

Uninterruptible battery backup for IBM AS/400 systems

by S. W. Steele

This paper describes the architecture and implementation of a DC-Uninterruptible Power Source (DC-UPS) designed as an internal component for IBM AS/400® processor and I/O towers. This DC-UPS supports a processor or I/O tower requiring a maximum of 3100 watts of input ac line power. Unlike the large majority of AC-Uninterruptible Power Sources (AC-UPSs) found in the marketplace, which supply 50–60-Hz alternating current, the DC-UPS supplies direct current as the backup power source to the power supplies of these IBM systems. This paper addresses the way in which the IBM DC-UPS design evolved, and how the DC-UPS is less complex, more reliable, and less costly than AC-UPS designs. It also discusses some of the design considerations required to maintain and manage a large battery string in an IBM computer system.

Introduction

In 1988 IBM announced the AS/400* system. While the AS/400 is an extremely successful computer for commercial applications, long initial program load (IPL) times due to abnormal system termination were not uncommon for larger systems [1]. To reduce exposure to abnormal system termination due to extended ac line outages (longer than 40 milliseconds), an internal battery

backup has been included as a standard feature for the AS/400 system since its initial announcement.

A distributed 29-volt dc (+29VDC) power bus was designed into the first AS/400 computers. The +29VDC power bus is created by one or more ac to +29VDC bulk power supplies. The +29V bus is distributed to dc power regulators that convert +29V into the voltages required for the processor, memory, and I/O of the AS/400 system. The +29VDC power bus allowed for a simple yet very robust battery backup of the dc bus. The battery backup in these systems comprises two series-connected, +12V valve-regulated lead-acid (VRLA) batteries which are charged from the +29VDC power bus. Whenever the voltage in the +29V bus falls below 26.5 V because of an ac line disturbance, a semiconductor switch turns on, resulting in a transfer of energy from the two storage batteries to the AS/400 system.

In the mid-1990s, it was determined that the distributed +29VDC power bus was not competitive for midrange and entry-level AS/400 systems, so an alternate method for internal battery backup was required. During this time many companies in the OEM UPS industry were providing quality battery backup solutions using AC-UPS architecture. A typical AC-UPS backs up the input ac line of a system with full-wave sinusoidal alternating current derived from a 48-V string of VRLA batteries through a dc-to-ac boost inverter. The backup ac power is in phase with, and has amplitude and frequency similar to, the ac line being backed up. **Figure 1** shows a block diagram of a typical low-cost AC-UPS.

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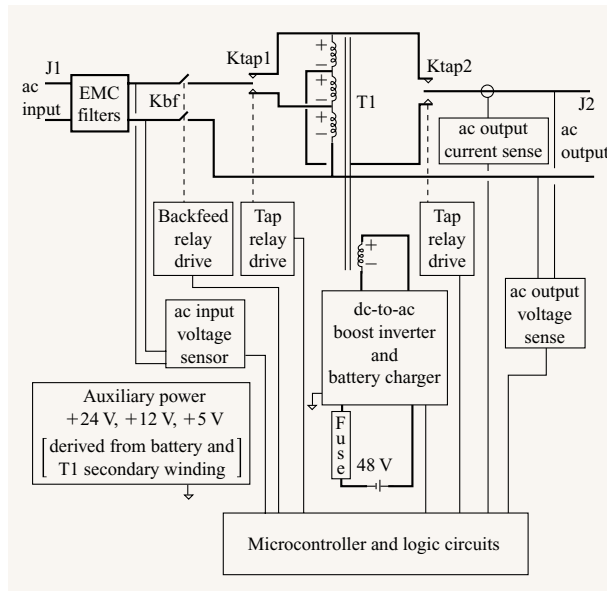


Figure 1

AC-UPS architecture.

Under normal ac line operation, alternating current is fed through autotransformer T1 and a series of relays (Kbf, Ktap1, and Ktap2) to the output. When the AC-UPS is in battery backup mode, the backfeed relay, Kbf, prevents the battery-derived output energy of the AC-UPS from backfeeding through transformer T1 onto connector J1. The tap-switching relays, Ktap1 and Ktap2, are used to connect different windings of the 50–60-Hz autotransformer T1 to regulate the ac output and the auxiliary converter on the basis of the ac line input voltage. During normal operation, the dc-to-ac inverter circuit is used to charge the 48-V battery string.

