Uninterruptible Power Supply in Distribution Substations' Auxiliary Circuits

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Abstract
This paper describes the integration of power electronic and energy storage applications in distribution substations. Auxiliary circuits must provide motor-driven power switches, protection relays and telecontrol systems with constant power supply, thus minimising power outages and their negative effects on consumers. Requirements on the apparatus are proportional to the distributed voltage levels.

Subthemes to be considered are charging rectifiers, lead acid batteries, battery management, inverters and static switches.

Keywords
Rectifiers, VRLA batteries, charging algorithms, inverters, static switches.

Introduction
Over more than 120 years, since the inventions by Thomas Alva Edison and Nikola Tesla, reliable supply of electrical energy has become a commodity. Behind a single wall socket is a huge infrastructure: energy generated in power plants is transmitted, transformed and distributed in numerous substations, which incorporate state-of-the-art symbiosis of power and control engineering. Actuators in switchgear are becoming more and more motorised, being controlled by advanced feeder and remote terminals. All these devices must be supplied by voltages different from distributed kV levels, any failure in auxiliary supply may cause malfunction in relay protection and immense damages on infrastructure. That is why grid enterprises pay much attention to the quality of support systems.

As for smaller substations with relatively less crucial loads, auxiliary supply can be implemented by consumer-level UPS with one phase 230 VAC output. Such a solution is a compromise between reliability and cost and therefore becoming obsolete.

So it comes out, that like any other infrastructures, substations need dedicated buffered power supplies, comprising of converters and storage elements. These components are described in the next part of the current paper. Most of the examples are derived from the requirements of two main state-owned energy companies in Estonia:

- Distribution Grid, responsible for low and medium voltage distribution up to 35 kV;
- Transmission Grid, administrating high voltage transmission infrastructure to 330 kV.

1. General characteristics

1.1 Voltages
In Distribution Grid, the auxiliaries are usually powered by 110 V DC supply. Some applications also use 48 V DC and 230 V AC buffered sources.

In Transmission Grid, newly constructed 110 kV substations' auxiliaries are fed by 110 V DC; 330 kV switchgear utilises 220 V DC backup systems. For some control and communication apparatus demanding 24 V DC or 48 V DC, DC/DC converters are additionally installed. Requirements also foresee an DC/AC inverter for PC workstations and other equipment needing AC supply [1].

1.2 Backup times
Technical requirements state minimal back-up time after input voltage loss to be 10 hours, at this point it must be possible to switch pre-defined maximum number of circuit breakers simultaneously.

1.3 Typical loads
- Feeder terminals and relay protection units;
- Motorised operating mechanisms;
- Automation and signalling units;
- Telecontrol devices.

2. Architectures
A typical DC auxiliary power supply, sometimes referred to as DC UPS, consists of a rectifier, lead acid battery bank, control and monitoring modules (Fig. 1). To increase reliability usually two or more rectifiers are connected in parallel redundant configuration. As for Distribution Grid, the batteries are usually located in the same enclosure with rectifiers, the Transmission Grid on the contrary requires batteries to be installed separately. The rectified voltage is then supplied to the loads over DC distribution panels containing switches and protective devices (fuses and/or circuit breakers).
2.1 Standby Parallel Operation

Here the load, direct current source(s) and battery are continuously in parallel. Thereby the charging voltage is the operational voltage and at the same time the battery bank voltage. With the standby parallel operation the DC source is at any time capable of supplying the maximum load current and the battery charging current. The battery only supplies current when the direct current source fails.

2.2 Buffer Operation

With buffer operation the direct current source is not able to supply the maximum load current at all times. The load current intermittently exceeds the nominal current of the DC source. During this period the battery supplies power. The battery is not fully charged at all times [2].

2.3 Redundancy

In redundancy configuration, basic devices connected in parallel are decoupled with the help of diodes (Fig. 2). Thus the failure of one rectifier does not affect the others, ensuring a continuous DC supply. The rectifiers must be dimensioned with enough reserve to take over the functionalities of a failed counterpart [3].

2.4 Power semiconductors

During the last decade, IGBTs have replaced previous prevailing SRC-based solutions. The result expresses itself in increased switching frequencies and decreased voltage ripple, which improves batteries' life expectancy. So output voltage and current instability of less than 1% and ripples below 0.5% can be achieved, whereas rectifier's overall efficiency lies over 93% [3].

2.5 Control and monitoring

A modern DC-UPS is controlled by a µP-based supervisory system assuring monitoring of all operation states and alarming in case of any abnormality. Alarms signalled are usually:

- overtemperature;
- mains power failure;
- battery disconnected;
- exceeding of maximum output DC voltage level;
- deep battery discharge;
- ground fault;
- watchdog.

Additional features mainly include a serial or Ethernet interface, battery circuit continuity detection and batteries' health monitoring. All data can be transmitted over remote terminal units (RTUs) to SCADA systems [1] [3].

