Power Quality Application Guide

LEONARDO POWER QUALITY INITIATIVE

Resilience

Improving Reliability with Standby Power Supplies

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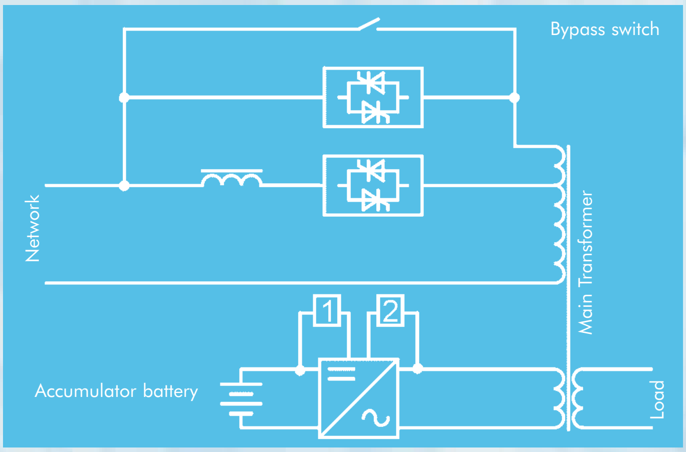

Resilience

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Resilience

Improving Reliability with Standby Power Supplies

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Wroclaw University of Technology
June 2003

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Improving Reliability with Standby Power Supplies

Introduction

The design of electrical power supply systems is a compromise between the interests of consumers - reliability and quality of supply - and those of the supply industry - realistic investment levels and operating costs. The flexibility allowed to deviate from 'perfect' power quality should be used to allow cheaper and simpler supply systems; it should not be wasted by permitting poor maintenance and operating procedures to compromise reliability.

Electrical equipment is designed to operate optimally under normal conditions, i.e. with a supply voltage that is within rated voltage and frequency tolerances with low voltage distortion and good phase balance and within the manufacturer's specified environmental conditions. Operation outside these limits can result in increased losses, poor efficiency and unpredictable operation. Large deviations can cause disruption due to the false operation of protection devices.

Voltage quality has a decisive influence on the operation of equipment. The voltage quality at the origin of the installation (the point of common coupling) is reduced further by the effects of other loads in the installation and the resistance of the cabling, so the voltage quality at the equipment terminals is much poorer. This is especially true in cases where loads with non-linear voltage-current characteristics are present.

Disruption caused by power interruption or poor voltage quality is always inconvenient and can be serious. In hospitals there is an obvious risk to patients undergoing operations or in intensive care. Public buildings, such as cinemas, theatres, exhibition halls, etc, where people are concentrated in relatively confined and unfamiliar areas, pose a particular risk during a power failure. Manufacturing industries, especially continuous process manufacturing (paper, steel) or high technology manufacturing (semiconductors), suffer long recovery cycles following any loss of power.

Category	Reliability requirements	Possible solution	Types of consumer
I Basic	Interruptions and failures in power supply can be relatively long, i.e. many minutes.	One line from the electrical distribution network. Standby power supply is not required.	Single family houses, low rise blocks of flats.
II Intermediate	Interruptions and failures in power supply should be limited to a few tens of seconds.	Diesel-electric generator set. Emergency lighting.	High rise blocks of flats.
III High	Interruptions and failures in power supply should be limited to the duration in the range from tens of ms up to 1 s.	Two independent lines from the distribution network. Standby power supply system equipped with automatic switching.	Large hotels, hospitals, TV and radio broadcasting, stations, airports.
IV Very high	Continuous supply. Power supply failure of selected loads is not allowed.	Zero transfer time standby system, long duration diesel-electric generator.	Banks, dealing houses.

Table 1 - Categories of electric energy consumers in relation to power supply reliability [5]

Virtually all commercial and industrial users of electricity will have individual loads or groups of loads that require higher quality of supply or higher reliability of supply than that available directly from the public supply. Often, the power requirements of these loads are relatively small and can be met easily by the use of auxiliary power supply equipment and/or un-interruptible power supplies. There is a wide variety of devices and reserve power supply equipment available on the market and the choice will depend on the characteristics of the load equipment and the type, duration and severity of the power disturbances that can be tolerated.

The availability of a power supply system is given by:

$$\text{Availability} = 1 - \frac{\sum_{i=1}^{n} t_{Fi}}{\sum_{i=1}^{m} t_{Bi} + \sum_{i=1}^{n} t_{Fi}} \tag{1}$$

where:

t_{Bi} - operation time number *i* between failures

t_{Fi} - time duration of power failure number *i*

m - number of operation periods between failures

n - number of failures in the observed time

The duration times of power failures must include the time required to recover from the stoppage, restart the process and achieve full production capacity. Re-starting a process is rarely instantaneous. Some processes require input from other, earlier, process stages and so cannot restart until the sequence is re-established.

Figure 1 illustrates a possible scenario where:

t_a - time of power failure

t_{ae} - equivalent time of power failure estimated from the values of lost production

t_s - time necessary for re-start of the production

E_e - standard efficiency

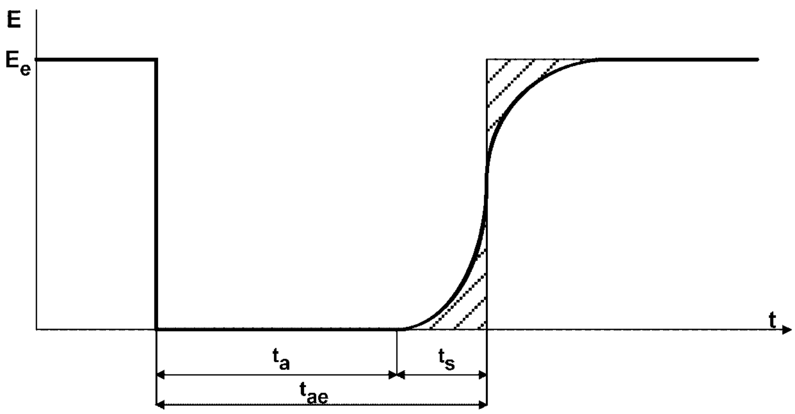


Figure 1 - Production efficiency following a power failure

The true time of the interruption should include the integrated shaded area. The cost of a power failure is not necessarily related to the duration of the event. Figure 2 illustrates several examples.

For many situations there may be a time independent element of cost that is incurred as soon as the event occurs. An example is paper making, where pulp is converted into paper in a continuous process involving many rolling and callandering stages requiring good tension control. Failure of the process control results in stoppage of the production process, and all part-processed product has to be removed and scrapped – a task that can take many man-hours. This case is represented by line 1 in Figure 2. The cost of a failure is relatively time-independent and very high.

The other extreme may be represented by a retailer of non-perishable goods. The lack of power results in a pause in trade, some of which is recoverable when the power is restored. This is represented by line 2 in Figure 2. Initial cost is low but increases with time as trade is lost for longer, although, if the duration is not too long, some trade will simply be displaced in time rather than lost.

Line 3 represents a data centre. Such a site will have some form of un-interruptible power supply (UPS) providing at least a short term backup so initial cost is small. However, since backup time is limited, some other action must be taken to ensure continuity of operation. There are many options. Line 3 supposes that a commercial remote standby site is alerted to prepare for a possible transfer of operations, incurring a significant one-off charge. Some planned time later, assuming that power has not been restored, the remote site is brought on-line, incurring time dependent charges. Following the failure, there would be an additional cost in restoring operation to the original site.