AC-UPS circuits are constantly measuring the input ac voltage, output ac voltage, and output ac current. When a loss of input ac voltage is detected, the boost mode of the dc-to-ac inverter opens relay Kbf. Energy is transferred from the 48-V battery string, converted to alternating current, stepped up through autotransformer T1, and fed to the AC-UPS output.

All of the energy of the AC-UPS is fed through autotransformer T1, so it must be rated at the output power of the AC-UPS. Since the autotransformer is a low-frequency (50–60-Hz) magnetic component, it will be very large. The dc-to-ac boost inverter is usually implemented with a high-frequency (~50-kHz) bridge converter.

AC-UPS designs require complex ac line sensing. Brownout, surge, and ac line transient immunity are major advantages of AC-UPS designs. During ac line transient conditions (i.e., lightning strikes or utility switching

disturbances), some AC-UPS designs (referred to as line-interactive AC-UPS) are capable of reacting rapidly and filtering out the disturbance with error-free, inverter-generated alternating current delivered to the power supplies connected to the AC-UPS output [2]. In 1996, an internal AC-UPS was designed into the midrange AS/400 systems.

Although the architecture of the internal AC-UPS results in noise-free and glitch-free alternating current, the cost, complexity, reliability, and AS/400 system interaction problems with the AC-UPS designs became a concern. By the late 1990s, a new backup system was required.

DC-UPS

Figure 2 shows a block diagram of a DC-UPS with a 192-V battery string [3]. A DC-UPS distributes full-wave rectified ac line voltage to power supplies connected to the DC-UPS output. The DC-UPS senses the ac line voltage and connects a 192-V battery string across the output for ac line outages greater than 0.02 seconds. A bridge rectifier and SCR device are required for battery testing and safety isolation from the ac line.

When the architecture of the AC-UPS is compared to that of the DC-UPS, it becomes evident that the DC-UPS is less complex than the AC-UPS. It is also shown that the added complexity of the AC-UPS is not justified for energy backup of computer systems and results in added cost and lower reliability. [The system power control network (SPCN) interface, battery monitor block, and 192-V to 48-V converter block shown in Figure 2 are discussed later.]

Direct current vs. alternating current for backup power

One of the most complex and expensive components of the AC-UPS is the dc-to-ac inverter. The inverter converts the output of a low-voltage string of batteries (48VDC) into a sinusoidal ac voltage that has the same frequency, the same phase, and nearly the same amplitude as the system's input ac line voltage. Power supplies used in AS/400 systems do not require alternating current as an input power source because they are designed with high-frequency power converters (HFPC).

In the late 1970s and early 1980s, power systems in the computer industry were revolutionized with the introduction of HFPC power supplies, which convert ac line voltages, through controlled switching, to produce the dc voltages desired for computer processing circuits. The switching frequency of HFPC designs can be as low as 20 kHz and as high as 1 MHz. HFPC supplies are smaller and much more efficient than their linear predecessors [4].

In 1989, IBM produced the RIOS Rack Power System,¹ in which a 48-V battery string, located at the bottom

¹ J. R. Kinnard, "RIOS Rack Power System," IBM, June 1989.

DC-UPS, which uses a bridge rectifier and SCR semiconductor devices to achieve the required safety isolation in place of the backfeed relay, is less complex and more reliable than an AC-UPS, since DC-UPS does not use relay components for critical circuits. It is common knowledge that electromechanical devices are less reliable than solid-state devices.

Cost

It has been shown that a DC-UPS design can satisfy the backup needs of an IBM system (and most other computer systems), with lower complexity and higher reliability, and at significantly less cost than an AC-UPS design. Analysis at IBM shows the cost of the DC-UPS to be 60% of the cost of a similarly sized AC-UPS.

