BATTERY REQUIREMENTS FOR UNINTERRUPTIBLE POWER-SUPPLY APPLICATIONS

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Summary

There is an expanding market for small-to-medium capacity secondary batteries for use in uninterruptible power supplies (UPSs). UPSs are commonly used to provide protected power to computer installations, point-of sale terminals, and essential telecommunications equipment. The capacity of currently available UPSs is, typically, from 500 VA to several hundred kVa, with power-backup from ten minutes to one hour at full load. All UPSs incorporate secondary batteries; usually sealed lead/acid cells. Battery requirements include: high reliability; extended operating life; tolerance to extended float charging; and good, deep-discharge characteristics at high discharge rates. Recent research and development experiences in the design of a range of UPSs is described and the need for batteries optimised for UPS applications is highlighted.

Introduction

Uninterruptible power supplies (UPSs) have been in use for decades in critical power-supply applications. Traditionally, their use has been limited to power supplies for essential telecommunications equipment, medical equipment, and emergency lighting. A variety of rotary and static power supplies, all including secondary batteries, has been used, generally providing power for the ten to fifteen minutes required to start, and bring a standby diesel generator on load.

The application of solid-state power electronics has enabled the development of compact, efficient, uninterruptible power supplies which are now finding a wider range of applications, particularly in the protection of computer-based equipment. Such equipment (including personal computers, minicomputers, and the disk drives of major computer installations and point-of-sale terminals) can be damaged by power interruptions, or data stored either in volatile memory or on disk can be irretrievably lost. UPSs provide a cost-effective means of protection against power failures.

The battery requirements for UPS applications are unique in that batteries must have long life and be suited to extended float periods while providing good, deep-discharge characteristics at high discharge rates. The

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author's company is currently designing a range of UPSs with ratings from 500 VA to 20 kVA, for both 220/240 V and 110 V power systems. Research into battery performance characteristics has highlighted the need for batteries optimised for UPS applications. This paper describes the architecture of typical UPSs and standby power supplies as well as the general characteristics of the requisite batteries, and discusses in detail the requirements of the ideal UPS battery.

UPS architecture

Two distinct designs are commonly used for power backup applications, as shown in Figs. 1 and 2. The most common architecture for non-critical applications is the standby power supply (SPS), in which the mains is normally connected to the load via a solid-state 'static' switch and the battery/inverter system is switched to the load only in the event of mains failure. The mains-powered battery charger is rated to recharge the batteries within a period of, typically, 4 - 10 h, and normally float charges the batteries. Advantages of the SPS include relatively low cost, low stress on the inverter (which is on load only on mains failure), and low charger rating (typically one-fifth of the inverter rating). Disadvantages are the lack of mains regulation and the mains-to-inverter transfer time of 3 - 10 ms, which may seriously affect certain loads. In addition, the SPS output is not isolated from the mains and the only transient and radio-frequency filtering is that provided in the mains-line filter.

The architecture of a true UPS is shown in Fig. 2. In this case, the inverter is always on line and the full load of the UPS is also carried by the charger, in addition to the power required for battery charging. There is normally no direct mains link between the input of the UPS and the output, unless a bypass line to protect against failure of the charger or inverter is provided. The UPS provides continuous, isolated, regulated and filtered

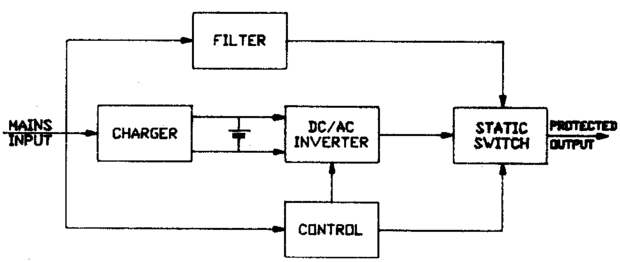

Fig. 1. Stand-by power supply architecture.

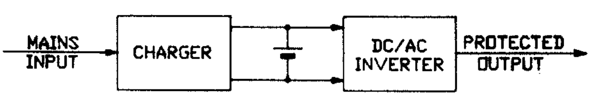

Fig. 2. True UPS architecture.

power to the load. The system is most suited to applications where any mains interruption, such as that during the transfer from mains to inverter in an SPS, could result in a disruption of the load operation. The UPS is also the appropriate source of backup power where good voltage regulation is required. While the UPS provides truly uninterruptible power and no discernible output transients on mains failure, its disadvantages include higher cost and the need for greater circuit reliability, as both charger and inverter must continuously carry the full load of the UPS.