At the other end of the technological scale, line 4 represents the situation at a poultry farm. For a short duration failure there is no effect, but then the lack of forced ventilation leads to the suffocation of the birds resulting in rapidly accelerating costs.

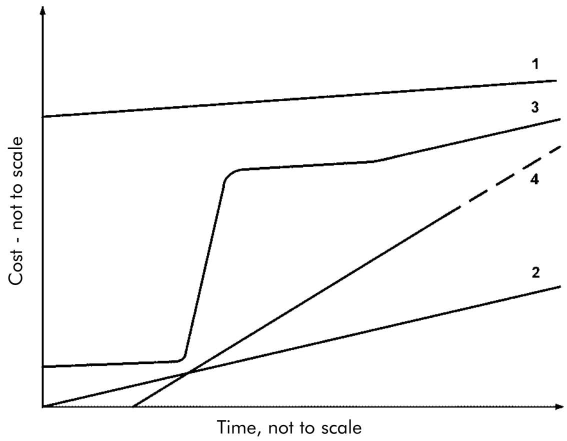


Figure 2 – Typical cost-time characteristics

These scenarios represent very different industries and yet have some common features. Firstly, if a failure is of sufficient duration it is possible for the cost of losses to reach levels comparable to the resources available to the organisation, putting future operation at risk. Secondly, during a failure and the subsequent recovery period the organisation may not be able to satisfy the needs of its customers, leading to a loss of confidence in the future. This applies especially to 'just in time' supply arrangements such as newsprint, which is manufactured, printed, read and disposed of in just a few days.

Complete failure - characterised by the total lack of voltage - is only one of many manifestations of voltage disturbances. Other issues are discussed in Section 5 of this Guide.

Standby power supply devices

Introduction

The important characteristics of a reserve power supply are:

- power capacity and stored energy
- transfer time
- maximum duration of generation
- efficiency
- cost of installation and maintenance.

The ideal device would have infinite power capacity and infinite stored energy as well as a zero transfer time, infinite duration of generation and low cost. Since such a device does not exist, various compromise approaches must be used. The choice of device depends on the application and requirement that is being supported. IT equipment, for example, demands a really continuous supply, i.e. zero transfer time in order to ensure data is not lost. Following the transfer, the equipment may be required to be supported for just long enough for an orderly shut down (say 20 minutes), or may require to be supported continuously so that work can continue. In the first case a UPS would be sufficient but in the second case an additional power source, such as a diesel generator would be required as a long-term source as well as a UPS to cover the generator start-up time. Alternatively, a paper making plant that has a large motor load could not be supported by a UPS for any reasonable time, so here a duplicated grid connection might be justified.

This section focuses on the standby power supply methods and devices. The grouping of these methods are shown in Table 2 and in Figure 3. They can be characterised by various parameters given in Table 2.

Duplicated feeder from the grid

Where the power requirement is high and the cost is justified, as in the case of continuously operating plant such as paper or steel making, two independent connections to the distribution grid may be provided. This approach is only effective if the two connections are electrically independent, i.e. a predictable single failure will not cause both network connections to fail at the same time. It depends on the network structure, and, often, this requirement cannot be met without the use of very long (and expensive) lines.

Type	Power capacity	Transfer time	Cost
Duplicated feeder from grid	Infinite	Very short	Very high
Engine generating sets	Effectively infinite	From long up to very short	Medium to high
Battery storage	Medium	Very short	Low
Un-interruptible power supply (UPS) systems	Medium	Very short	Medium to high
Compressed air energy storage (CAES)	Low to medium	Very short	Medium to high

Table 2 - Application features of reserve power supply methods and devices

The use of two independent connections from the distribution network does not mean that other reserve supplies are unnecessary. This type of measure is unlikely to reduce the number or severity of voltage disturbances however, because the networked nature of the distribution system allows dips – the effect of faults - to propagate over very wide areas.

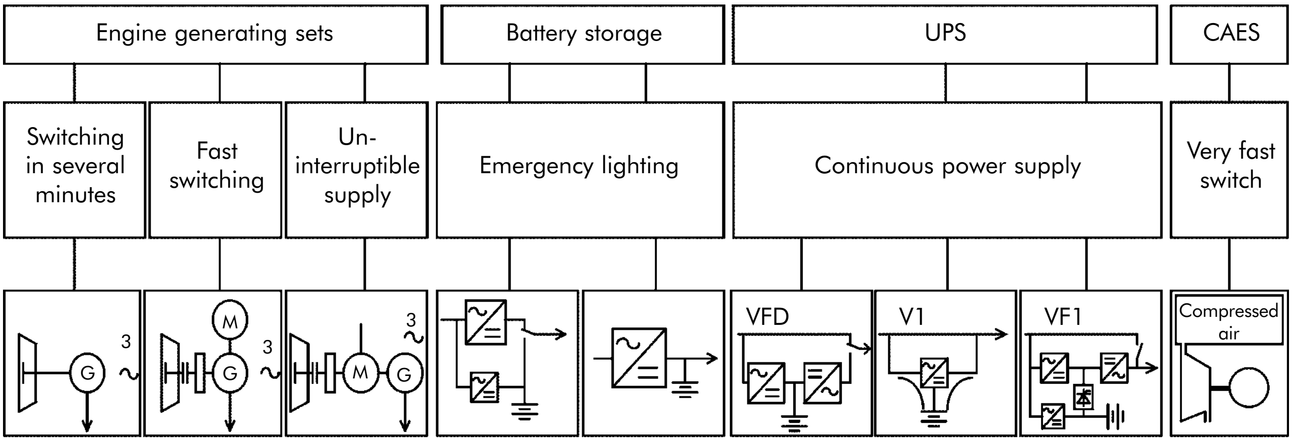


Figure 3 - Types of reserve power supply devices

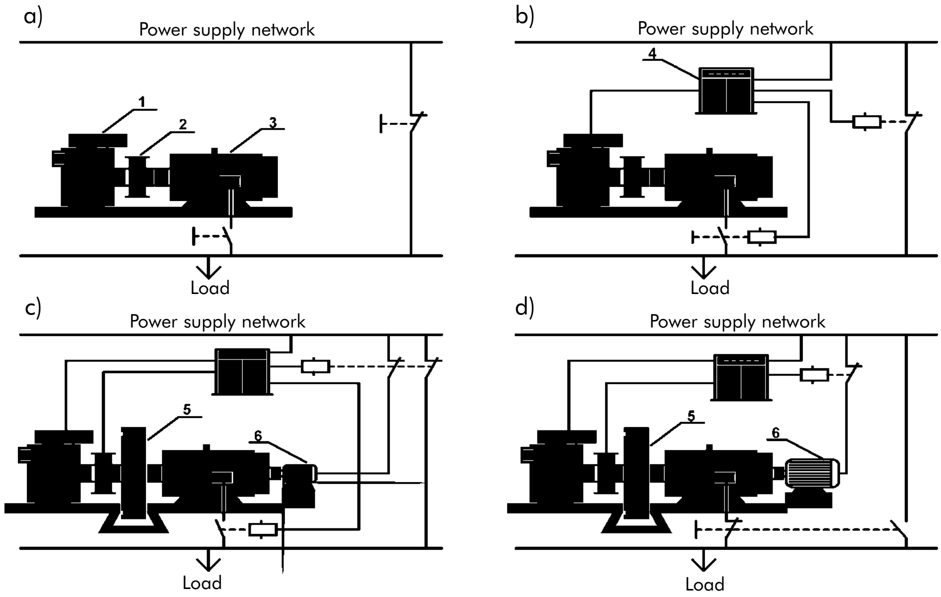
Engine generating sets (EGS)

Engine generating sets usually consist of one or more internal combustion diesel engines as the source of mechanical energy, a generator to convert mechanical to electric energy, accelerators, control and regulation systems and switchgear. This type of equipment may be designed for relatively long-term operation, say up to several hours or days, or may be designed for continuous operation. EGSs are available in a wide range of power ratings, usually from a few tens of kW up to few MW. Gas turbines are often used where large powers, in the range of a few MW or more, are required, e.g. for peak lopping or co-generation plants.

