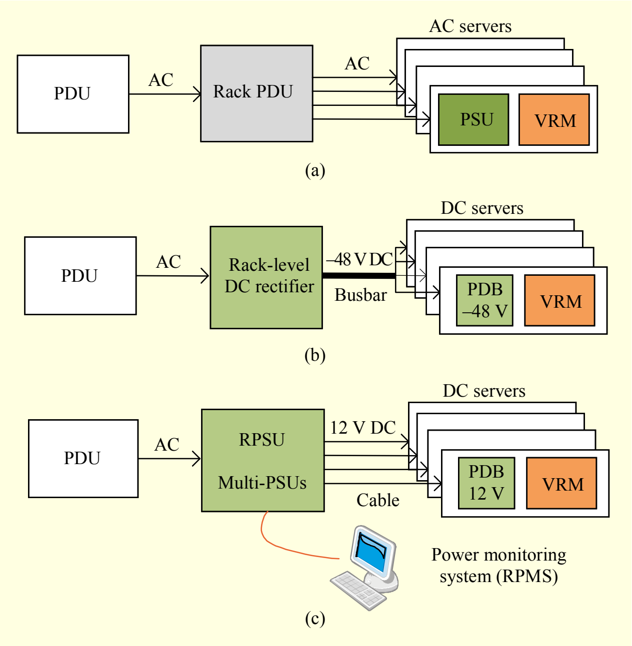


Fig. 1. Power delivery in a rack: (a) conventional AC power delivery, (b) conventional rack-level DC power delivery, and (c) proposed rack-level DC power delivery.

Another problem is related with power stability. Generally, a volume server or a PC does not provide redundant power. The PSU will turn off when it happens to fail. If a volume server provides 1+1 redundant power, the power stability of the server can be improved, but the decrease in power efficiency is between 50% and 60%.

Finally, there is a power monitoring problem. It is impossible to monitor the power consumption of volume servers. Power monitoring functions are not offered for low-cost volume servers except blade or high-end servers with an attached hardware power monitoring system.

In this paper, we deal with a rack-level DC power solution that is compatible with existing servers and racks. Our solution also solves volume server power problems.

Figure 1(a) shows the rack power delivery normally used in an AC-based data center. In such a case, AC power is delivered to a server PSU from a power distribution unit. The PSU converts power from AC to DC that is compatible with ATX power specification. Finally, the motherboard's voltage regulator modules generate DC power for the CPU and other chips.

In the conventional rack-level DC power supply shown in Fig. 1(b), the rectifiers installed at the top of the rack convert AC input power to –48 V DC, which is conducted through DC busbars inside the rack to the individual systems. Each server does not have a PSU, but only a PDB, which generates ATX-compatible power from single DC power.

The key advantage of the rack-level DC rectifier system is that it supports rack-level redundant power without any change in power infrastructure. Therefore, this system can provide a better mean time between failure ratings than an AC-based system [12].

The rack-level DC rectifier, however, is not successful in the commercial market due to certain problems. Low compatibility in the server and rack is one such problem. Only a rack built in the busbars and a server that uses –48 V single DC power can be used in the system. Next, the power efficiency is only slightly better than in an AC system. Usually, the power efficiency of a rack-level DC system is calculated by the product of the power efficiency of the rack rectifier and PDB. The power efficiency of a high-end rectifier product reaches 90%. The power efficiency of a PDB can be changed according to the rack DC voltage. The PDB changes from –48 V to ATX compatible power, such as 12 V, 5 V, 3.3 V, and 5 Vsb. The power efficiency of a –48 V PDB is below 85% using a normal switching power component. Then, the system power efficiency can be calculated as 76.5% at most. It will drop to 70% if the system operates at low loads. Finally, the conventional system does not support network power monitoring, which is a very important function in a data center.

This paper proposes an improved architecture of a conventional rack-level DC supply, as shown in Fig. 1(c). The proposed system uses a rack voltage of 12 V DC. Conventionally, 350 V and –48 V are used in rack-level DC voltage [6]. Using 350 V as high-voltage DC (HVDC) is only done in some high-end server systems [15]. As mentioned above, –48 V is not good power efficiency for a PDB. For DC power delivery at the rack-level, considering power loss, the current is made suitable below 20 A by using a cable. As a multicore-based, low-power processor widely used in the market, the power consumption of a volume server or PC does not exceed 200 W in a burn state or 100 W in an idle state. The 12 V DC rack-level voltage can provide up to 240 W of power for each server, which is enough power for a volume server or PC. The advantage of a 12 V rack-level voltage is that it can make a highly efficient PDB since a 12 V PDB can use 12 V directly at the motherboard without any DC/DC conversion. The power efficiency of a 12 V PDB can be over 95%. Therefore, the maximum efficiency of a rack-level DC system can reach about 85% when using a 12 V DC rack-level voltage. This is higher power efficiency than an AC-based system by about 10% to 15%.

