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Standby-battery autonomy versus power quality

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Abstract

Batteries are used in a wide variety of applications as an energy store to bridge gaps in the primary source of supplied power for a given period of time. In some cases this bridging time, the battery's "autonomy", is fixed by local legislation but it is also often set by historically common practices. However, even if common practice dictates a long autonomy time, we are entering a new era of "cost and benefit realism" underpinned by environmentally friendly policies and we should challenge these historical practices at every opportunity if it can lead to resource and cost savings.

In some cases the application engineer has no choice in the design autonomy; either follow a piece of local legislation (e.g. 4 h autonomy for a "life safety" application), or actually work out what is needed! An example of the latter would be for a remote site, off-grid, using integrated wind/solar power (without emergency generator back-up) where you may have to design-in several days' battery autonomy.

This short paper proposes that a battery's autonomy should be related to the time expected for the system to be without the primary power source, balanced by the capital costs and commercial risk of power failure. To discuss this we shall consider the factors in selecting the autonomy time and other related aspects for high voltage battery systems used in facility-wide uninterruptible power supply (UPS) systems.

Keywords: Uninterruptible power supplies; Standby batteries

1. Critical ac loads

During 2000 Europe caught up with the USA, in that more than 30% of all the power generated was consumed by electronic data systems (together with associated plant) whilst USA business losses due to poor power quality were estimated to be US$ 75 billion [1].

The types of loads connected to UPS have rapidly shifted towards the single-phase switched mode power supplies (SMPSs)—as found in nearly all IT and telecom equipment, such as PCs, servers, routers, etc., whilst three-phase loads, including those for mainframe computers, have substantially reduced. This trend to SMPSs has increased the incidence of high load current distortion and exacerbated the problems arising from harmonic distortion of the supply voltage, phase load imbalance, high frequency neutral currents and troublesome neutral-ground voltages. Fig. 1 shows a typical mixed load in a City of London "dealer desk" application. At the same time the 0 V ride-through capabilities of "computer" loads has increased from the 10 ms of the original CBEMA [2] power curve (see Fig. 2) to the 20 ms suggested in IEEE466 [3].

Our dependence on IT systems at work and at home also fosters intolerance to unavailability. Of course, hardware manufacturers are loath to admit just what the real tolerance limits of their particular equipment are, particularly bearing in mind the consequential losses of IT failure. Consider that the revenue loss can vary considerably depending upon the type of business, as shown in Table 1 [1]. These figures, though dated and of USA origin, clearly show the order of magnitude but take no account of loss of customers arising from loss of power.

2. Mains power quality

One of the biggest problems in assessing mains power quality from a computer load's point of view is that there are several factors which have to be considered and very few of those are in the control of the distribution and supply company. Table 2 shows the power supply factors that affect an individual computer load within a building. With the exception of small business and home applications the use of UPS has become the norm and all but the last two of the factors in Table 2 are dealt with by using UPS. To risk a

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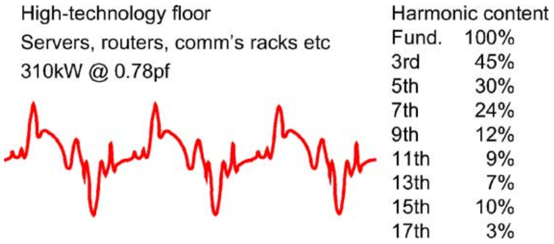

Fig. 1. Typical distorted load current profile.

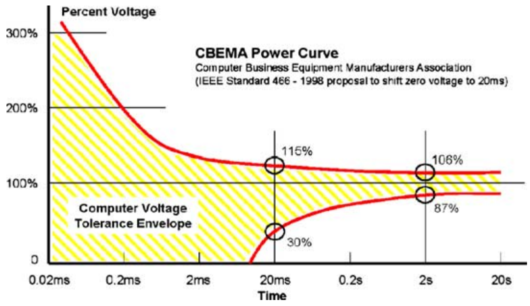

Fig. 2. Computer voltage tolerance envelope.

critical load to the vagaries of the utility supply is no longer considered as an option. The issue that remains is that of the UPS/battery autonomy—just how long will the UPS battery have to bridge the primary electrical power failure for?