EGSs are also used for special applications where no power network is available, such as marine applications, or where a short-term, high demand requirement exists, such as major televised sports events. These applications are not covered in this section of the Guide.

EGSs can operate in two different ways, distinguished here as group I and group II.

Group I EGSs start-up at the time of power failure (4a, b). The starting of the diesel engine is performed using the energy from secondary batteries. In this arrangement there is clearly a delay between power failure and the time when the generator can support the load. In the simplest arrangement the EGS is switched manually (Figure 4a). However, usually the sets are switched on automatically (Figure 4b), with



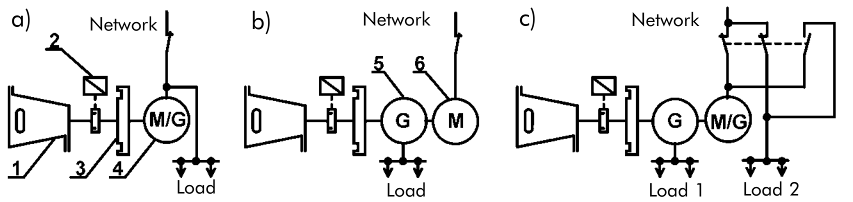
1 Combustion engine with starter
2 Clutch
3 Generator
4 Switchgear
5 Flywheel
6 Electric motor to drive flywheel and generator
a) With manual operated switching on/off
b) With automatic start-up of the generator, delay from a few seconds up to about 180 s
c) and d) With a flywheel driven by an electric motor, delay time 0.5-2 s and zero, respectively

Figure 4 – Engine generator sets

typical delay times in the range of 6-15 seconds for small units and up to about 180 seconds for large ones. In order to reduce start-up and transfer times, some EGS engines are continuously heated to operation temperature while stationary.

Group II EGSs have shorter transfer times of less than about 2 seconds (Figure 4c) or zero transfer time (Figure 4d). These arrangements are equipped with a high inertia flywheel mechanically connected to the generator. While power is available, the flywheel and generator are driven at the correct speed by an electric motor. In the arrangement of Figure 4c, when an outage occurs, the electromagnetic clutch connects the rotating flywheel with the engine, which starts and drives the generator. Start-up of the engine and taking up of the load is done automatically within 0.5 - 2 seconds.

In the arrangement shown in Figure 4d, during the normal system operation, power is supplied not from the distribution network but from the generator, which is driven by an electric motor supplied from the network. In the case of power failure the inertia of the flywheel provides the energy to start the engine via an electromagnetic clutch. Thus, the combustion engine drives the generator, which delivers electrical power with zero transfer time. Figure 5 shows some possible implementations of the concepts illustrated in Figures 4c and 4d.



1 Combustion engine/turbine
2 Electromagnetic clutch
3 Flywheel
4 Generator adapted also for operation as an electric motor
5 Generator
6 Electric motor

Figure 5 – Engine generator sets, equipped with flywheels, for zero transfer time

a) With generator operating under normal supply conditions as a motor
b) With generator continuously driven by a motor
c) With generator driven in normal supply conditions by motor/generator:
Load 1 – supplied without interruption, load 2 – supplied with a short interruption during switching-on of the reserve supply from motor/generator or during return to supply from the network.

Appropriately designed EGSs can meet most requirements for reserve power sources as well as continuous power supply. Zero transfer times can be achieved and power quality can be high if the generator is suitable for the intended load (i.e. the source impedance is sufficiently low).

On the other hand EGSs, especially high power units, have some disadvantages. They are noisy (the average noise level is from 70 – 95 dB), large and heavy, and they require large fuel storage, air intake and exhaust systems. Consequently, these generators are usually installed in separate buildings, relatively distant from occupied buildings.

Battery storage

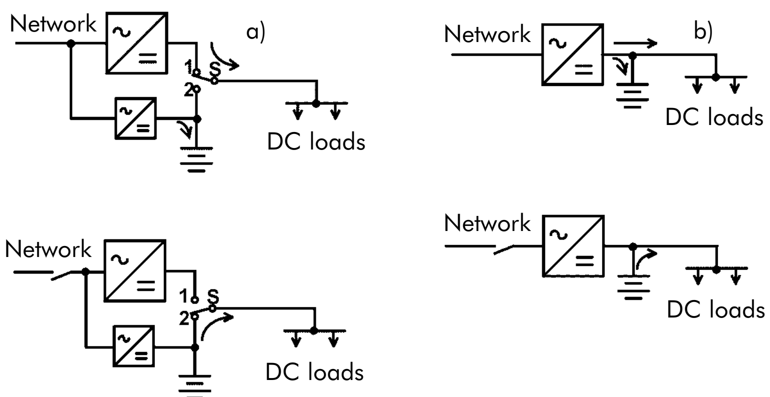
Secondary batteries are used in electronic UPS systems and, as described above, in some types of diesel-electric generator sets to start the diesel engine and supply control circuits. They are also widely used in self-contained units such as emergency lighting, safety equipment and computer and telecommunications equipment. Batteries are mainly used for supplying DC loads or loads that can operate on DC as well as AC circuits, e.g. lighting. Batteries used for supplying AC loads are equipped with DC/AC converters.

Large capacity self-contained battery units can be used as energy stores to cover peak energy demand in the MV supply network. However, this application is not discussed here.

There are two basic design philosophies of battery storage solutions. In the first, the load may be powered by the main supply until it fails, after which the load is switched on to the battery supply (Figure 6a). In the second solution the load is always supplied by the battery, which is constantly charged by the main supply whenever it is available (Figure 6b).

In Figure 6a the DC load is normally supplied from the main supply via the main rectifier while the battery is charged continuously via a second, separate rectifier. When the main supply fails, or the voltage is out of tolerance, the load is switched to the battery by a switch with a short, but not zero, transfer time. This type of system is suitable for emergency and evacuation lighting.

The arrangements in Figure 6b show a DC load being supplied directly from the main rectifier in parallel with the battery. When the main supply is available it is used to power the load and charge the battery. When the main supply is not available, the battery supports the load. Transfer time is zero, making this arrangement suitable for the support of volatile memory in computer based equipment. In fact this arrangement is also commonly used for functional and convenience reasons in consumer equipment, e.g. to preserve time keeping in video recorders and radio alarm clocks. The zero transfer time is an evident advantage of this solution. However, the reliability of the set shown in Figure 6a is higher than that from Figure 6b because, in the first case, the battery is supplied through an independent rectifier. The efficiency of secondary battery chargers is estimated in the range 90-97%.