2.6 Storage elements

Lead acid batteries still remain the most popular and cost-effective energy storage methods in power engineering and telecommunication sectors. The technology has not really developed in terms of its chemistry since its introduction and batteries of all shapes and sizes, available in sealed and maintenance-free products, are mass-produced today. In their price range, lead-acid batteries provide the greatest energy density, i.e. the amount of energy produced per mass unit; have the longest life cycle and a large environmental advantage if recycled, while 97 percent of the lead is recycled and reused in new batteries [4].
3. Battery designs and selection

Any electrochemical battery is assembled of several cells in series connection. A single lead-acid cell has a nominal voltage of 2 volts; the total output voltage depends on the number of cells in series. To achieve required DC voltage level and capacity, the batteries in bank are connected in so-called parallel, series or compound strings. For example, a 110 V battery bank is normally composed of 51 cells [1]. Besides nominal voltage, one differentiates between [5]:

- float voltage - battery voltage at no load current (with battery disconnected);
- charge voltage - the voltage a battery reaches while being charged. In standby parallel operation, a 110 V bank is kept on a constant 115...118 V level;
- discharge voltage - the voltage of a battery while discharging, determined by the charge state and load current.

The cut-off voltage refers to a value, where the battery is disconnected from the load to avoid deep discharge, threatening to reduce battery's life time. Lead-acid batteries' typical cut-off voltage is 1.6 V.

3.1 Flooded batteries

Flooded or vented design refers to batteries requiring periodic replenishment of water lost through electrolysis [6]. This battery type is still used in large UPS applications. The design is quite simple: negative plates made of lead or lead alloys are sandwiched between positive plates of lead or lead alloy with an additive of calcium or antimony. Their grid structure is filled with paste-like mixture of lead and its oxides PbO and Pb3O4. Sheets of non-conductive, microporous material, called a separator divide the plates. The plate assemblies are placed in a thermoplastic container, which is filled with sulphuric acid electrolyte diluted to certain density.

In any form of lead acid batteries, ionisation processes take place, where sulphuric acid and water molecules dissolve into oppositely charged ions. The ionisation, independent on operation modes, is always in balance with recombination. Due to constructional peculiarities and electrolysis, the recombination processes are hindered, causing water loss in flooded design.

3.2 VRLA batteries

Valve regulated lead acid battery (VRLA) blocks differ from flooded cells in that they are designed to recombine their active chemicals within a sealed container that only vents under special circumstances [7]. Their plate design, size and weight and container are also different. Due to their closed construction these types of cells are also known as “maintenance-free” or “sealed”. There are two main types of VRLA battery technology, absorptive glass mat (AGM) and gel.

The absorptive glass mat resembles the flooded battery design because it uses standard plates, but it also has a higher density of electrolyte. However, as its full name suggests, the AGM has a special glass mat used to absorb and immobilise the electrolyte. The AGM permits the exchange of oxygen between the plates, thereby making the system recombinant, yet it still provides the electrical separation needed to prevent shorting of the plates. The thicker the glass mat, the greater the ability to store immobilised electrolyte, reduce the effect of dry out over the life of the battery, and prevent shorting of plates. The AGM's safety vent is the second major difference in design. The safety vent has several purposes, preventing the release of oxygen during normal operation as well as maintaining sufficient pressure within the cell.

The gel cell is in some respect similar to the AGM because the electrolyte is suspended. The electrolyte in a gel cell has a silica additive that causes it to set up or stiffen. The recharge voltages on this type of cell are lower than the other styles of lead acid battery. This is probably the most sensitive cell in terms of adverse reactions to overvoltage charging.

It should be mentioned that gel batteries have become a de facto standard in industrial buffered power supplies thanks to the lack of liquid electrolyte and the slogan of being maintenance-free. In reality, they need more careful exploitation and charging methods as earlier flooded types [3] [5].

3.3 The Eurobat standard

Eurobat, the association of European storage battery manufacturers, has issued its own classification of lead-acid batteries, dividing them into four categories according to life expectancy (Table 1).

<table>
<thead>
<tr>
<th>Life time in years</th>
<th>Category</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥12</td>
<td>Long Life</td>
<td>LL</td>
</tr>
<tr>
<td>8-12</td>
<td>High Performance</td>
<td>HP</td>
</tr>
<tr>
<td>5-8</td>
<td>General Purpose</td>
<td>GP</td>
</tr>
<tr>
<td>3-5</td>
<td>Standard Commercial</td>
<td>SC</td>
</tr>
</tbody>
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Table 1: the Eurobat classification [8]

As for crucial infrastructure power supplies, the requirements accept only LL type batteries [1].