To get some idea of the scale of our task we can look at some 1998 historical data on "dark-bus", that is, actual failure of the voltage rather than transient voltage depressions, at the 11 kV distribution point for average UK urban and rural sites (see Table 3) [4]. Such data as this is, unfortunately, no longer published since the UK power industry privatisation and the change in role of the Electricity Council.

Table 1
Revenue loss

Type of organisation	Million UK£/h
Dealer/brokerage	8.960–11.68
Credit card centre	3.520–4.960
Pay per view call centre	0.107–0.180
Airline booking call centre	0.107–0.180
Cellular phone switch site	0.061–0.070

Table 2
Utility power quality factors

HV generation and transmission grid
  Transients, frequency variations, trips

Local MV distribution
  Overhead or underground, radials, rings
  Civil works or adverse weather

Neighbourhood consumers
Your transformer source impedance
Your internal power distribution and grounding
Your other critical loads causing interference

Table 3
UK dark-bus at 11 kV

MDT (h)	MTBF (years)	
	Urban	Rural
0.01	3.1	0.39
0.02	3.2	0.40
0.08	3.7	0.46
0.20	4.1	0.50
0.33	4.4	0.55
0.50	4.9	0.60
0.65	5.7	0.70
0.80	6.8	0.80
1.00	8.2	0.90

MDT: mean down time (duration); MTBF: mean time between failure.

Up to date data of this kind can be found in the UK from some of the regional distribution companies, although they are not obliged to report on black-outs lasting <1 min or major voltage depressions at all. For example, Yorkshire Electricity reported, in May 1997, that their average customer was without power for a total of just under 1 h (an improvement of 2 min on prior year) and that their urban customers risked a 1 h power cut every 2.9 years [5].

With the increasing deregulation of power generation and distribution companies around the globe generally leading to lower maintenance and, subsequently, lower power quality at the consumer connection, it is clear that both the technical and commercial need for UPS is growing. It is also clear that for the type and power capacity of application we are considering it would be uneconomic and technically risky to try to install batteries to bridge such power failures.

Fig. 3 is a compilation of UK data showing the broad relationship between the lengths of time of a power deviation versus the MTBF of that deviation. The relationship will change from site to site and from country to country depending upon the spinning reserve, resilience and load factor of the distribution system. This type of data can be modelled and an example will be presented in the Symposium.

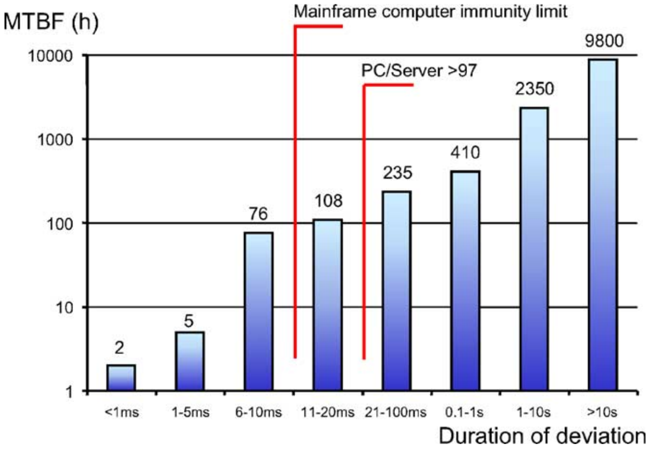

Fig. 3. Compilation of data for power outage vs. MTBF.

Other, generally low power, applications (e.g. radio base stations) or where a low battery voltage alarm can trigger an orderly load shutdown, can be designed around such "utility only" scenarios. However, for our large UPS application it is the norm to have emergency standby generators and so we now turn to this aspect of the power system.