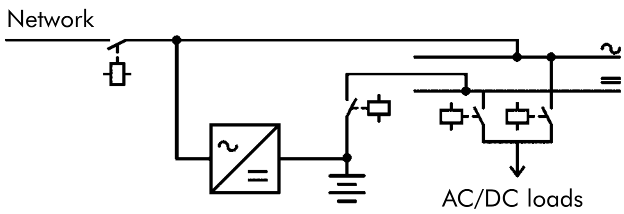
a) System with switch S
b) Continuous power supply:
1 Supply path from the network
2 Supply path from the battery.

Figure 6 - Different options of standby power supply of DC loads using AC/DC converters and accumulator battery

The battery capacity must be sufficient to supply power either until the main power supply is again available or the required function - evacuation, safety shutdown - has been completed. Generally, battery-charging times greatly exceed discharge times, so the duty cycle of these systems is low. The system should be designed such that a fully discharged battery is recharged in a maximum of 6 hours.

Emergency lighting is particularly important in public buildings such as exhibition and sports halls, theatres, cinemas, large office buildings, etc. Fittings designed for emergency lighting normally have a built-in reserve supply. Hospital operating theatres have similar but more stringent requirements. Light sources can often be supplied with either alternating current or direct current with continuity of supply being more important than quality. An example of this power supply system is shown in Figure 7.

Figure 7 - Supplying system of loads which can operate on AC as well as DC; the accumulator battery is used as standby power source; switching occurs with a short interruption



Un-interruptible power supply (UPS) systems

UPS classification

UPS systems are now commonly used as standby power supplies for critical loads where the transfer time must be very short or zero. Static UPS systems are easily available in ratings from 200 VA to 50 kVA (single-phase) and from 10 kVA up to about 4000 kVA (three-phase). As well as providing a standby supply in the event of an outage, UPSs are also used to locally improve power quality. The efficiency of UPS devices is very high, with energy losses ranging from 3% to 10%, depending on the number of converters used and type of secondary battery.

The basic classification of UPS systems is given in the standard IEC 62040-3 published in 1999 and adopted by CENELEC as standard EN 50091-3 [1]. The standard distinguishes three classes of UPS, indicating the dependence of the output voltage and output frequency on the input parameters:

- VFD (output Voltage and Frequency Dependent from mains supply)
- VI (output Voltage Independent from mains supply)
- VFI (output Voltage and Frequency Independent from mains supply).

However, in practice, this classification closely corresponds to classification by internal structure:

- passive standby
- line interactive
- double conversion.

Table 3 shows the main properties of these classifications of UPS device and a short description of the three mentioned UPS classes is presented below.

EN 50091-3 Classification	VFD	VI	VFI
	Passive standby	Line interactive	Double conversion
Cost	Lowest	Medium	Highest
Voltage regulation	None	Limited	Yes
Frequency regulation	None	None	Yes
Transfer time	Short	Zero	Zero

Table 3 - Classification and characteristics of standard classes of UPS

Passive standby (VFD)

This type of UPS (Figure 8) has two operating modes. Normally, the power for the load is provided from the main input, optionally via a filter/conditioner to remove transients or provide a measure of voltage regulation. The rectifier provides charging current for the battery. In 'stored energy' mode, the load power is provided from the battery via the inverter. Changeover from 'normal' to 'stored energy' mode occurs when the main supply voltage is out of tolerance via a switch with a short (but not standardised) transfer time. Typically, the maximum battery supply duration is about 3 hours while requiring 6 hours to recharge.

This is the simplest, most compact and least expensive topology, but it has some serious disadvantages. It provides no isolation of the load from supply-side disturbance and provides no voltage or frequency regulation. Its non-zero transfer time means that there is a short but definite break of power at the time of switch-over, making this topology unsuitable for many applications, especially IT systems.

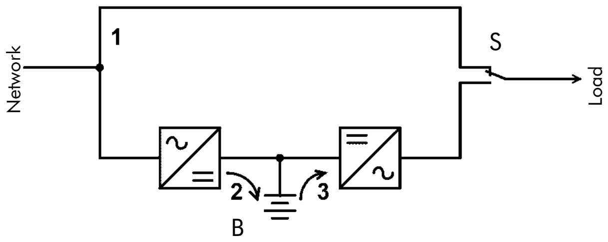


Figure 8 - The block diagram illustrating the principle of the passive standby (VFD) UPS device

S Switch

B Accumulator battery

1 Normal conditions

2 Battery loading under normal conditions

3 Energy flow when supplying power from the battery

Line interactive (VI)

The line interactive topology is shown in Figure 9. The inverter is bi-directional, i.e. it acts as a rectifier to charge the battery when mains power is available but acts as an inverter to produce standby power from the battery when mains power is not available.

The line interactive UPS has three modes of operation. In normal mode the load is supplied with conditioned power via the static switch. The inverter operates to provide output voltage conditioning and to charge the secondary battery. The output frequency is equal to the main supply frequency. In stored energy mode the load is supplied with energy from the battery via the inverter. The static switch opens to prevent power being fed back onto the main supply. This type of UPS may also have a bypass mode in which it allows the load to be connected directly to the main supply in the event of a UPS failure or for maintenance purposes.

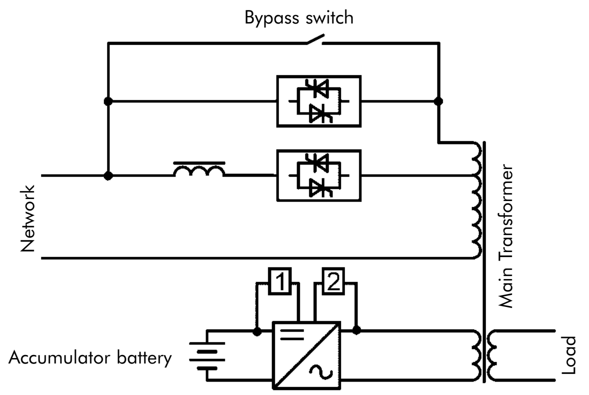


Figure 9 - The structure of the line interactive (VI) UPS with the single energy conversion

1 Control loop of phase and amplitude modulation

2 Control loop of accumulator battery charging

The line interactive UPS offers lower cost than the double conversion topology but has several disadvantages. Frequency control is not possible, isolation from main supply defects, such as transients and over-voltages, is poor, and the degree of conditioning that can be achieved is limited because it is a shunt device.

One variation of the line interactive UPS is the so-called Delta-design, shown in Figure 10.

The Delta-UPS is equipped with two DC/AC inverters: the delta-inverter (1) (Figure 10) and the main inverter (2). Both inverters are connected to the same secondary battery (B). The rated power of the delta-inverter is rated at about 30% of the load power, while that of the main inverter is 100% of the load power. The delta-inverter is connected to the secondary winding of the transformer (Tr), the primary winding of which is connected in series between network and the UPS-output.

The main inverter (2) is the fixed voltage source and it controls the magnitude and wave-form of the output voltage at the power balance point (PBP) (Figure 10). Thus, the voltage across the primary transformer winding is the result of the difference between the actual network voltage on the UPS-input and the fixed voltage in the PBP. The primary winding voltage controls voltage of the secondary winding.