Design requirements for a 3-kW DC-UPS

The design requirements for a 3-kW DC-UPS as an internal component of an IBM AS/400 system are described as follows:

- Rectify and feed through ac line voltage (between 180VAC and 259VAC), from a line cord connected to an ac wall outlet. The feedthrough efficiency must be greater than 98% for a maximum load of 3100 W. The DC-UPS contains a rectified ac distribution bus having five standard, 10-A ac outlets to connect up to five AS/400 system ac-to-dc power supplies to the DC-UPS.
- Charge a 192-V battery string at a maximum constant-current rate of 0.5 A when the AS/400 system is powered on.
- Determine when the ac line voltage has fallen below the amplitude required to operate the AS/400 system's ac-to-dc power supplies, and close MOSFET switch Q1 connecting the 192-V battery string to the AS/400 system's rectified ac distribution bus. The battery string output efficiency must be greater than 95% at maximum load. During battery backup mode, the DC-UPS must supply energy to the AS/400 system for a minimum of two minutes.
- Communicate through a customized serial protocol interface with the system power control network (SPCN) of the IBM machine. SPCN is a microprocessor-based operating system that controls all aspects of the IBM system's power network, including power on/off sequencing, field-replaceable unit (FRU) isolation, and enabling battery backup and battery testing.
- Be able to switch on a 192-V-to-48-V converter and open the battery string switch Q1 under SPCN command. The 3-kW DC-UPS will keep the 48-V bus up for a minimum of 36 hours with a 20-W load under battery string power. The 192-V-to-48-V converter is 89% efficient. This mode, referred to as *continuously*

powered memory (CPM), is used to keep the AS/400 memory alive until operational ac line voltages return.

- Implement a battery "path" test of the 192-V battery string circuits by closing battery string switch Q1 and sensing current through resistor Rs upon request from SPCN.
- Implement a battery capacity test under SPCN control to accurately determine the end of life of the 192-V battery string.
- Feed through rectified ac voltage to the AS/400 power supplies connected to the DC-UPS outlets when any or all of the battery string components are disconnected.

When the above requirements are realized using the DC-UPS architecture shown in Figure 2, the operation of a 3-kW DC-UPS is as follows. During the ac feedthrough operation, the ac line connected to the DC-UPS, at connector J1, is fed through bridge rectifier BR1. When the RMS sensor detects that the alternating current is greater than 170VAC, the silicon-controlled rectifier (SCR) Q2 will conduct, and rectified ac voltage will exit through the output connectors J2. The 3-kW DC-UPS uses the ac-line input to charge the 192-V battery string and to power the DC-UPS housekeeping circuits. The auxiliary and charging circuits of the DC-UPS draw a maximum of 225 volt-amperes (V-A) at a minimum power factor of 0.8 from the ac line.

The battery string backup function is enabled and disabled by SPCN. The root mean square (rms) sensor internal to the DC-UPS continuously monitors the amplitude of the ac line. When the ac-line voltage is less than 175VAC, logic in the DC-UPS connects the 192-V battery string to the DC-UPS output. Once the 192-V battery string is supplying power to the IBM system power supplies, SPCN will detect when the ac line has returned to a nominal operating range (by monitoring the state of the rms sensor via the serial interface) and instruct the DC-UPS to open the battery string switch Q1. The DC-UPS logic will continue to monitor the rms sensor signal and close the battery string switch whenever this signal becomes active as long as SPCN has enabled the battery string backup function.

Mechanically, the 3-kW DC-UPS is a six-piece battery backup system consisting of one 3-kW charger assembly, four 48-V battery-pack assemblies, and one cable assembly connecting the four battery packs to the 3-kW charger assembly. Each battery-pack assembly consists of four 12-V valve-regulated lead-acid (VRLA) batteries connected in series. The four battery packs connect to the 3-kW charger assembly in series, resulting in a 192-V battery string. The complete battery backup system is connected to the system's power supplies through ac/dc receptacle connectors mounted to the 3-kW charger assembly chassis. The DC-UPS connects to the SPCN

network and the system's 48-V continuously powered memory (CPM) bus through a backplane connector mounted to the 3-kW charger assembly chassis.

The mechanical design point for the battery pack uses either 7-AH (amp-hr) batteries or 12-AH batteries. At present, 7-AH batteries are in use, with the capability of using 12-AH batteries for future increased holdup time requirements. The 7-AH battery form factor used for the 3-kW DC-UPS is the most common VRLA battery form factor in the industry.

Design considerations for a DC-UPS

Several tradeoffs and considerations must be made when designing a DC-UPS battery backup system: the battery string voltage to use, the kind of battery string monitoring that should take place, how the batteries will be charged, etc. The following sections address these considerations.