The proposed RPSU has embedded systems and power sensors built-in. Therefore, the RPSU can be operated more smartly using firmware. Power and environment monitoring is also possible with rack power monitoring software (RPMS) through a network in the proposed system.

The proposed system gives full compatibility for a standard rack and server. To provide compatibility for all racks, the RPSU and servers are connected by a cable. The busbar which is conventionally used in a rack has very little power loss but is not compatible with a standard rack. The method for cable connection is simply connecting two lines, +DC and GND, from RPSU to PDB, just as in an AC cable connection. While the cable connection has a voltage drop across the cable causing power loss, it has very little effect on system efficiency. A 12 V PDB can be replaced for an existent PSU and provides ATX compatible power for all volume servers and PCs.

III. RPSU System Design

As shown in Fig. 1(c), the RPSU system consists of three main components: RPSU, PDB, and RPMS. RPSU is a rack-mountable smart rectifier; the PDB is a DC/DC converter that changes single 12 V DC power into ATX compatible power; and the RPMS is web-based network monitoring software for RPSUs. In this section, we will deal with the design of these components.

1. RPSU Design

Generally, thirty 1U volume servers can be installed in a standard 36U rack or 42U rack. Their average power consumption is under 3 kW at an idle state and 6 kW at a burn state. Therefore, considering the power redundancy, the capacity of the rack rectifier requires about 6 kW to 7 kW. At least two highly efficient power modules are required to provide rack-level *N*+1 power redundancy.

Figure 2 shows the hardware block diagram of RPSU. The RPSU has two AC input power sources with an input voltage range of 100 V to 240 V and frequency range of 50 Hz to 60 Hz. Each AC source provides power for four power modules, where one is for power modules 1 through 4, and the other is for 5 through 8. The capacity of the power module is 800 W. Therefore, a total of eight power modules can provide

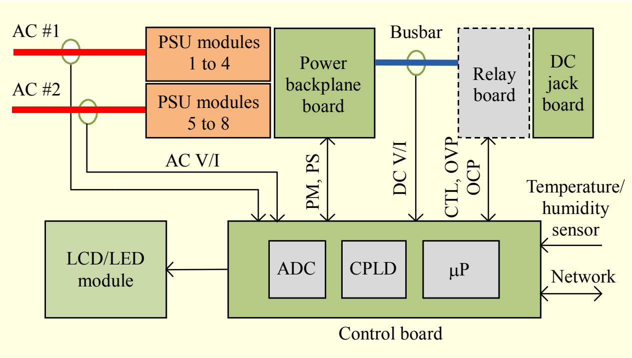


Fig. 2. RPSU hardware block diagram.

6.4 kW DC power to the system.

The output current of the eight power modules is shared in the power backplane board and is delivered to the relay board via a busbar. The relay board uses a relay component for the on/off control output node. If the on/off control of a node is not needed, a relay board is not necessary in the RPSU. The DC jack board has 38 output ports, and each port sets a maximum limit of 25 A current. The LCD and LED boards display the state of the power modules, on/off state of the output port, temperature, and humidity.

The control board mainly consists of an ADC, CPLD, and embedded processor. The processor collects data on input AC power, output DC power, temperature, and humidity through a senor. Based on the sensing data, the control board automatically controls multipower modules optimally (see section IV in the modeling part) and generates an alarm or warning regarding the power or environment for management. The control board controls the on/off states of the output node and detects over/under voltage and over current. An embedded Linux OS is used in the processor to support web-based monitoring of the RPSU.

The newly designed RPSU can be mounted on a 19-inch standard rack and is 3U in height. All power modules are hot-pluggable at the front. There are 38 output ports, two AC inputs, a sensor interface, network interface, and serial interface at the rear.

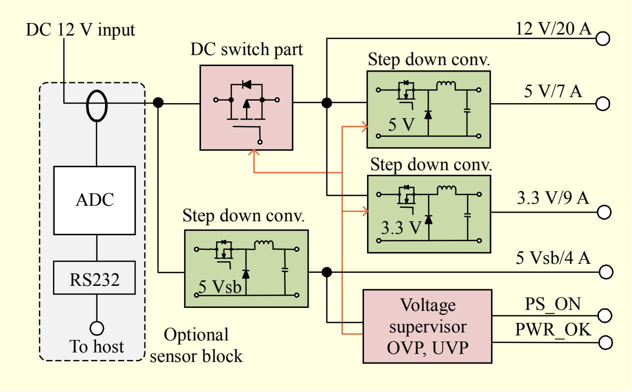


Fig. 3. PDB hardware block diagram.