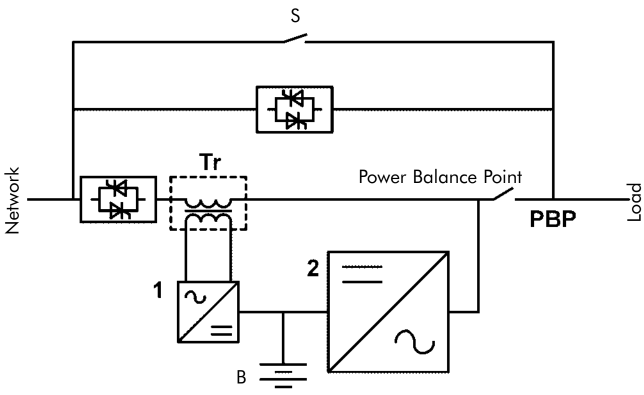


Figure 10 - The block diagram of the Delta type UPS

1, 2	Converters
S	Bypass switch
Tr	Transformer
B	Accumulator battery
PBP	Power balance point.

The role of the delta-inverter is to produce the current flow in the secondary winding, which induces in the primary winding the current of such value, so that it compensates the power difference between the network and PBP voltages.

Furthermore the delta-converter corrects the power factor in order to maintain it at a value near 1 and the main inverter compensates harmonics in the load current. Thus, the current supplied from the network has a sine-form and is in phase with the supplying voltage. The five typical operation modes of the Delta-UPS are shown in Figure 11.

In normal operation, when the supply voltage is equal to that of the PBP, the voltage across the primary transformer winding is equal to zero (Figure 11a). Both inverters, (1) and (2), are on, and the load power is supplied from the network only. For reactive loads and for non-sinusoidal load currents, both inverters work together to correct the power factor and harmonics in the current supplied from the network.

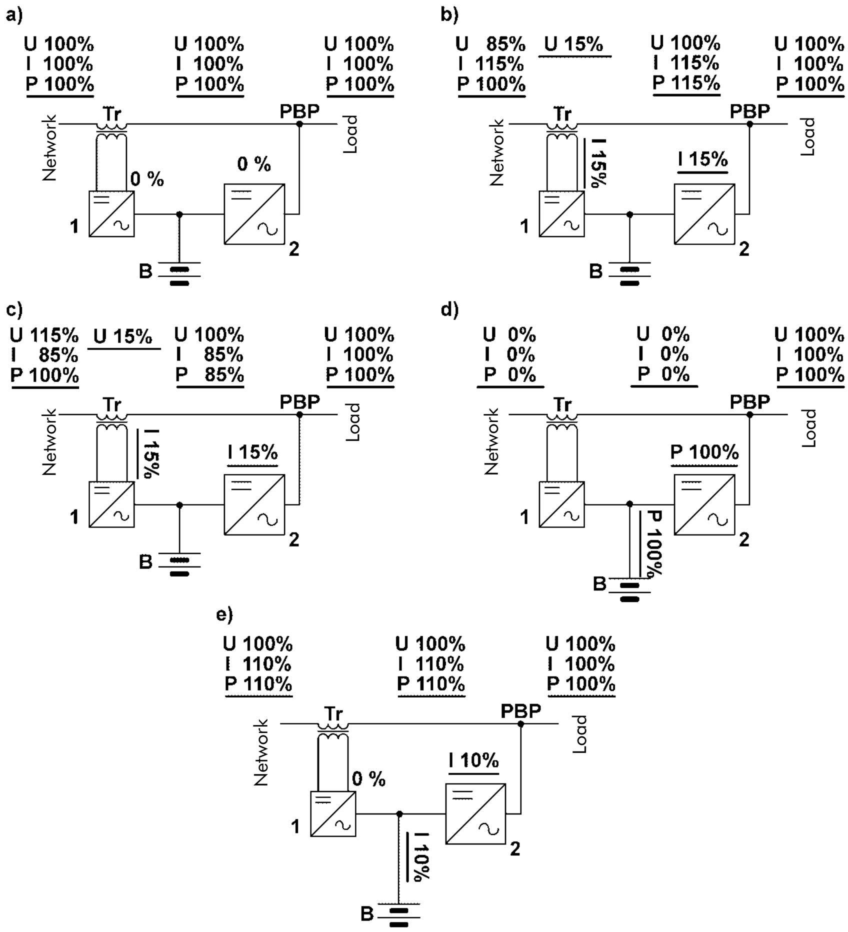


Figure 11 - Illustration of various operation modes of the Delta-UPS

U – Voltage, I – Current, P – Power
Other denotations are the same as in Figure 10

If the supply voltage is lower than that at the PBP, the voltage across the primary winding of the transformer (Tr) is non-zero (Figure 11b). The main inverter (2) charges the network with an additional current and the delta-inverter (1) generates the current in the secondary transformer winding in order to induce in the primary winding a higher current which, multiplied by the network voltage, gives the demand power. Thus, a higher current is drawn from the supply in order to compensate for its lower voltage, and the 100% of the load power is supplied from the network (Figure 11b).

If the network voltage is higher than the fixed voltage in PBP (Figure 11c), the polarity of the difference in voltage across the primary transformer winding (Tr) is opposite to that in the previous case, shown in Figure 11b. The delta-inverter (1) loads the supply network with less current, while additional current is supplied to the PBP via the delta-inverter (1) and the main inverter (2), in order to stabilise the load current at the demand value (Figure 11c). The primary voltage of the transformer is controlled from the network voltage, and the output voltage in PBP is maintained at the fixed, rated value by the main inverter.

In the case of outage, the Delta-UPS operates in the stored energy supply mode (Figure 11d) with the whole load power being supplied from the battery via the main inverter (2).

In normal operating conditions, independent of the value of supply voltage, the secondary battery (B) is continuously charged (Figure 11e). After operation in stored energy mode the battery is recharged via the main inverter (2), which draws an additional current from the supply for that purpose.

Double conversion (VFI)

The double conversion topology is shown in Figure 12. It is connected in series and the total load power is delivered via the output inverter.

In normal mode the load is supplied via the rectifier/charger/inverter combination - hence the name double conversion. The battery is connected to the DC link and is charged continuously.

In stored energy mode the inverter supplies the load with energy from the battery. As far as the load is concerned, nothing has changed - the power is supplied through the inverter, but now the source of energy for the inverter is different. There is absolutely zero transfer time so this topology is ideal for sensitive loads.

In bypass mode the static switch connects the load directly to the mains supply, in the event of failure of the UPS.

The advantages of the double conversion UPS are the very good isolation from the upstream supply, good voltage regulation, good frequency regulation (if appropriate) and the zero transfer time between energy sources. Note that, if the bypass facility is to be used, the frequency of the output must be synchronised to that of the main supply, negating the frequency control capability and, if the nominal output voltage is different from the source, a transformer will be required in the bypass.

The disadvantages of the double conversion UPS are higher cost and marginally lower efficiency.

