PREDICTING & IMPROVING POWER RELIABILITY

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INTRODUCTION

The availability for use or reliability of a telecommunications installation is dependant on a number of critical factors. Perhaps the most fundamental is whether or not the facility is online with all systems functioning correctly. This state can only occur, and be relied upon, if the systems are operating in environments that they have been designed for and in particular are receiving power of an acceptable quality. This paper explores the reliability of the sources of power available and how they can be used to maintain quality critical supplies at the point of use, thereby improving the reliability of the installation as a whole.

Before starting it is probably best to define what exactly is meant by power quality. Ideally in the UK, pure sinusoidal current is supplied at 50Hz either at 230 volts phase to neutral, single phase or at 400 volts phase to phase, three phase, with angular displacement of 120 degrees between phases. These can be considered as 100% pure supplies and any deviation reduces this purity and hence reduces the quality. A pure or clean sinusoidal supply is shown in Figure 1.

In practice the supply from the mains is subject to variations in supply voltage above and below the desired values, spikes, surges and sags in the voltage level, voltage harmonics and high frequency noise, long and short interruptions in supply, variations in supply frequency and variations in the angular displacement between phases. Several of these possible disturbances are superimposed on a sine wave in Figure 2.

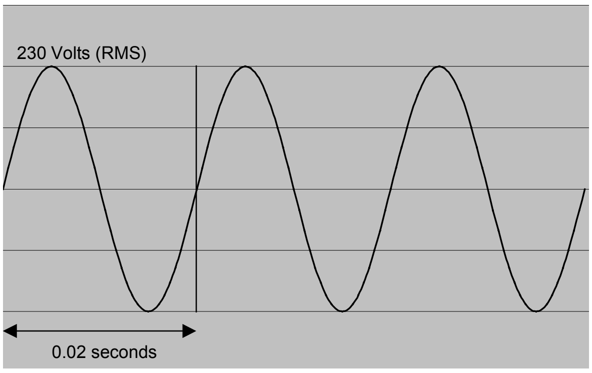

Figure 1: Pure, single phase, sine wave.

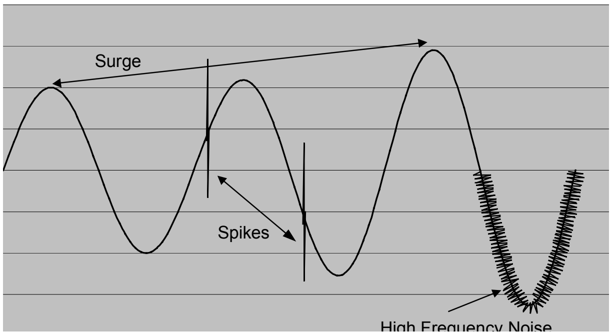

Figure 2: Spikes, surge and noise on a sine wave.

Electrical and electronic equipment is susceptible in varying degrees to the quality of power supplied, in particular to interruptions, even for very short durations, such as 10 milliseconds, will cause modern electronics to shutdown or reset, spikes and transient over voltages which can permanently damage or prematurely age components, and harmonics which can overload supplies, corrupt data and cause equipment aging.

Preventing these disturbances is achieved via the use of generators, uninterruptible power supplies, surge suppression devices, filters, etc, improving the unconditioned or raw power from the local electricity company.

By definition, the supply system providing high quality power to the disturbance critical loads is only as reliable as the components within that system. Therefore it is desirable to determine the reliability of that supply system.

A reliability study is seldom precise due to the lack of availability of component reliability data, over simplification of systems in order to make studies financially feasible, the error margin on equipment failure rates and human error when analysing the system for study. With this in mind it is prudent to consider a reliability study as an approximation, a stated accuracy of +/– 20% is not uncommon.

The role of a reliability study should be to enable quantitative comparison of relative systems or to give an indication of the level of reliability of an individual system.

Before moving on to the methods of carrying out a reliability study and how the separate sections of a power system can be analysed, it is unavoidably necessary to refer to the terminology as defined in IEC standard 271, which occurs in the information provided by equipment manufacturers and in the reports from the electricity suppliers.

Keeping it to a minimum the essentials are;
MTBF, Mean Time Between Failures. For a stated period in the life of an item, the mean value of the length of time between consecutive failures,

computed as the ratio of the total cumulative observed time to the total number of failures.
MDT, Mean Down Time. The mean value of the length of time that equipment is in a failed state.
Failure Rate, (λ): For a stated period in the life of an item, ratio of the total number of failures to the total cumulative observed time. (1/MTBF for non repairable systems)
MTTF or MTFF: Mean Time To First Failure. The mean time before the occurrence of the first failure.
MTTR: Meant Time To Repair. Mean active repair time required to restore the system to an operating condition
MUT: Mean Up Time. Mean failure free time between completion of an earlier repair and the next failure.

The next section of this paper looks at the sources of power available, the distribution systems, the methods of backing up the primary power sources, the conditioning of the power before it is delivered to the point of utilisation and quantifies in terms of relative reliability the options available to the designer.

POWER SUPPLY SYSTEMS

Power supply systems can vary greatly between installations depending on their location, age, load requirement, original methodology, extensions and many other factors, therefore it is not possible to design one system that fits all situations.