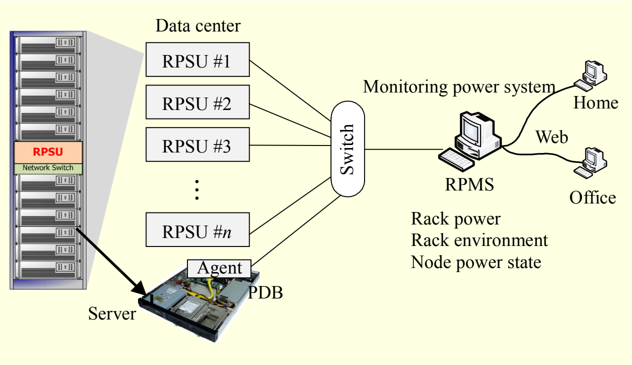


Fig. 4. RPMS system configuration.

2. PDB Design

The PDB generates ATX compatible power from 12 V single DC supplied from the RPSU. Considering the PDB efficiency and cost, this paper proposes a method that uses 12 V directly to ATX power from the RPSU without any conversion.

A hardware block diagram of the PDB is shown in Fig. 3. If 12 V power is input into the PDB, the PDB first generates 5 Vsb using a step-down converter. The 5 Vsb provides power for server standby and the voltage supervisor chip of the PDB. The voltage supervisor chip controls a 12 V bypass switch and step-down converter of 3.3 V or 5 V when PS_ON is inputted. If the output of 3.3 V or 5 V has a problem, the voltage supervisor chip also has over-voltage protection and under-voltage protection functions. If all of output voltages are valid, the PDB generates a PWR_OK signal for the motherboard. All signals generated from the PDB are compatible with ATX power specifications [16]. The PDB can optionally support node current and voltage sensing using an ADC, and this sensing information is transferred to the host server or PC agent software through RS232.

The PDB is designed with maximum 20 A current, and can therefore provide up to 240 W of power. The output specifications of PDB are 12 V/20 A, 5 V/7 A, 3.3 V/9 A, and 5 Vsb/4 A. The size of the PDB is a small form factor of 10 cm×6 cm. Thus, it can be installed in any volume server or PC in place of a PSU.

3. RPMS Design

The RPMS is a monitoring system for power and environment information of RPSUs in a data center. If the RPMS receives a user terminal request, the RPMS responds with data that is collected from RPSUs and saved in a database. The user terminal is serviced from the RPMS through a web-based simple object access protocol.

Figure 4 shows the RPMS system configuration. There are many racks in the data center. Each rack has one RPSU. The RPMS monitors RPSU information, such as the state of the power module, power consumption, temperature, and humidity around the rack. It also monitors the node on/off state through the network. The RPMS also monitors each node's power state using a power agent located in each server that communicates with the PDB sensor. Using an Apache web server, the RPMS can be accessed anywhere through the Internet. The RPMS can

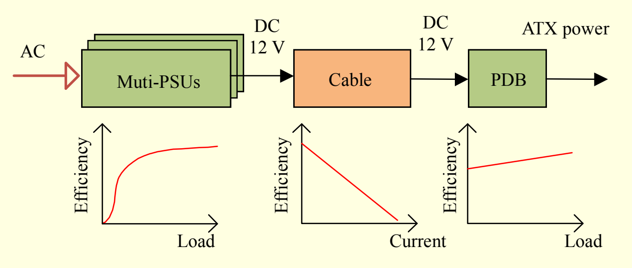


Fig. 5. Power efficiency modeling of RPSU system.

analyze the power consumption of RPSUs and show hot zones in the data center. If problems occur, such as a power module failure or high temperature, the RPMS immediately informs the data center manager. Moreover, the RPMS helps the data center manager create power and cooling policies more easily.

IV. Power Efficiency Modeling of RPSU and 48 V Systems

The power efficiency modeling of the RPSU system is mainly divided into three parts: the RPSU, cable, and PDB (Fig. 5). It can be expressed as the product of multi-PSU efficiency in the RPSU, cable efficiency, and PDB efficiency as

$$Eff_{\mathrm{RPSUSystem}} = Eff_{\mathrm{Multi-PSU}} \times Eff_{\mathrm{Cable}} \times Eff_{\mathrm{PDB}}. \quad (1)$$

Each part has a specific load-efficiency characteristic which we will discuss in relation to the power efficiency modeling in more detail in this section.