3. Emergency power generation

Energy storage is an essential part of any UPS system and lead-acid batteries fulfil that role in the majority of cases. Other forms of UPS energy storage include kinetic energy (flywheel) systems but these have, by necessity, very short autonomy times (typically 3–15 s depending on load and type) and are integrated with rapid start diesel engines as prime movers—the, so-called, "diesel UPS" systems. These can be mechanically or electrically coupled systems.

In both cases, battery-backed UPS with emergency power generation (EPG) back-up and diesel UPS, the engine provides the energy to bridge major power failures. This is most often by diesel engine powered alternator sets which are sized to feed both the critical UPS load (with the critical associated mechanical cooling systems for the computer load heat rejection cycle) as well as other building loads such as communications, safety systems, lifts, lighting, ventilation and security, etc. In some cases, where the general load is large in comparison to the critical load, diesel UPS installations also incorporate a separate EPG system.

We shall just consider battery-backed UPS with separate EPG support. The primary control trigger for the EPG system is "auto mains failure" but it can also be activated by a "call to start" from the UPS system if the mains power quality is so poor that the batteries are called upon to contribute energy.

The successful substitution of the mains power supply by the EPG installation depends upon many factors (and is a subject for a paper in its own right), however, maintenance has always proved to be the key to success. In Table 4 are listed the most important aspects of generator performance, always assuming that the sets and the control systems are well maintained in a high "state-of-readiness". Here batteries (almost invariably) play another clear and vital role—cranking duty. The number of EPG starting failures that have been attributed to poorly maintained starting batteries are legion.

There is no reliable data for "failure to start"—clouded as it is with poor maintenance problems, if not exhaust smoke—but engines must be kept warm, the fuel fed by gravity and the starting batteries at full charge and in peak condition. Under these circumstances it has been quoted by some multiple site users that "one failure in 1000 attempts" is a reasonable figure to use. This is, of course, for a single set and many installations of the size and criticality that we are considering here are in "$N + 1$" redundant configurations where the problem (of a single set failing to start) is overcome. However, it is the case that the more the number of sets there are in parallel the more problems can arise with paralleling controls. Time delays can arise in getting all sets, one at a time, synchronised and onto the busbar before the group is ready.

That said, in general, an EPG installation comprising 2 × 1 MVA sets (for example) should be up and running and ready to accept the load within 10–15 s of the utility supply failing. Larger systems, with higher power multi-sets in parallel, will take longer—perhaps up to 1 min or more. It is, of course, possible to start a lot faster than this, indeed the engines associated with diesel UPS machines have to reach full speed (1500 1/min) and take full load in one step well within 2 s, but higher quality engines should be specified and a heavy "black-smoke" start accepted as the injectors push extra fuel into the cylinders to promote maximum acceleration of the turbocharger impellers. Note that in some parts of the world local legislation specifies a starting time for certain applications—like those involving life safety.

One last point can be taken from Table 3: Diesel fuel has a high energy density and can be safely stored on site. It can suffer from stratification if stored for a long time and may need cycling (stirring) through the storage tank. It is common practice in many places to have a "day tank" in the plant room (although, confusingly, not always containing 24 h consumption) and a bulk fuel store elsewhere—often with several days or weeks supply capacity. Apart from fuel for regular testing (which should be monthly at least) Table 3 implies that a city centre location would not need more a few hours supply to cover for a "decade" event—and that all that is needed is a strong supply chain for re-fuelling in the event of extraordinary events (e.g. force majeure).