Battery string voltage

The choice of battery string voltage is driven by many conflicting requirements. Affordable VRLA batteries are available only in 12-V or lower voltage sizes. The larger the battery string voltage amplitude, the more batteries there are in a string, and the greater the number of cables and cable terminals that are needed, but the battery string discharge current is lower. The smaller the battery string voltage amplitude, the fewer batteries, cables, and connectors, but the higher the battery string current during high-power discharge.

The battery string voltage was made compatible with the front end of existing state-of-the-art power-supply design circuits operating between 180VAC and 259VAC. At 259VAC, the instantaneous rectified input ac voltage to a power supply is between zero and 366 V. The power-supply input voltage permits the maximum battery voltage to be as high as 366 V.

Another factor to consider is power-supply safety spacings. Power supplies operating in the 200VAC range (180VAC to 259VAC) must have safety spacings that meet safety requirements published in UL1950 [6]. Any two points in the power supply that can have a potential voltage of 259VAC are required to have 4-mm spacings for clearance (the shortest distance between two conductive points through air) and 5 mm for creepage (the shortest distance between two conductive points measured along the surface of the insulation). The maximum dc voltage that can be applied to these same spacings is 250VDC. In order to avoid impact on the front-end spacing requirements of present state-of-the-art power supplies operating in the 200VAC range, the maximum battery voltage of the DC-UPS must be less than 250VDC.

Sixteen 12-V VRLA batteries were used to obtain the battery string voltage. The battery string can be broken

into manageable, replaceable, separate battery packs with four batteries contained in each pack. The maximum battery voltage is 235VDC during battery voltage charging, and the minimum operating battery voltage is 160VDC during discharge.

Battery string voltage monitoring

For previous battery system designs, the practices used to safely manage a battery string included temperature-compensated charging, charger overcurrent and overvoltage protection, and a fuse in series with the battery string. These practices worked well with the smaller 24-V battery strings which are used in the DC-UPS design. However, the 192-V DC-UPS battery string is eight times larger in amplitude than previous designs. Engineering and safety concerns with large battery strings in the telecommunications industry are well documented [6–8]. Most of the hazards involve the voltage distribution within a large battery string becoming unbalanced. Therefore, for the 192-V battery string of the DC-UPS, the voltage of each 48-V section of the 192-V battery string was monitored to determine whether the string was becoming unbalanced during charging or discharging.

During battery charging an algorithm is run internal to the DC-UPS charger once each hour. If the battery string sections are determined to be out of balance, charging stops and an error is posted on the system control panel instructing the operator to have the complete battery string replaced. On the basis of battery string characterization testing at IBM, a 10-V imbalance between 48-V sections of battery string is required to trip the charging monitor.

During battery high-power discharging, an algorithm is run internal to the DC-UPS charger once every five seconds. If the battery string sections are determined to be out of balance, an error is posted on the system control panel instructing the operator to have the complete battery string replaced. On the basis of battery string characterization testing at IBM, an imbalance of about 25 V between 48-V sections of battery string is required to trip the discharging monitor.

Battery string charging

The main function of a battery backup system besides supplying reliable backup power is to charge the battery string. Battery strings are perishable components with a finite life; when a battery string reaches the end of its life, it must be replaced. Because of the cost associated with battery string replacement in the field and the environmental consequences of battery disposal, it is desirable to charge batteries in a manner that promotes the longest life of the battery string. There are many methods for charging battery strings, and they can be

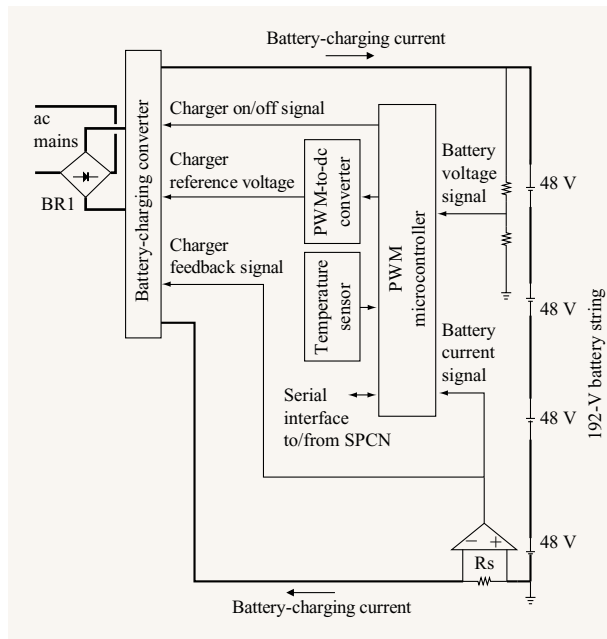


Figure 3

Battery-charging circuits.