1. Modeling of Multi-PSU in RPSU

Because all PSUs have a unique load-efficiency characteristic, the modeling of a multi-PSU is possible after first measuring the load-efficiency characteristic of the PSU. The PSU used in an RPSU must satisfy the following conditions:

- 12 V single output
- Over 88% power efficiency at typical load
- Hotplug capability
- Active current sharing
- Rack-mountable form factor
- 800 W to 1.5 kW power capacity

We selected the GIN-3800V power module from ZIPPY, Ltd., which satisfies the above conditions [18]. The GIN-3800V has a power capacity of 800 W. We first measured the load-efficiency of the GIN-3800V in order to model the multi-PSU load-efficiency characteristic using a DC electronic loader and power meter. This is shown in the 1PM curve in Fig. 6, which is the one power module without redundancy. The maximum efficiency of the GIN-3800V is up to 88% over loads of 40% load, and reaches 80% over loads of 15% load.

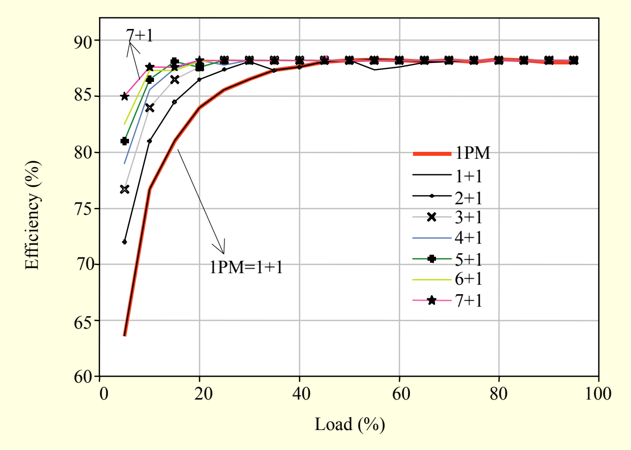


Fig. 6. Optimally controlled multi-PSU power efficiency supporting N+1 power redundancy.

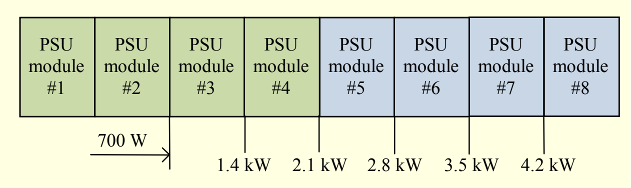


Fig. 7. On/off boundary values of RPSU power modules.

The RPSU operates optimally according to the load by supporting N+1 redundant power. For example, the RPSU needs at least two power modules for a 1 kW load. Since the power capacity of one power module is 800 W, the RPSU turns on three power modules to support 2+1 redundant power. The RPSU automatically turns the on/off control of the power module according to the boundary values shown in Fig. 7. Although the unit boundary value is 800 W, it uses 700 W as a safety margin at 100% load in case a power module happens to fail at 1+1 mode. When three power modules (PSU #1 to PSU #3) are operating in the RPSU, if any of them happens to fail, PSU #4 replaces the failed module to support the auto-failover of the power module.

When the on/off control of power modules is provided optimally by a load with N+1 power redundancy, there is an advantage of efficiency at low loads. Figure 6 shows a load-efficiency graph according to the number of power modules when using the optimal control method in a multi-PSU providing N+1 redundant power [8], [9].

The power efficiency lowers to ensure power redundancy when using 1+1 redundant power. The power efficiency of the 1+1 configuration is the same as that for one power module without redundancy. As the number of power modules increases, the power efficiency increases at low loads.

When using more than four power modules, the RPSU can be operated with maximum power efficiency at loads over 20%. Our experiment used eight power modules and obtained 88% efficiency over 10% load with a 7+1 power configuration. Therefore, the RPSU power efficiency can be simply expressed as

$$Eff_{\text{Multi-PSU}} = Eff_{\text{MAX}} = 88\% \quad \text{(Over 640 W load).} \qquad (2)$$

2. Cable Modeling

A cable used between the RPSU and PDB causes a voltage drop, which is caused by the resistance of the cable. The resistance is proportional to its length and reduces with wire thickness. The DC voltage drop is expressed as

$$V_{\text{drop}} = \frac{35.6 \times I \times L}{1{,}000 \times S}, \qquad (3)$$

where 35.6 is the coefficient in a two-wire DC, I is the current (A), L is the cable length (m), V_{drop} is the voltage drop (V), and S is the conductor area (mm^2) [19].