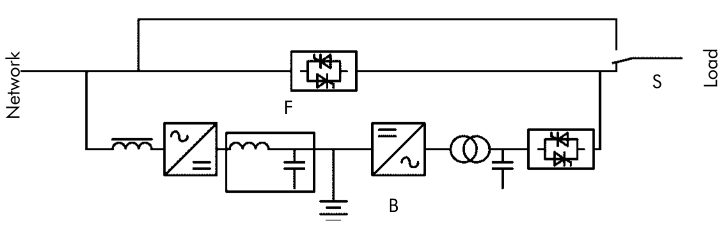


Figure 12 - The basic structure of a double energy conversion UPS

B Accumulator battery
F Filter
S Switch

Mitigation of disturbances using UPS

UPS systems can also be characterised by the degree of isolation which they provide between supply-side and load-side and the potential power quality improvement provided. Figure 13 illustrates ten types of disturbances that can be reduced using the particular class of UPS system.

The simplest UPS devices belong to the VFD class and limit the first three power disturbances. These are standby devices of the type shown in Figure 8, so there is a short transfer time during switching over. Thus, they are limited to use with loads that can tolerate short power failures.

Loads demanding a higher level of voltage stability require class VI devices, which limit five disturbances. These are usually line interactive UPS devices (e.g. shown in Figure 9).

Loads requiring the highest power quality and supply reliability require VFI class UPS devices, eliminating or limiting all ten types of disturbance. They are normally on-line devices, with the double conversion.

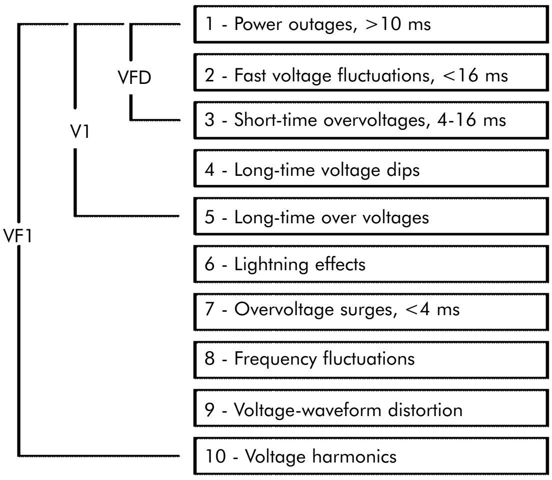


Figure 13 - Classification of UPS devices according to effect on their mitigating disturbances [1]

Increasing system availability using UPS devices

Static UPS systems are very reliable but, in the event of a failure, the consequences can be very serious. To protect the load against this, a bypass switch is provided to connect the load directly to the main supply. Obviously, while the UPS is bypassed, the load is not protected against disturbances or power failure.

The majority of UPS devices are equipped with a by-pass circuit or by-pass switch (Figure 14), which provides alternate paths of energy flow through the UPS device. This switch is usually operated manually to supply loads directly from the network when maintenance of the UPS is required.

The availability of the system is increased dramatically by adding additional redundant units. The concept of redundancy is explained in Section 4.1 of this Guide. In general, the expected load is served by a number of smaller units operating in parallel, as shown in Figure 15. If N units are required to support the load, then at least N+1 units would be installed. As a result, one unit can fail without affecting the operation.

If the load increases above the capacity of the installed units, it is simple to add another unit of the same rating.

Energy sources

Introduction

According to the statistical data [6], about 97 percent of all power outages in the MV-supply network last less than 3 seconds. These power failures are caused mainly by atmospheric discharges, auto-reclosing taking place after 0.3 to 3 seconds. Outages longer than 3 seconds occur only in about 3% of all power failures, and are usually caused by a fault in equipment in the network. The time duration of such events is significantly longer, in the range of minutes, hours or days. There are therefore two distinct requirements for energy sources. The first is for long duration – maybe up to several hours – with moderate energy, while the second is for very short time – up to a few minutes – at very high energy levels. Both types of energy store should also meet the following additional requirements:

- high energy storage
- low self discharge rate
- fast charge rate
- low maintenance requirement
- high reliability
- fast energy release rate.

For combustion engines the energy source is clearly some form of fossil fuel, which has the advantages of having high energy density, instant 'recharge' by refuelling and a practically infinite supply.

For static UPS systems the usual energy store is the secondary battery. However, in the last few years, new energy storage systems, such as flywheels, super capacitors and superconducting magnetic energy storage (SMES) have been developed to the point of commercial viability. The main difference between secondary batteries and new systems is the time period over which the stored energy can be delivered. Secondary batteries are able to deliver energy in short time periods, say tens of seconds or few minutes, as well as for long time periods, say few hours or tens of hours. However, the new storage systems are designed mainly for short time periods, say seconds to tens of seconds, to cover very short outages or to reduce the impact of voltage dips.

The energy storage system is maintained in a fully charged state while main power is available and then discharged when the supply fails. Ideally, the storage system must be capable of being recharged very quickly after main power is restored so that it is again available.

The main characteristics of energy storage systems are discussed in the following sub-sections.

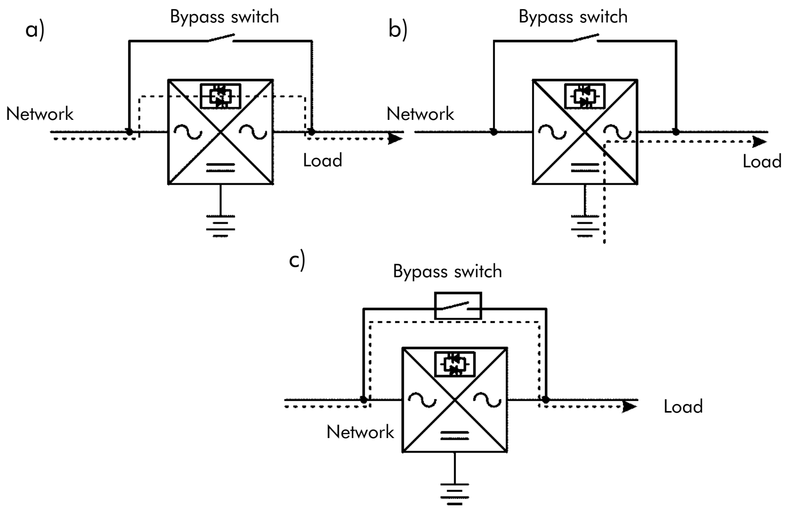


Figure 14 - Diagrams of three routes (dashed lines) of energy flow through a UPS in various operating conditions

a) Power from network through static switch – normal operation
b) Power from the accumulator battery – standby source operation
c) Power from network through bypass switch.

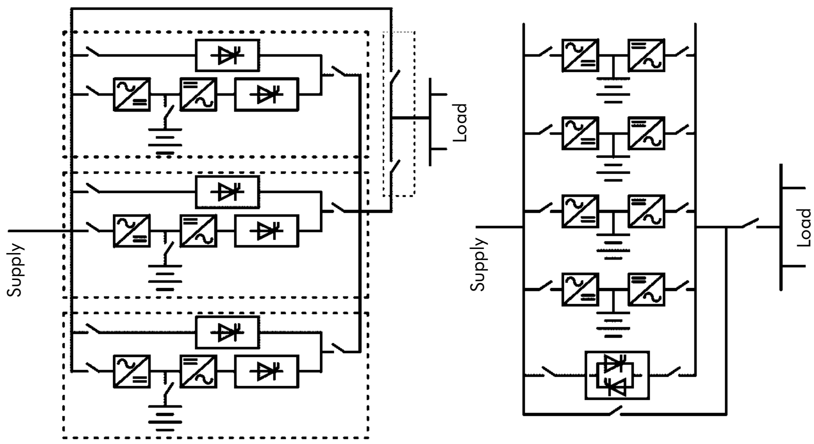


Figure 15 - Systems of UPS devices in parallel operation

a) With bypass and static switch in UPS device
b) With one main bypass and one main static switch.