The technology used in backup power systems has evolved over the period of their application. Thyristor circuits have traditionally been used in battery chargers, but switched-mode power supplies are now being used at charging capacities up to 10 kW. High-power, solid-state switches have been employed in inverters for some years, normally driving the load through a 50 Hz isolating transformer. Recent developments in inverter design include the use of transformerless circuits using high-frequency, pulse-width modulated inverters, commonly using power MOSFETs, and the use of high-frequency cycloconverters to generate sinewave outputs.

In general, high-frequency switching technology allows more efficient chargers and inverters to be implemented. Circuit efficiency of the inverter may be as high as 85%, allowing much more efficient usage of the energy stored in the batteries. Other benefits of high-frequency switching technology include lower power dissipation (allowing circuitry to run cooler) and more compact UPS systems.

Typical UPS performance requirements

The requirements for UPS and SPS batteries are determined by the performance schedules of the backup supplies. A power backup time of 10 min is generally considered to be the minimum acceptable for most applications, though some systems may require considerably longer backup times. The shorter backup times are more demanding on UPS batteries, as the batteries must operate at higher discharge rates. Given the UPS power rating, the circuit efficiency and the battery voltage, the battery capacity can be determined.

High reliability is an essential requirement for UPSs. The latter must be intrinsically more reliable than the available mains power, otherwise the UPS is of no benefit. With developments in switching power circuitry, it could be argued that the reliability of the UPS is largely determined by that of the batteries. It is considered that a mean time between failure of at least three years is required. With UPS battery rail voltages between 48 V and 240 V being typical, a large number of batteries may be used in a UPS, resulting in a greater probability of failure, so good battery life is essential.

Other UPS performance requirements are important for particular applications, such as output waveform quality and transient response under changing load conditions. However, these do not affect battery requirements and are not discussed in this paper.

Battery types

UPS battery characteristics are summarised in Table 1. The most common battery used in UPS systems is the lead/acid battery. Large UPSs require large numbers of batteries; vented wet cells are normally used and are racked according to normal battery practice. Small UPSs commonly use sealed lead/acid cells which allow flexibility in operating position and minimal maintenance. In general, nickel/cadmium batteries are not used, though the claimed reliability of these batteries makes them suitable for such application. Problems with nickel/cadmium batteries include the wide range of cell voltage over charge and discharge operation (which can cause inverter design problems in the UPS architecture), and low energy density.

TABLE 1

UPS battery types

Lead/acid batteries (2 V per cell)

(i) Wet cells
- 25 W h kg^{-1}
- 40 W h l^{-1}

(ii) Sealed cells
- 30 W h kg^{-1}
- 75 W h l^{-1}

Nickel/cadmium batteries (1.2 V per cell)
- 10 W h kg^{-1}
- 15 W h l^{-1}

Battery requirements

From the above, it is seen that the essential requirements of UPS batteries are as follows:

(i) high reliability, with a minimum life of three years;
(ii) good, extended float-charge characteristics;
(iii) good, high discharge-rate performance;
(iv) minimal maintenance requirements.

Other battery requirements that are important in some applications include:

(i) tolerance to a wide range of operating temperature;
(ii) high energy density;
(iii) ruggedness and good resistance to damage in transport;
(iv) operation in any orientation (sealed batteries only).

These requirements are discussed in more detail below.

Battery life

Battery reliability is essential for satisfactory UPS operation. While the reliability of typical UPS circuitry is the subject of some differences of opinion, many in the power-backup industry, and many users, consider that the batteries determine the system reliability. This is particularly so in the larger UPSs, which may contain up to 100 batteries.

A minimum life of three years is required. Proven reliability is a factor affecting choice of batteries by the UPS manufacturer, though it is difficult to establish the validity of life figures published by battery manufacturers, particularly for new technology batteries which may offer considerable benefits in UPS service. For this reason, some UPS manufacturers take the conservative approach and use only batteries of known reliability.

The nature of batteries also makes quality assurance for the UPS manufacturer difficult. The life and capacity of a battery is affected by its history, including factors such as time since manufacture, storage temperature, and charge state. It is both expensive and time-consuming for UPS manufacturers to screen batteries by subjecting cells to full charge/discharge tests, though selected samples are normally subjected to full testing. The UPS manufacturer must be confident that installed batteries will last for a minimum of three years in service.