There are 1.5 mm^2, 2.5 mm^2, 4 mm^2, 6 mm^2, and 10 mm^2 conductor areas in a commercial cable product. The average cable length can be set to 1 m in the RPSU system if the RPSU is installed in the center of the rack. The efficiency of the cable can be expressed by input voltage and drop voltage as

$$Eff_{\text{Cable}} = \frac{P_O}{P_I} \times 100 = \frac{V_O \times I}{V_I \times I} \times 100 = \frac{100 \times (V_I - V_{\text{drop}})}{V_I}. \qquad (4)$$

Put (3) into (4). Then a graph of the cable efficiency can be drawn as in Fig. 8 using the conducting area of the cables. A conductor area of at least 4 mm^2 is required to satisfy less than 1% power loss for a 10 A load (Fig. 8). Our research used a 6 mm^2 conductor cable considering a cable thickness that can be installed in the rack. Therefore, in the RPSU system, the cable efficiency can be expressed as

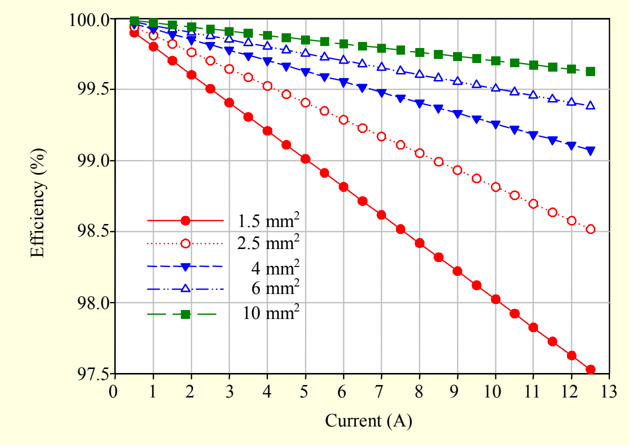


Fig. 8. Power efficiency of cables by conductor area (1 m length).

$$Eff_{\text{Cable}} = \frac{100 \times (12 - 0.00593 I)}{12} = 100 - 0.049 I. \qquad (5)$$

3. PDB Modeling

We modeled the PDB on the description in section V. Since the PDB is designed with 12 V bypass architecture, the power efficiency of 12 V is better than 3.3 V or 5 V, as shown in Fig. 9. Therefore, the PDB has its lowest power efficiency in an idle state, which has the lowest 12 V power consumption of any computer operation. As computer load increases, the 12 V power of the PDB linearly increases. However, the 3.3 V and 5 V powers hardly change with load in a volume server or PC. Therefore, as the PDB load increases, the efficiency of the

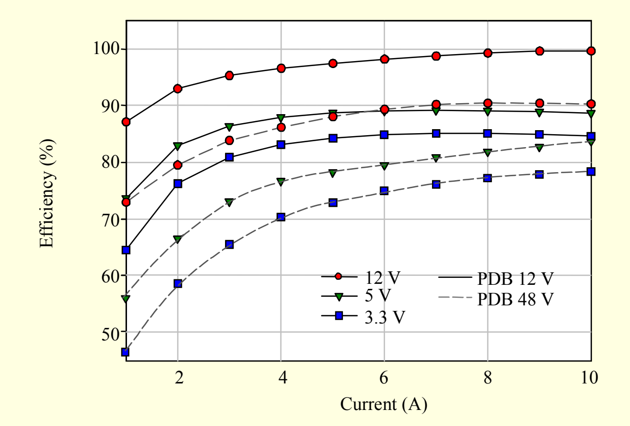


Fig. 9. Measured efficiency of PDB at 12 V and PDB at 48 V at 12 V, 5 V, and 3.3 V.

Table 1. HP DL320G5 specifications.

Unit	Specifications
Processor	Intel Xeon Quad-Core 3200
Memory	DDR2 2G ECC
HDD	500G SATA
Management	iLO2
PSU/capacity	Delta DPS-400AB-1/450 W

Table 2. PDB at 12 V and PDB at 48 V efficiency measurement.

Item	PDB at 12 V	PDB at 48 V
P_{in} (W)	56.0	63.25
$P_{12\text{ V}}$ (W)	17.7	
$P_{5\text{ V}}$ (W)	16.1	
$P_{3.3\text{ V}}$ (W)	18.6	
Efficiency (%)	93.5	82.85

PDB also linearly increases. Using linear modeling, the PDB power efficiency can be expressed as

$$Eff_{\mathrm{PDB}} = a + b \times (I - I_a), \tag{6}$$

where a is the PDB efficiency in an idle state, b is the gradient, I is the current, and I_a is the idle current.

An HPDL320G5 server with specifications as shown in Table 1 was used in an experiment of the PDB power efficiency. Table 2 shows the experiment results: I_a is 4.7 A (I_a=P_{in}/12 V) and a is 93.5%. Supposing that the power efficiency of the PDB converges to 99% when the load current passes over 20 A, the coefficient b in (6) can be solved by using two points, (4.7 A, 93.5%) and (20 A, 99%). The power efficiency of the PDB can finally be expressed as

$$Eff_{\mathrm{PDB12\,V}} = 93.5 + 0.36 \times (I - 4.7) = 0.36I + 91.8. \tag{7}$$

4. Modeling of RPSU System

The power efficiency of the RPSU system is a product of the efficiency of a multi-PSU, as in (2); cable, as in (5); and PDB, as in (7) under higher than 640 W load conditions:

$$Eff_{\mathrm{RPSUSystem}} = \frac{88 \times (100 - 0.049I) \times (0.36I + 91.8)}{10{,}000}. \tag{8}$$

The efficiency of the PDB is seven-times higher than the cable loss as the current increases in (8). As the server load increases, we can expect high system-power efficiency. The power efficiency of the RPSU system is 82.1% in an idle state, 83.5% at I=10 A, and 86.3% at I=20 A. Thus, the power efficiency range of the RPSU system is from 82.1% to 86.3% based on the power efficiency modeling.