During exploitation, the batteries fall out of order not simultaneously, but gradually one by one. Therefore the total replacement is not reasonable. In advanced chargers a controller continuously monitors batteries' health and determines defective cells or batteries. Data collected and recorded by the continuous monitoring system include overall voltage, environment (ambient temperature), float current, string currents, charge and discharge currents, internal resistance, cell temperatures, cell voltages, and discharge time. Detailed historical data allows forecasting battery replacement [3].
3.4 Battery efficiency

Energy efficiency is calculated on the amount of power used from the battery while discharging divided by the amount of power delivered to the battery while charging in percent. A lead-acid battery has an efficiency of only 75-85%, the energy lost appears as heat and warms the battery. Keeping the charge and discharge rate of a battery low, helps keep a battery cool and improves the battery life.

3.5 Capacity and standby time

Battery capacity refers to the total amount of energy stored within a battery. Rated capacity is given in Ampere-hours (Ah), which is the product of the current times the number of hours to total discharge. The capacity is normally compared with a time of 10 or 20 hours (also known as the hour rating) and a temperature of 20 ºC. There are five factors that dictate the capacity of a battery:

- size: the volume and plate area of a battery increases with capacity;
- temperature: as a battery gets colder, its capacity decreases;
- cut-off voltage: to prevent damage, the cell's cut-off voltage should be limited;
- discharge rate: the rate of discharge, measured in amperes. As the rate goes up, the capacity goes down;
- history: deep discharging, excessive cycling, age, overcharging, undercharging all reduce capacity.

So it comes out that selection of a battery is not simply a matter of multiplication of load current and necessary standby time. As expressed by the modified Peukert's equation [9], the standby time is not proportional to the load current:

\[ t = r_h \cdot \left( \frac{Q}{I \cdot r_h} \right)^k \]

where \( r_h \) is the battery hour rating, \( Q \) – capacity at \( r_h \), \( I \) – discharge current and \( k \) – Peukert's exponent for that particular battery type (for VRLA type batteries, generally \( k = 1.15 \)). In practice, the battery banks are over-dimensioned by 20...50%.

4. Charging algorithms

The prerequisite to start charging a battery is the charging voltage being greater than voltage on battery bank's terminals. The difference between battery and rectifiers' voltages determines the charging current and recharge time.

The main criteria in choosing a charging curve are the considerations about battery's health and avoidance of whole system's overvoltage. Excess charging means temperature rise in cells, which is the ultimate cause of failures. Every 8°C rise in temperature cuts the battery life in half [10]. The manufacturers have worked out several algorithms, which are included in rectifier's control software.

Usually combined charging curves are used. By IU-characteristic (Fig. 3), the first stage is carried out with constant current, which in second stage is changed over to constant voltage. This the most common curve in industrial backup power systems.

4.1 Constant-voltage charging

Here the charging voltage remains constant, while the current decreases over time as the battery's internal resistance increases with charge level. The initial charging current is limited by charger's control circuits. A cell's voltage is continuously kept on 2.25...2.3 V level.

4.2 Constant-current charging

Constant-current charging simply means that the charger supplies a relatively uniform current, regardless of the battery charge level or temperature. Thus the voltage varies during process. This method is more common for automotive batteries.

4.3 Equalising charging

An equalising charge is a special extended normal charge that is given periodically to batteries as part of a maintenance routine. It ensures that all the sulphate is driven from the plates and that all the cells are restored to a maximum density and that the cell voltages are as much as possible uniform. While the cell voltage can reach 2.5 V for a couple of hours, it may be sometimes necessary to disconnect a bank in a redundant system (Fig. 2) during equalising procedure to avoid system's overvoltage.

4.4 Boost charging

This method is used when a battery must be recharged in the shortest possible time. The charge starts at a much higher rate than is normally. In this case, the most important parameter to monitor is the battery's temperature using special probes. Thus charging voltage (typically 2.35...2.4 V/cell) and current are limited.
5. Inverter and static switch

In large Transmission Grid substations, the inverter, powered by DC UPS, is intended to feed possible computerised equipment in control building, such as PC workstations and servers, where uninterrupted AC supply is needed.

A static semiconductor switch with synchronising near the inverter feeds automatically the station workstation PC load from AC mains to inverter in case of a power failure (Fig. 4). Transmission Grid’s requirements state for inverter’s parameters [1]:

- DC input voltage deviation ± 30%
- AC voltage with regulation range 230 V ±5%
- AC voltage tolerance ± 2%
- Minimum power 2000 VA/1400 W
- Frequency 50±0.2 Hz
- Harmonic distortion with linear load ≤5%

Conclusions

Uninterruptible power supplies play an important role in any crucial infrastructures, not only in power distribution, but also in telecommunications, life support systems, railways, banking etc. In these segments, longer standby times are more decisive than peak power. Any designer must pay attention to following questions:

- How to obtain reliability?
- How to ensure availability?
- How to increase batteries’ life time?

As power electronics industry has made immense developments, bringing along improved efficiency, stability and MTBF parameters, one might think that the weakest link is still the battery. However, modern VRLA types with life expectancy ≥12 years disprove this opinion. Such batteries have proven to be recyclable and more cost-effective in comparison to emerging alternative technologies. In this respect, double-layer capacitors or flywheel storage seems not yet to be lucrative.

References