Battery life is also determined by conditions in service. Most UPS systems are continuously on line and the batteries are on continuous float charge. The design of the battery charger and the float performance of the batteries are therefore critical to UPS reliability, as discussed below. In addition, some batteries may require periodic discharge to ensure extended life and to test the discharge performance of the batteries. Operating temperature also affects battery life and charging requirements. Batteries also exhibit ageing effects, and capacity may be reduced by operation at sustained high temperatures. It is essential for UPS applications that the decline in capacity does not seriously reduce the UPS backup time. In specific terms, expert guidance from battery manufacturers spelling out the operating conditions required for maximum battery life in UPS service would be appropriate.

Battery charger requirements

Charger requirements differ for SPS and UPS applications. In the SPS, the charger is required only to charge the batteries and does not carry any of the output load. In normal service, the batteries are fully charged and the charger is merely used to provide the necessary float charge. In the true UPS, the charger must carry the full load of the inverter (see Fig. 2), as well as charge the batteries, all from the same charger output. A more complex and reliable high-power charger circuit is therefore essential. Normally, the charger is rated for the full UPS output load, plus losses in the inverter, together with a margin for battery charging of 20% of the rated UPS output.

For lead/acid batteries, charger requirements are well established. In larger UPS installations, a charger which allows full control of boost and float charge modes is normally required, and it is possible to optimise the charger output characteristics to meet the battery demands. A boost charge voltage of 2.50 V is usually specified and a float voltage of 2.25 V per cell is standard. Some critical applications may call for in-circuit monitoring of the voltage of each cell in the UPS battery string. In smaller UPSs, cost pressures may result in non-optimal charger characteristics, in which a boost mode is not available. However, it is essential that the float-charge characteristics are optimised for long battery life. The charger is normally designed to provide a constant-current output for battery charging, with output voltage limiting at the desired float voltage. The charger output voltage will then vary by, typically, 10% over a full charge cycle, as shown in Fig. 3, and the inverter control circuitry must compensate for these changes to maintain a regulated a.c. output.

A potential problem with battery charging is the temperature dependence of the battery terminal voltage, which, in turn, results in a temperature dependence of the optimum float voltage. For UPS installations designed to operate over a wide range of ambient temperatures, temperature compensation of float voltage may be required to ensure long battery life. Overcharging must also be avoided, particularly in UPSs using sealed batteries. Gassing of cells can then affect capacity, and dangerous gases may not be able to dissipate safely.

Nickel/cadmium batteries are also used in UPSs. As noted above, the cost and relatively low energy density of nickel/cadmium batteries tends to limit their application, and the recommended charger characteristics also present problems. While the nominal cell voltage of a nickel/cadmium cell is 1.2 V and does not vary significantly during cell discharge, the recommended float voltage is 1.40 V - 1.42 V and the charge voltage is 1.7 V - 1.75 V. A more complex charger is therefore required to provide optimum

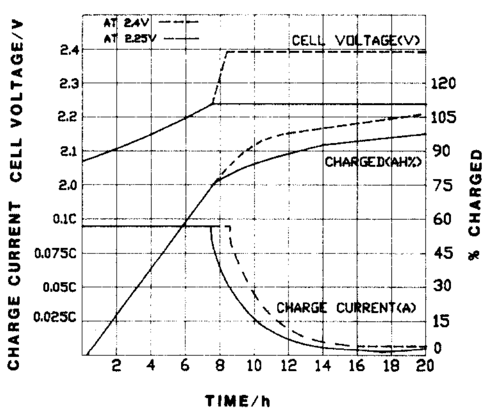

Fig. 3. Typical constant-current lead/acid battery charge characteristics.

charge and float conditions. Nickel/cadmium batteries give rise to a problem in the true UPS architecture (Fig. 2). The battery rail voltage could be any voltage between 0.85 V and 1.75 V, depending on whether the batteries are at the end of their discharge or are on charge. This poses a design difficulty for the inverter circuitry, which must provide regulated a.c. output over this range of input voltages. This problem is much less severe for lead/acid batteries, for which the operating cell voltage range is normally 1.8 - 2.5 V.

Battery capacity and discharge characteristics

Typical lead/acid discharge characteristics are shown in Figs. 4 and 5. Figure 4 gives the voltage of a typical sealed lead/acid cell, as a function of discharge time, for a range of discharge rates. Normally, small, sealed batteries are rated at a 10 h ($C/10$) or a 20 h ($C/20$) rate, and batteries are typically operated at 20 times their rated current for a 10 min backup time.