5. Modeling of 48 V DC Rack System

A conventional 48 V DC rack power system generally has an N+1 power configuration and uses an internal rack busbar instead of a cable. Although a 48 V DC rack power system does not control power optimally based on load, multipower module modeling uses the same value as in the RPSU because modeling varies according to the power configuration and power module product. Assuming that the busbar is a lossless line, instead of a local PSU, we focus only on the modeling of a 48 V PDB.

The 48 V PDB can also be expressed as (6). Using the experimental results in Table 2, we can solve the coefficient. Idle current I_a is 1.32 A (I_a=P_{in} /48 V), and a is 82.85%, as in Table 2. To unify the current scale of PDB at 48 V with PDB at 12 V, multiply the voltage coefficient (4=48 V/12 V) with the current. At 12 V, maximum efficiency is measured as 93.5% for a 20 A load. Therefore, PDB at 48 V converges to maximum efficiency when the load current passes over 20 A. Coefficient b in (6) can be solved using two points: (1.32 A×4, 82.85%) and (5 A×4, 93.5%). The power efficiency of the 48 V can finally be expressed as

$$Eff_{\mathrm{PDB48\,V}} = 82.85 + 0.72 \times (I - 1.32 \times 4) = 0.72I + 79.05. \tag{9}$$

The power efficiency of a 48 V DC rack power system is a product of the efficiency of a multi-PSU, as in (2), and PDB at 48 V, as in (9) under load conditions higher than 640 W:

$$Eff_{\mathrm{48\,V\_System}} = \frac{88 \times (0.72I + 79.05)}{100}. \tag{10}$$

V. RPSU System Test

1. Power Efficiency Measurement of PDB at 12 V and 48 V

The power efficiency of the PDB is the sum of the output powers divided by the input power. It can be defined as

$$Eff_{\mathrm{PDB}} = \frac{\sum_i P_{O,i}}{P_{\mathrm{in}}} = \frac{P_{12\,\mathrm{V}} + P_{5\,\mathrm{V}} + P_{3.3\,\mathrm{V}}}{P_{\mathrm{in}}}, \tag{11}$$

where P_{in} is the input DC power, $P_{12\,\mathrm{V}}$ is the output power at 12 V, $P_{5\,\mathrm{V}}$ is the output power at 5 V, and $P_{3.3\,\mathrm{V}}$ is the output power at 3.3 V.

An HP DL320G5 server was used in the experiment, as detailed in Table 1. The PDB at 12 V and PDB at 48 V can be replaced after removing the local PSU in a server, as shown in Fig. 10(b). Table 2 shows the measured values of P_{in}, $P_{12\,\mathrm{V}}$, $P_{5\,\mathrm{V}}$, and $P_{3.3\,\mathrm{V}}$ for a server in an idle state taken using a power meter and ATX cable jig. The measured power efficiency of the PDB at 12 V was 93.5%, while that of the PDB at 48 V was 82.85% in an idle state.

The load-efficiency of each voltage in the PDB can be measured by connecting an electronic loader for each load and changing its values while simultaneously measuring the input power. Figure 9 shows the measurement results. Consider the results of PDB at 12 V. As the load increases, the power efficiency of 12 V almost reaches 100% since PDB at 12 V uses 12 V power directly from the RPSU. For 5 V, it reaches 89% maximum efficiency, while 3.3 V reaches 86%. For PDB at 48 V, the power efficiency at 12 V is up to 91% for a 10 A load, while the efficiency for 5 V and 3 V is up to 84% and 78%, respectively. PDB at 48 V has lower power efficiency than PDB at 12 V at all voltages.

2. Power Efficiency Measurement of RPSU System

To measure the power efficiency of the RPSU system, an


(a)

(b)

(c)

Fig. 10. RPSU system: (a) front view, (b) server installed PDB, and (c) rear view.