Table 4
Emergency power generation: factors for success

Engine starting reliability
Transfer switching reliability
Dynamic performance when "cold"
Step load capacity, without excessive speed (=frequency) drop
Reliable paralleling control
Steady-state frequency and slew rate
AVR and governor specification
Low alternator impedance

4. Uninterruptible power supplies (UPS)

It is generally observed that users regard UPS as "kicking-in" for the utility electrical supply when it fails. This is not incorrect per se, but conceals two important features—firstly that a "series on-line" UPS system, the most reliable topology, processes all of the energy all of the time (and so does not "kick-in", operating at full load all the time) and secondly that it continuously conditions the fidelity of the voltage supplied to the critical load. Indeed,

Table 5
Historical UPS battery problems

High ambient temperature, which accelerated drying out
Terminal post-corrosion
Accelerated internal corrosion caused by alloy differences between top bars and the grid plates when welded together
Failure of the lid to jar weld, causing leakage, partly due to the desire to use flame retardant plastics whose thermal welding properties were not fully understood. Often exacerbated by rough handling during installation

in a typical UK city location, a UPS spends >99.95% of the time per year as an advanced power conditioner—providing sinusoidal voltage with a close frequency tolerance regardless of changes in the load. Of course the typical critical power client is looking for at least 10 years of continuous voltage supply from their UPS so the missing 0.05% (4 h per year) is of great interest!

Reliability analysis of all UPS systems highlights that, all other things being equal, two factors affect the continuity of the critical output voltage bus; utility power quality and energy storage system reliability. The first is rather intuitive, since with perfect mains quality (for many technical reasons absolutely impossible) there would be no need for UPS equipment! However, this does depend upon the UPS being capable of always transferring the critical load to the utility in the event of an internal UPS failure. The second factor, battery system reliability, overrides all other reliability issues and we shall now consider what the application engineer should consider when specifying such an installation.

5. Batteries for UPS

5.1. History

Batteries for UPS had a very bad press in the early 1990s. This was caused by the rush to change over from the traditional 18–25-year life lead-acid wet-cells (Planté) to "10-year, maintenance free, sealed lead-acid". The change was driven (and, within Europe, strongly in the UK) by the perceived advantages of the new technology over the old–much lower cost, higher power density, no maintenance and no ventilation needed. The truth turned out to be quite different with some cells only lasting 2 years and the "topping up" maintenance was replaced by regular cleaning and rigorous capacity and/or impedance testing. Unlike the claim, these cells were never "sealed"—they gassed on recharge and lost water through evaporation, and are much better described today as valve regulated (VRLA). Indeed the major problems arose from the claimed features—batteries were pushed out of expensive dedicated plant rooms (valuable semi-conditioned space) into "cupboards" and neglected. Although these problems are now behind all high-quality battery manufacturers it is worth mentioning the principal historic failure modes and these are shown in Table 5.

We can, even today, learn from the first and last of these. Continuous high ambient temperature will shorten the available service life (see below) and a careful and professional battery installation process will protect your investment.

5.2. Safety

No one should ever underestimate the apparently benign nature of a UPS stationary battery. It may appear more peaceful than a flywheel weighing several tons and spinning at a few thousand rev/minute but it will contain much higher potential energy. For example a diesel UPS flywheel rated to discharge 1.65 MW for 10 s contains 4.6 kWh compared to a 1.1 MW, 5 min battery storing 92 kWh.

A typical UPS will require a dc bus voltage of 360 V (180 cells in series) and we should remember that the battery cell/mono-block is the only electrical component in the world that cannot be turned off and isolated—it always has (unless absolutely discharged) the capacity to deliver thousands of Amps of short-circuit current.

These factors suggest that it is preferable to have dedicated battery plant rooms, with the ability to isolate the strings into lower voltage sections and to ensure that only trained staff, using fully insulated tools, carries out all working. The design should always incorporate individual battery string isolation where multiple strings are applied.

5.3. Service life

Battery cells are a "wear item", a consumable. They have two end-of-life failure scenarios, age (e.g. internal corrosion) and use. In UPS applications in Europe it is almost inconceivable that "use", wearing out, will cause the premature failure of the battery. This is because the cells are rated, typically, for 1000 full discharge/recharge cycles. Consider a 10 year design life cell (capacity at the end-of-life being 80%) that achieves full term service—this is equivalent to a major utility supply failure (with no standby diesel supply) occurring every 88 h! As we have seen above, over 10 years the average UPS system is unlikely to face more than one event of this magnitude and the more frequent short/shallow discharges will not have any material effect.