divided into three categories: constant voltage, constant current, and taper current. All other methods are usually variations of these three. For constant-voltage charging, a current-limited voltage source is applied to a discharged battery string until the battery string charging current decreases to a small fraction of the initial charging current. For constant-current charging, a nonvarying constant-current source is applied to a discharged battery string until the battery string reaches a certain voltage level. Taper-current charging employs a 50–60-Hz transformer and a rectifier to supply a constant voltage across the discharged battery string. As the battery string voltage increases, the resistance of the windings in the transformer forces the charging current to decrease [9].

Each method has its advantages and disadvantages. Constant-voltage charging is the most efficient, fastest, and most conventional method, but it can force too much current into a damaged battery string, causing thermal runaway conditions [10]. Constant-current charging tends to eliminate any voltage imbalance when charging a large battery string, but after the battery string is fully charged, the continued constant current can damage the batteries. Taper-current charging is very economical, but it relies on an ac line voltage that may vary, resulting in undercharging or overcharging of a battery string.

Battery strings in backup systems spend most of the time in a charging state. Once a battery string is fully charged, it is desirable to maintain full charge by

continuous long-term constant-voltage charging at a level sufficient to balance battery string self-discharge. This maintenance charging is known as float charge [11]. Maximum battery string life requires charging at the proper float voltage [12]; the proper float-charge voltage is a function of ambient temperature. To maximize battery string life, it is important that the charger be temperature-compensated. VRLA battery manufacturers supply temperature-dependent float-voltage curves for battery string application designers.

In the past, AS/400 battery backup designs used a mixture of constant-voltage and constant-current, temperature-compensated charging circuits and algorithms. For all of these designs, the output of the battery-charging converter (using HFPC techniques) is directly connected to the battery string. A battery string presents an unpredictable stability component in the analog control loop of HFPC charger circuits. Successful control-loop stability of constant-voltage battery-charging circuits can be obtained in the laboratory. However, in the field, as the battery string ages or is placed in different environments, the characteristics of the battery string with respect to its control-loop components can change in an unpredictable manner. This unpredictability in the field renders circuit stability analysis during development impossible for all cases. Therefore, it has been determined that any battery charger connecting the output of an HFPC charging circuit directly to a battery string can, over time, become unstable and cause undercharged or overcharged battery strings, requiring earlier battery string field replacement.

With the above charging and battery string characteristics in mind, a unique battery string charging algorithm for the DC-UPS was used which combines temperature-compensated constant-current and constant-voltage charging [12].

Figure 3 shows the circuits used for battery string charging of the DC-UPS. The battery-charging converter circuit controls only the battery-charging current. This converter acts as a controlled-current source for the battery string. The battery voltage is not part of the feedback control loop of the battery-charging circuit. The battery voltage is controlled by the charger's microcontroller. The microcontroller turns the charger current source on and off in order to satisfy the battery voltage and current charging algorithm. The battery string voltage and current charging are monitored by the microcontroller's analog-to-digital (A/D) inputs.

Charging the 192-V battery string is a three-phase process in which phase 1, phase 2, and phase 3 are respectively called constant-current charging, constant-voltage charging, and float charging. **Figure 4** shows typical battery voltage and current waveforms for this charging algorithm assuming 30°C.

During the constant-current phase of battery charging, the current going into the battery from the charger is constant while the battery voltage rises. The pulse-width-modulated (PWM) output of the microcontroller is set by parameters downloaded from SPCN through the serial interface. The PWM output of the microcontroller connects to a PWM-to-dc converting circuit. The output of this converter becomes the reference for the charger circuit feedback loop; this loop is designed to set and control the current going into the batteries for the complete range of charger input/output voltages.

When the AS/400 containing the DC-UPS is plugged into alternating current but not powered on, the charger provides a maximum of 0.08 A of constant current. In this condition, no AS/400 system air-movement devices are operating, and 0.08 A has been determined to be the maximum current which can readily be handled from a thermal standpoint. When the AS/400 is powered on, the charger provides a maximum of 0.5 A of constant current into the battery string. The 0.5-A current level was chosen on the basis of the energy budget of the AS/400 system.