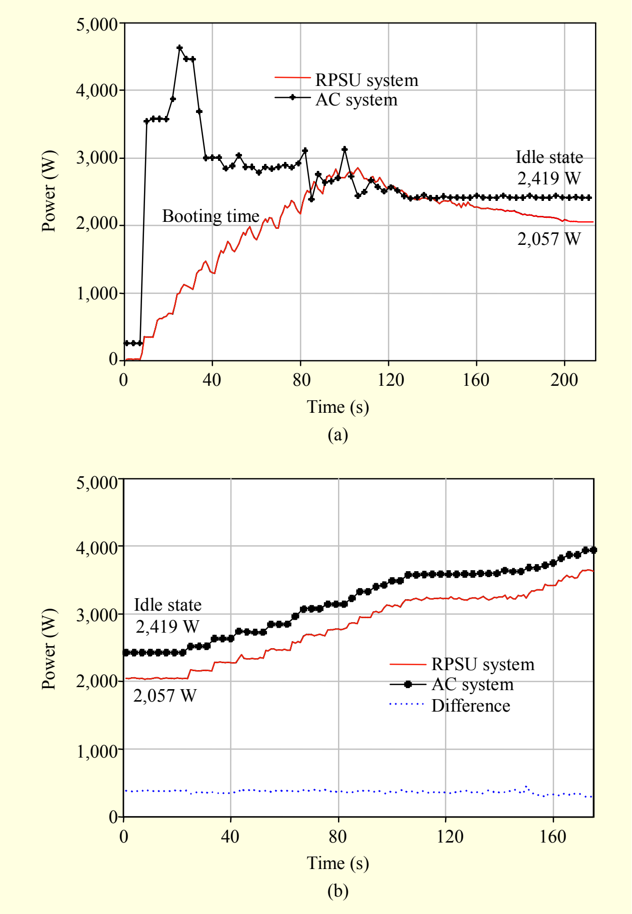
RPSU was installed in the middle of a rack, as shown in Fig. 10(a), and the PSUs were replaced with PDBs at 12 V in each server, as shown in Fig. 10(b). After that, each server was connected to an RPSU by a cable, as shown in Fig. 10(c).

An HP DL320G5 server, as described in Table 1, was used for the experiment. To compare the power consumption of the RPSU system with that of an AC system, the other rack was made using conventional AC servers. Each system used 30 servers. The measurements were carried out while booting and continuously changing the load.

While booting, the AC system has a peak power consumption of 4.8 kW, which reduces to 2,419 W in an idle state as shown in Fig. 11(a). On the other hand, the RPSU system has a peak power consumption of only 2.8 kW because delayed booting at each node is performed by a power-up sequence. In addition, the RPSU system shows 2,057 W in power consumption at an idle state, which means a 15.75% increase in power efficiency compared with the AC system.

Next, the power consumption was observed while continuously increasing in the CPU load from an idle state. The differences in power consumption between the RPSU and AC systems were obtained as shown in Fig. 11(b). We found that the RPSU system can save about 300 W to 410 W of power in all loads. The differences in the power efficiency of the two systems are up to 16.2% at low load conditions and down to 7.7% at high loads. This is because the power efficiency of the AC system continuously increases by load, but the RPSU system hardly changes.

To verify the accuracy of the RPSU power efficiency modeling in the previous section, we measured the power efficiency of the RPSU system. We summed the power efficiency of the AC system and took the difference in power efficiencies of the two systems, which were obtained in Fig. 11. Since all servers have the same load-efficiency characteristic in an AC system, we measured the load-efficiency characteristic of one server, which is shown in Table 3. We measured the input AC power and output DC power, which is the sum of the power at 12 V, 5 V, and 3.3 V, to calculate the power efficiency of the server. The power consumption was measured by continuously increasing the CPU load in four-step increments from an idle state, which is the same method used in the experiment shown in Fig. 11(b). The power efficiency was 65.8% in an idle state and 73.5% at a maximum load state. A plot of power efficiency versus load current in an AC system is shown in Fig. 12. Finally, we obtained the RPSU system efficiency from the power efficiency of the AC system and the difference of the two systems (see Fig. 12).



(a)

(b)

Fig. 11. Experiment of power consumption about RPSU system and AC system: (a) booting period and (b) continuously increasing load.

In the AC system, efficiencies from 65.8% to 73.5% were observed from an idle state and greater than an 8 A load,

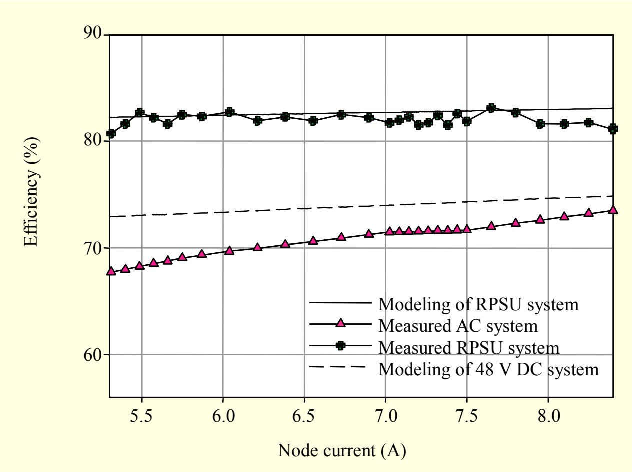


Fig. 12. Power efficiencies of RPSU, AC, and conventional 48 V DC rack system according to node current (30 servers).