As a client or designer we should remember to specify the autonomy required at the start and at the end of the battery life. Note that specifying "15 min at end of life" will require the battery to be oversized by 25% but this could well provide over 30 min autonomy for several of the early years—and a possible unnecessary investment.

5.4. Temperature and ventilation

The rated "design life" of a cell will be given at a fixed temperature, usually 20 or 25 °C. Below the design temperature the Ah capacity will reduce and the life will be extended, and vice versa—above it the design life (and actual life) will reduce. The simple rule is that for every 10 °C rise the design life is halved, so at 40 °C ambient your "10-year, 20 °C" battery will become your "2.5-year" battery. It is worth noting that *some* bad history came about from this problem, however, much blame was laid at this door that ignored one fact: To have the life shortening effect the elevated temperature must be constant. Brief excursions, even lasting several days (or even a few weeks), will not have a detrimental effect of any significance. Batteries have a stable thermal gradient and give off negligible heat, even during discharge, so keeping the room temperature around 20–22 °C requires very little energy or plant—and certainly much less than the energy required to feed losses in kinetic energy storage systems.

VRLA cells do vent hydrogen during recharge although in small quantities compared to wet-cells. The air change requirement in a dedicated battery room is in the order of one per day—met by almost any building system—although high spots should be guarded against to avoid gas collection. The cell manufacturer will have this data to hand.

5.5. Redundancy

With the energy store playing such a critical role in the system reliability it will, in principle, be clear to anyone that having a multi-module ($N + 1$ redundant) UPS system with a common centralised battery system is a bad idea, but it is still done! More importantly we should consider the case for multi-string batteries.

There are two ways of increasing the Ah capacity of a fixed length (e.g. 180) string of cells: Use a cell (or mono-block) of increased Ah capacity OR place multiple strings in parallel. However, the series capacity progression of commercially available cells makes step changes in battery capacity rather drastic, particularly in the larger frame sizes.

The usual argument put forward about avoiding a single string battery on redundancy grounds is valid, but not as valid as it first appears—since the most common failure mode of VRLA cells is short-circuit not open-circuit, in >20:1 ratio. On the other hand two strings will rarely give adequate autonomy (and much less than "half") if one string fails or is taken out of service for maintenance. The real reason UPS providers will offer multi-string solutions is to utilise the most cost-effective cells (which, for production volume reasons, is usually the 150–160 Ah, 6 V mono-block).

So, as a rule of thumb, you should avoid one string, be very careful above five strings (calling into question the ability of the system to equalise the strings' charging current) and always ask the supplier what autonomy you will achieve with one string out of service. In general, but not always for the lowest cost solution, aim for three strings as the design target with 60% of the desired autonomy with one of the three strings "out".

5.6. Autonomy

Specifications are written for autonomy times varying from 5 to 30 min without apparent factual or logical basis. The type of cell best suited to this application is very similar that of Telecom (the differences between suitability for long discharges (>4 h) and short discharges (10–20 min) has minimised) and, therefore, gives no advantage in choosing autonomy times (at the start of life) shorter than around 5 min. As we have seen, the design autonomy should take into account the availability and reliability of the emergency power generation and transfer switch operation. If the EPG system is considered reliable and will start and be ready to accept load within, say, 10 s—why specify a 20 min battery?

6. Conclusions

Having reached the end of our brief review it should be clear that much careful consideration should go into the specification of battery autonomy. In the symposium presentation we shall review a real application with detailed capital costs (often the ultimate driver) and consider the technical issues and lifetime costing. The designer must therefore try to balance the clients perceived "critical load" needs with use of space, capital cost, maintenance and replacement costs as well as the usual engineering practicalities.

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