The charger enters the constant-voltage phase from the constant-current phase when the microcontroller detects that the battery string voltage is at a value linearly interpolated from the constant-voltage charging column in **Table 1** and then multiplied by 1.01. When the battery string enters the float charge phase, the charger is turned off until the microcontroller senses that the battery terminal voltage is equal to or less than a value linearly interpolated from the float charging column in Table 1 multiplied by 0.99. The multiplying factors 1.01 and 0.99 allow the battery voltage to rise and fall 1% above and below the constant-voltage target. These factors are sized large enough to allow battery voltages between on/off transitions to be manageable by inexpensive microcontroller circuits, but small enough to be seen as a constant voltage by the VRLA battery strings. While the charger is off, the microcontroller changes the PWM value by multiplying it by 0.9.

When the battery voltage reaches the target voltage multiplied by 0.99, the charger is turned on with PWM output at 90% of the previous value, thus forcing the charge current to be 90% of the previous value. A 90% decrease in the battery charge current for every off/on transition during the constant-voltage charging phase guarantees stable time management by the microcontroller circuits and simulates an exponential decay in battery-charging current for the VRLA battery string. The charger stays on until the microcontroller senses the battery voltage reaching the target voltage multiplied by 1.01. At this point the charger turns off, and the microcontroller calculates a new value for PWM ($PWM_{\text{previous}} \times 0.9$) output. When the microcontroller senses that the battery

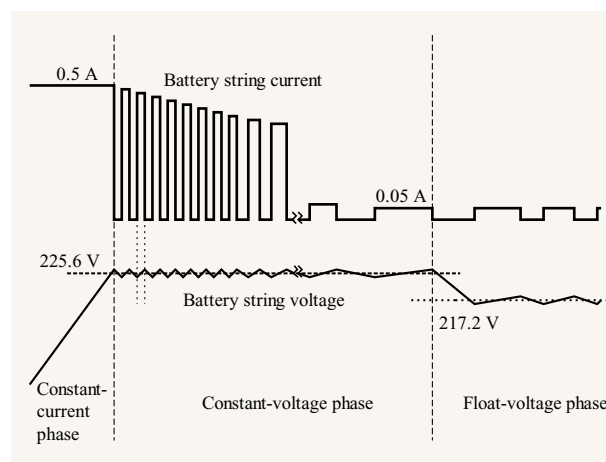


Figure 4

Battery string voltage and current-charging waveforms.

Table 1 Temperature and voltage table for battery string charging.

Temperature (°C)	Constant-voltage charging (V)	Float charging (V)
10 or lower	235.6	226.6
20	229.6	220.8
30	225.6	217.2
40 or higher	221.7	213.1

voltage is at the target voltage multiplied by 0.99, the charger turns on.

This cycle of turning the charger on and off, which decreases the charge current by 10% each time, continues until the charge current is less than or equal to 0.05 A. At this point, the microcontroller transfers the charger into the float charge phase. When the battery string enters the float charge phase, the charger is turned off until the microcontroller senses that the battery terminal voltage is equal to or less than a value linearly interpolated from the float charging column shown in Table 1 multiplied by 0.99.

At this point the charger is turned on, with PWM at a value equivalent to a charger output current of 0.05 A. This should force a charging current of 0.05 A into the batteries. The charger stays on until the microcontroller senses that the battery voltage is greater than or equal to the target voltage multiplied by 1.01.

This cycle of turning the charger on and off, each time forcing 0.05 A into the battery string, continues until the battery is discharged by the IBM system. Above 50°C, the battery charger is disabled by the microcontroller.

Conclusions

Modern computer systems using HFPC power supplies and requiring battery backup can save significant expense, reduce complexity, and increase system reliability by using a DC-UPS instead of an AC-UPS. The DC-UPS design described in this paper is capable of supplying 3100 W of backup energy for 120 seconds, followed by 20-W CPM backup for 36 hours. If CPM is not required, this DC-UPS design can support a complete 3100-W system for ten minutes. This design can also be upgraded from 7- to 12-amp-hr batteries for longer backup times.

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*Trademark or registered trademark of International Business Machines Corporation.

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