The problem of battery de-rating under such severe discharge conditions is apparent in Fig. 5, which shows the percentage of available $C/10$ capacity for different discharge rates. It can be seen that typical sealed batteries give less than 50% of their rated capacity at 20 times their rated discharge current. The performance of nickel/cadmium batteries is marginally better at, typically, 55%, for the same discharge conditions. Obviously,

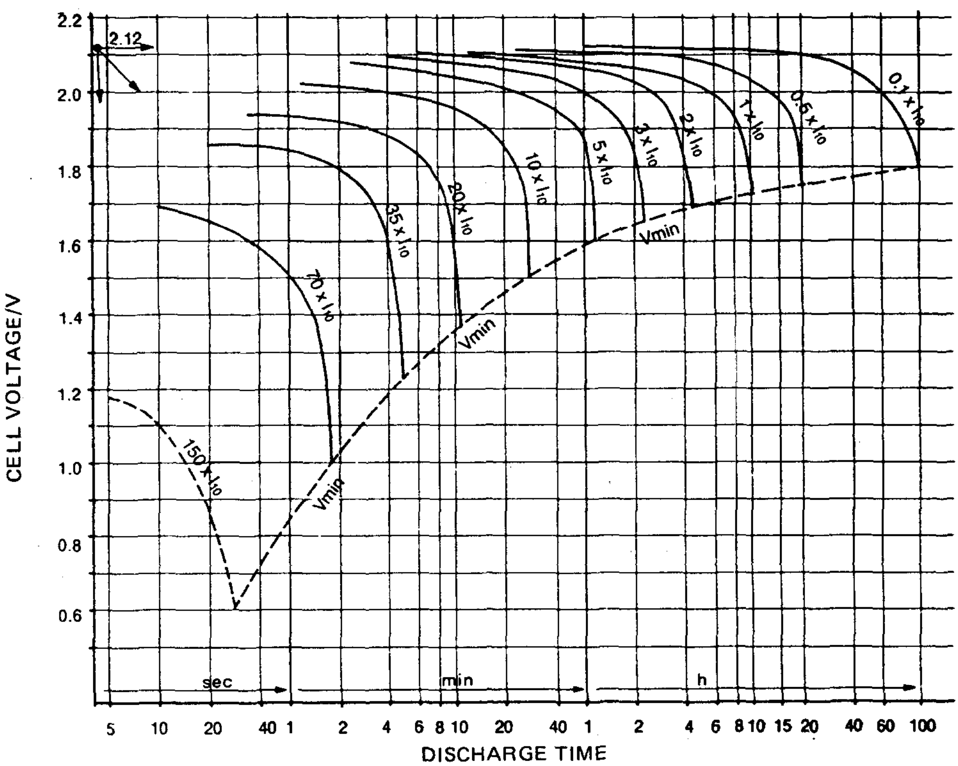

Fig. 4. Typical lead/acid battery discharge characteristics.