Secondary batteries (accumulators)

The choice of battery type is usually made by the equipment supplier, but users must be aware of the type of battery used and the maintenance procedures required – these parameters may influence the choice of equipment. The main types of secondary batteries and their basic properties are shown in Table 4.

Stationary batteries, where the weight is unimportant, are usually of the lead acid type because of their lower cost.

	Sealed lead-acid	NiCd	NiMH	Li ion
Cost	Low	Medium	High	Very high
Energy density (Wh/kg)	30	50	75	100
Voltage per cell (V)	2.27	1.25	1.25	3.6
Load current	Low	Very high	Moderate	High
No of charge/discharge cycles	200 - 2,000	1,500	500	300 - 500
Self discharge	Low	Moderate	High	Low
Min recharge time (hours)	8 -16	1.5	2 - 3	3 - 6
Exercise requirement	180 days	30 days	90 days	none
Environmental hazard	High	High	Low	High

Table 4 - The main types of secondary batteries and some of their generic characteristics

Flywheels

Flywheels are used in some conventional motor-generator sets to store the mechanical energy required to start a combustion engine in the event of main power failure. In that case, only about 5% of the energy of the flywheel can be used to produce electrical energy directly because the change in speed, and therefore frequency, is too great.

When used as the energy source, the flywheel concept is totally different. The flywheel is 'charged' – by maintaining its rotational speed – by the main supply. When the supply fails energy from the flywheel is used to generate electrical energy at variable frequency and voltage, which is converted to standard frequency and voltage by an electronic inverter. Because the stored energy is proportional to the square of the rotational speed, about 50% of the speed range can be used. Flywheel constructions are characterised as high or low speed [7].

High speed flywheels are constructed from glass or carbon fibre materials, which are about 5 times heavier than steel. Due to thermal reasons and high centrifugal forces, the flywheel/rotor of generator is a permanent magnet. The flywheel/rotor rotates in a vacuum and is equipped with magnetic bearings in order to avoid the mechanical friction forces. High-speed flywheels operate in the range of rotational speed from 10,000 up to 100,000 revolutions per minute. They are currently being built with outputs up 250 kW with a stored energy of 8 MW.

Low speed flywheels operate in the range of up to 6,000 rpm. Because of a lower rotational speed in comparison with high speed flywheels, a considerably larger moment of inertia is necessary in these constructions, which results in heavier weights. The flywheel is made from steel and it is not necessary to operate in vacuum, but a partial vacuum or a low density gas can be used in order to reduce frictional losses. The motor/generator is a synchronous machine with exciter windings on the rotor. These windings create losses and heat, but the advantage over the high speed flywheel generator is the possibility of regulation of the excitation. Low speed flywheel systems can be manufactured in ratings up to 2 MVA and they are able to deliver energy for 1-30 seconds.

Low speed flywheels are often used as combined systems with traditional engine generator sets. A typical example is presented in Figure 16. The

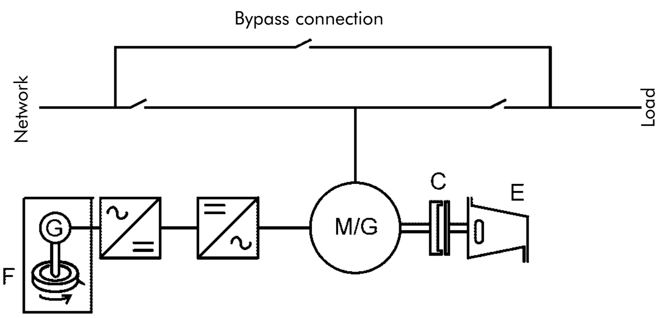


Figure 16 - Diagram of a combined system flywheel with engine generator set

F Flywheel short time storage system
G Motor/generator of the flywheel storage system
M/G Motor/generator
C Electromagnetic clutch
E Diesel engine or gas turbine.

flywheel provides power during the period between the loss of utility supplied power and either the return of utility power, or the start of a sufficient back-up power system (i.e. engine generator set). Flywheels provide 1-30 seconds of ride-through time, and engine generator sets are typically online within 5-20 seconds.

Super-capacitors

Super-capacitors (also known as ultra-capacitors) have extremely high capacitance achieved by the use of active carbon, activated carbon fibres or ruthenium oxide (RuO_2) as electrode materials. Electrodes made of these materials have a much larger active electrical surface compared to classical metal films. Super-capacitors serve in the system as DC energy sources, providing power during short duration interruptions and voltage sags. By combining a super-capacitor with a battery-based UPS, the cycling of the batteries is reduced because they provide power only during the longer interruptions and their life time extended. Small super-capacitors are commonly used to extend battery life - effectively by peak lopping - in electronic equipment, but large super-capacitors are still in development. They are expected to become viable for energy storage in the very near future.

Superconducting magnetic energy storage (SMES)

Superconducting storage systems store energy in the magnetic field of a large coil carrying direct current which can be converted back to AC as required. Low temperature SMES, cooled by liquid helium, is commercially available. High temperature SMES, cooled by liquid nitrogen, is still in the development stage and may become viable as a commercial energy store in the future.

In the SMES device, a magnetic field is created by circulating a DC current in a closed coil of super-conducting wire. Electrical losses are negligible. To extract power, the path of the circulating current is repeatedly opened and closed by a solid-state switch. Due to its high inductance, the coil behaves as a current source that can be used to charge a capacitor that provides a DC voltage input to an inverter that produces the required AC voltage. SMES systems are large and can have power capacities from 1 up to 100 MW, but they are generally used for very short times, in the range 0.1 – 1 second.

Compressed air energy storage (CAES)

In CAES the energy stored in compressed air is used to drive air turbine-electric generator systems. Depending on power and quantity of stored energy the CAES systems can be used for standby supply and ‘peak lopping’. The philosophy of such devices is similar to that of engine generator sets. The air storage system is maintained at pressure by a compressor that runs intermittently while power is available. The power range available is from a few tens to some hundreds of kVA.

CAES systems used as standby supply are equipped with air tanks, while for ‘peak lopping’ applications natural cavities such as aquifers, or man made cavities such as mines in hard rock or hydraulically mined salt caverns are often used. However, this kind of CAES is not discussed further in this Guide.

Comparison of various energy storage systems

Energy storage systems can be used in UPS systems in various combinations. As mentioned above, super-capacitors can be used together with the secondary batteries to cover short-term energy demand and extend the life-time of the battery. Each energy source is characterised by

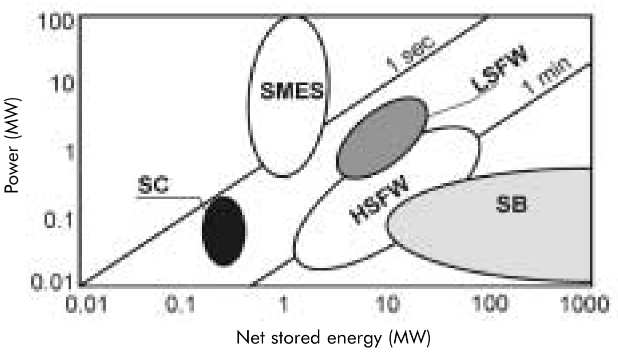


Figure 17 - Power v energy characteristics of different energy storage systems [7]

See Table 5 for definition of abbreviations the stored energy capacity and electrical power available, from which the time in which the energy can be delivered is derived. Figure 17 summarises these parameters for various energy storage systems [7].