respectively. In the modeling of the conventional 48 V DC rack system in (10), the power efficiency ranged from 72.5% to 74.9%, as shown in Fig. 12. This is about a 6.7% improvement in efficiency in an idle state and 1.4% at a maximum load state compared to the AC system. This shows the conventional 48 V DC rack system has a small improvement in efficiency. On the other hand, 7.7% to 16.2% efficiency improvements were observed from the RPSU system.

In the modeling of the RPSU system, the range of power efficiency is from 82.0% to 83.1%. We found an error in the power efficiency between the modeling values of the RPSU system described in (8) and the measured values of the RPSU system. In all ranges, the results show the measured power efficiency is lower than the modeling power efficiency. The average error was about 0.7%. The error is caused by the effect of power consumption in the RPSU hardware component and in the standby power of multi-PSU modules that were not considered in the modeling of the RPSU system. To make a more accurate power efficiency model of the RPSU system, these effects need to be included in the power efficiency model.

We proved through measurement that the RPSU system gives *N*+1 redundant power as well as a steady power efficiency of more than 80%, which improves the power efficiency by more than 10% over a conventional AC system and 48 V DC rack system.

3. Power Sensing Accuracy of RPSU

Figure 13 shows the difference between sensed power from the RPSU and measured power from a power meter. To obtain the data, the RPSU was connected to a DC electronic loader by a cable jig, as shown in Fig. 14. We changed the electronic loader while simultaneously measuring the power consumption of the RPSU using the power meter. The sensed value from the RPSU was recorded into an RPMS database.

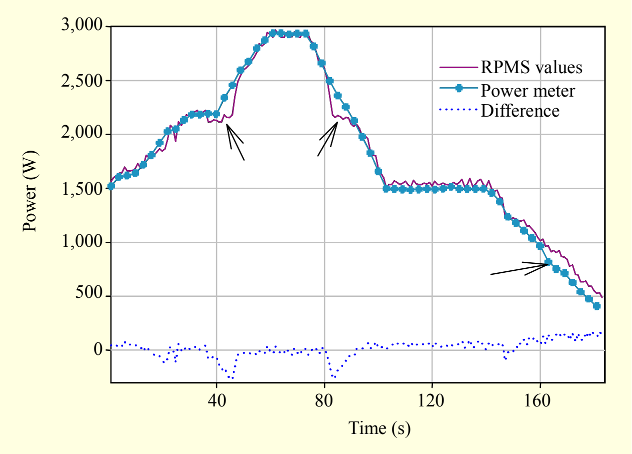


Fig. 13. Difference between sensing power from RPSU and measured power from power meter.

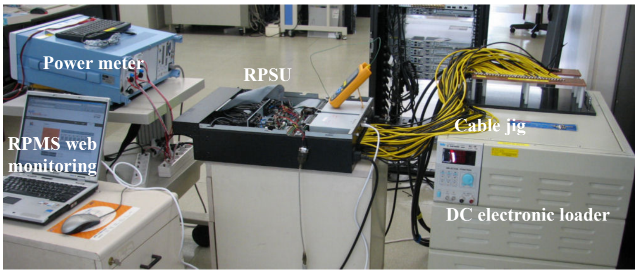


Fig. 14. Test configuration for measurement of RPSU power efficiency and sensing accuracy.

At a load of more than 1 kW, the error range of the RPSU power sensing is the number of decades of watts. In the case of rapid power changes of 40 s and 80 s, the error range was about 100 W, which was caused by the delay of power sensing.

As the load decreases below 1 kW, the error increases. This is related to the nonlinearity error of AC current sensor in the RPSU. Thus, the RPSU firmware has an algorithm to compensate the error of the sensor value at a low load to guarantee the accuracy of RPSU.

VI. Conclusion

This paper proposed RPSU, a rack-level smart DC rectifier, which is fully compatible with existing data center power infrastructures, racks, and servers. The RPSU system can solve power problems in a volume server, such as low-power efficiency, no power redundancy, and no power monitoring. The measurement results of the RPSU system show over a 10% power efficiency improvement compared to an AC system providing *N*+1 redundant power. Moreover, the power information of the RPSU system can be monitored through a network. We expect that the RPSU system can be widely used in data centers, public computer environments, offices, and Internet cafés.

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