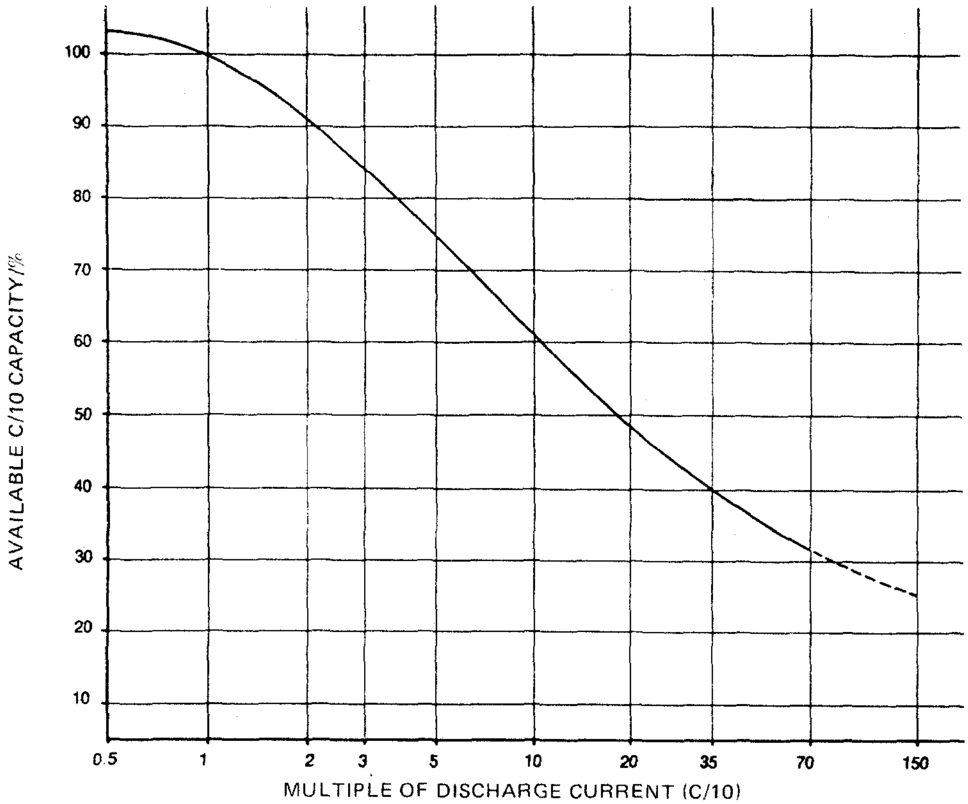

Fig. 5. Lead/acid battery de-rating with load.

more of the rated battery capacity is available if the UPS is required to provide a longer backup time, but then a greater ampere-hour battery rating is still required.

There is clearly a need for batteries optimised for short discharge periods for UPS applications. This requirement is in conflict with the requirement for good, extended float performance as, traditionally, batteries have been optimised for either deep discharge or extended float operation. One factor in favour of UPS applications is the relatively low number of deep-discharge cycles during the life of a UPS. Typically, there may be only four deep-discharge cycles per year, and then some of these may be battery tests to ensure correct operation of the system.

Battery maintenance

Low battery maintenance is necessary for UPS applications. In smaller UPSs, sealed lead/acid batteries have become standard equipment, and with developments in this technology, the use of high-capacity sealed batteries is now possible. Sealed batteries are essential for UPSs mounted in enclosed cases, offering flexibility in battery mounting, as they can be used in any orientation. For small UPSs, a test backup cycle is recommended at periods of three months to verify battery capacity. A problem common to all small UPS systems is that the UPS is generally used in a non-technical environment and specialist maintenance staff are not available. Therefore, all battery maintenance must be minimised.

Larger UPS installations generally require conventional wet-cell batteries. These are installed either in special ventilated cabinets or in special battery rooms. Regular maintenance of wet-cell batteries is required, and in some UPS systems it is possible to isolate and remove part of the battery string for maintenance while the UPS is on line. Many large UPS applications are in telecommunications where technical staff are normally available to perform battery maintenance, and the need for regular battery attention is not seen as a disadvantage. While sealed or low-maintenance batteries can be used in large UPS systems, the additional capital cost is not normally seen to be warranted.

As in any battery application, periodic test discharges may be required to ensure correct battery performance and capacity. Occasional boost charging may also be necessary to equalise cell charges. Some means of monitoring cell condition on-line is also of benefit in large installations. It would also be useful to monitor automatically cell conditions in small UPS systems, so that the user can be confident that the desired power backup will function when necessary.

Requirements for special batteries

In addition to the requirements for batteries optimised for UPS applications, current developments in UPS technology have indicated the need for special UPS batteries, particularly for smaller UPS systems.

Traditionally, a low battery voltage has been used for smaller UPS systems. This results in less efficient inverter design as the currents in the power switching devices are high and the internal voltage drops are high relative to the battery voltage. A step-up transformer is also required to obtain the required mains voltage. There would be considerable benefits if the battery voltage could be made closer to the mains voltage. This would involve the development of fractional ampere-hour batteries with voltages of up to 240 V. The battery output could then be switched directly to the mains by the inverter circuitry and highly efficient, small, UPS systems could then be developed for special, dedicated applications. It would also be possible to incorporate a UPS system into electronic equipment at present sensitive to mains failure, avoiding the need for an external facility.

Conclusion

A sizeable market has always existed for batteries for standby power systems. This market is now expanding as the benefits of uninterruptible power supplies are being appreciated in providing protected power to critical equipment. Major applications for UPS systems include: computer installations, from single microcomputers through to full mainframes; computer-based equipment such as point-of-sale terminals and electronic funds transfer terminals; essential telecommunications equipment; and security systems. The unique requirements of batteries in UPS service include the need for: high reliability; good, extended float performance; and good, deep-discharge characteristics at high output discharge rates. While currently available batteries provide satisfactory performance in UPS service, there is a clear need for batteries optimised for UPS applications.