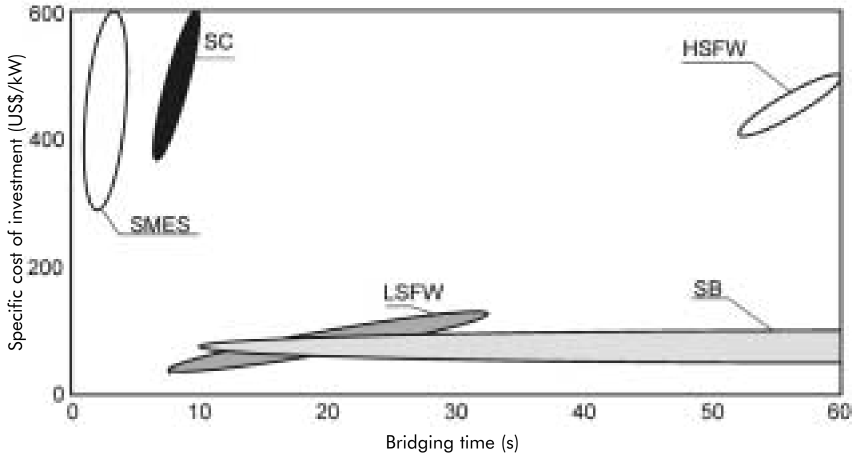


Figure 18 - Specific cost of investment for different energy storage devices versus their bridging times [7]

See Table 5 for definition of abbreviations

The short-term energy sources are still in the development phase so the investment costs are still relatively high (Figure 18). However, in the future, with improvements in design and manufacture and increased production volumes, the cost of these devices will drop.

The efficiency of energy storage systems used in UPS depends not only on the charging and discharging operation, but also on the idling losses. In practice, idling losses are dominant because the UPS system operates for the majority of the time in standby mode. Thus, the specific losses per Watt-hour of the storage devices are the significant factor of energy storage systems' efficiency. At present, the losses of short-term energy sources are very high in comparison with losses of traditional storage systems. Only super-capacitors are comparable with secondary batteries in terms of specific loss. Specific losses of various energy storage systems are shown in Table 5.

Type of energy storage device	Specific losses per Wh	Self discharge time
Superconducting magnetic energy storage (SMES)	35 W	1.7 min
Low speed flywheels (LSFW)	2.2 W	30 min
High speed flywheels (HSFW)	1.2 W	50 min
Super-capacitors (SC)	0.026 W	1.6 days
Secondary batteries (SB)	0.023 W	Very long, over a few months

Table 5 - Specific losses of different energy storage devices [7]

Example of a practical emergency supplying solution

In practice, in order to ensure a required availability level, it is often necessary to use a combination of devices such as is shown in Figure 19. Loads are divided into two groups according to their priority level. For example, IT equipment should have the highest priority (category IV, Table 1) and should be supplied by a UPS system. Loads that can tolerate a certain transfer time could be supplied by the engine generator set.

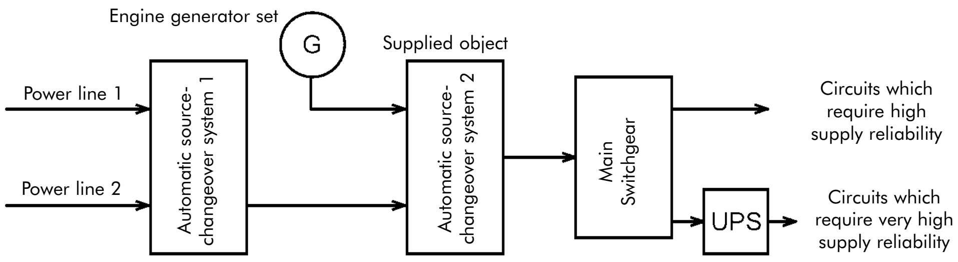


Figure 19 - Example of a high availability supply

The switching operations in circuits such as that in Figure 19 are done by automatic source-changeover systems (ASCS). An example of a practical solution of the ASCS is shown in Figure 20. Basic parts and operation diagram of the ASCS are described below.

The input controller measures the voltages of basic and reserve sources sequence of control signals shown on the time diagram at the bottom of the Figure 20.

Conclusions

It is now the case that most industrial and commercial consumers operate many loads that require higher power quality than that available directly from the supply network. Improving the performance of the network is both difficult and expensive, so it is left to the consumer to take action to mitigate the effects of poor power quality.

There is no single solution. The most appropriate solution will be determined by the power level involved, the quality and reliability level required, the quality and reliability of the incoming power, geographical location and cost.

Solutions are available for every scenario, at a cost, and a detailed analysis is necessary to select the correct and most economic solution for the particular application and working environment.

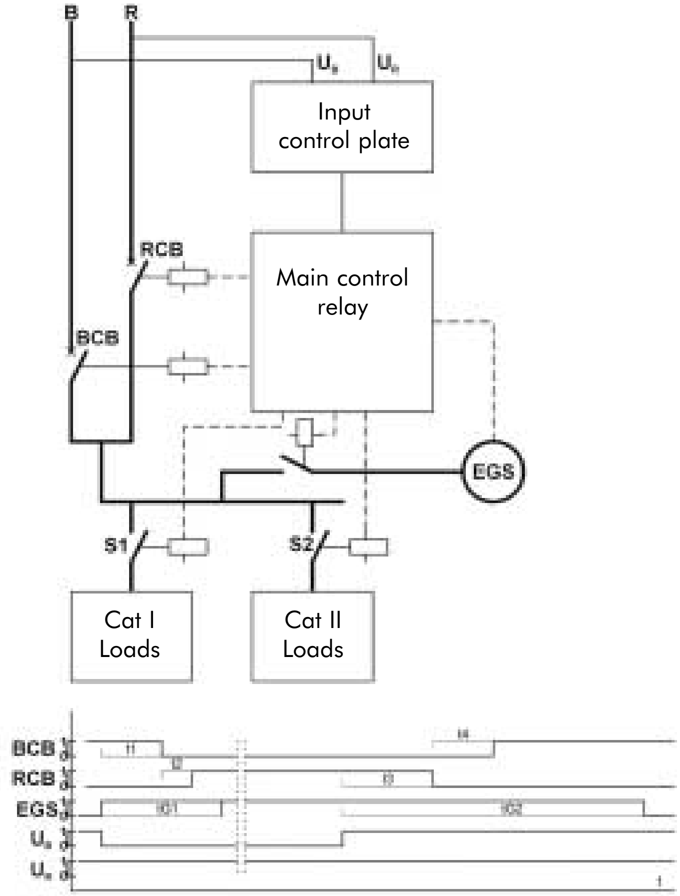


Figure 20 - Block diagram of a low voltage automatic source-changeover system and time diagram of its operation

B	Normal source
R	Alternative source (separate network line)
BCB, RCB	Circuit breakers operated in normal and alternative sources respectively
S1, S2	Switches loads of higher and lower category respectively
EGS	Engine generator set
U_B, U_R	Measured normal and alternative voltages respectively

Explanation of time symbols in the text.

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