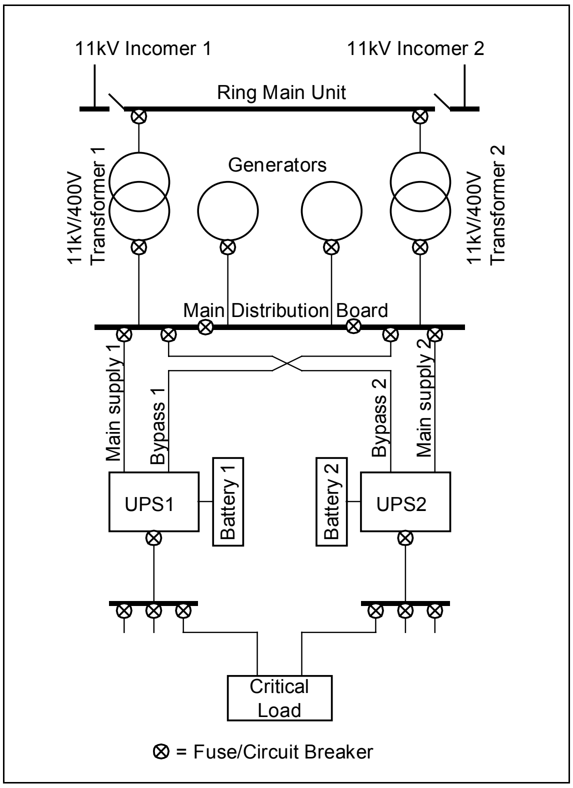

Figure 3: Example power system schematic.

For the purposes of this paper a theoretical system supplying critical loads is used. It is not based on a single project and is being used to demonstrate various points from a variety of sources.

When starting a reliability study it is a good idea to construct a detailed one line diagram of the system in question. The one line diagram helps identify possible points of weakness at the outset, i.e. where a single failure jeopardises the entire system, and it also helps in breaking down the system in to separate sections for study.

Looking at the example system in Figure 3, the first identifiable section is the primary power supply area or substation, containing the 11kV incomers, their circuit breakers, the ring main unit and the distribution transformers.

The back-up power supply generators and section of switchboard they are connected to, are the next section for study.

The 2 UPS systems, the switchboards feeding them and the circuits downstream of them are taken as the next section with the switchgear being examined in isolation later on

Before more detailed analysis of the sections just identified it is necessary to provide an overview of the methods available for performing reliability analysis on the system components and the system as a whole. These methods facilitate the examination of the effects of different component configurations or technology selections on the relative reliability of power supply systems.

RELIABILITY STUDY METHODS

The methods of predicting reliability and availability, described in this paper, first started to be developed in the early 1960s fuelled by military requirements, the emergence of the first computers and the space industry.

Several methods of reliability analysis are now available depending upon the information required.

These studies can be performed either manually or with software, the latter being more suitable for all but the simplest systems due to the number of calculations required. Software based studies allow modifications to be made more rapidly and can be integrated with reliability databases.

Often a reliability study on a system starts with a failure modes, effects and criticality analysis.

Failure modes, effects & criticality analysis. This is a procedure for identifying potential failure modes of elements within a system, identifying the effect and grading them according to their criticality. The results obtained identify the critical and non-critical system failures. Several ways of doing this are described in the standards IEC812, MIL-STD-1629A and BS5760 Part 5.

The evaluation is based on a combination of the probability of occurrence of failure with the seriousness of its consequences, if the aim is to determine the events which could cause the failure of an operations centre, then the failure of the electricity supply would be classified as critical and earn a high score in the criticality ranking. The failure of lighting might not be classified as being so important and so would receive a lower grade. All the identified elements with their failure modes, causes, effects and criticality are recorded in a tabular format. This table allows the less critical failures to be discarded and the more important concentrated upon in further studies.

Fault tree analysis. This is a method of calculating the probability of failure of a system by analysing the reliability and availability of the components within the system. The aim of the analysis is to calculate the likelihood of this failure in terms of system unavailability in hours per year and at the same time identify the most likely causes of this failure thereby allowing performance improving modifications to be identified.

The analysis is based on a graphical representation of the combination of events that could cause an identified event or failure.
This failure, called the Top Event, is analysed and the immediately preceding events, which could cause its occurrence, identified. These causal events are linked to the Top Event via logic gate symbols, such as AND or OR gates. The causal events are then broken down into their constituent causes through logic gates and so on until the independent basic events are reached. As a simple example the Top Event might be the failure of power to a switchboard with the basic events being supply transformer or grid supply failure, or generator failure.

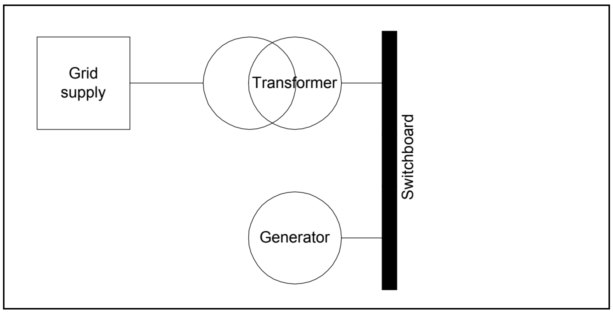

Figure 4: Example switchboard and supplies.

A simplified version of this example is shown in Figure 4 with the logic gate representation shown in Figure 5.

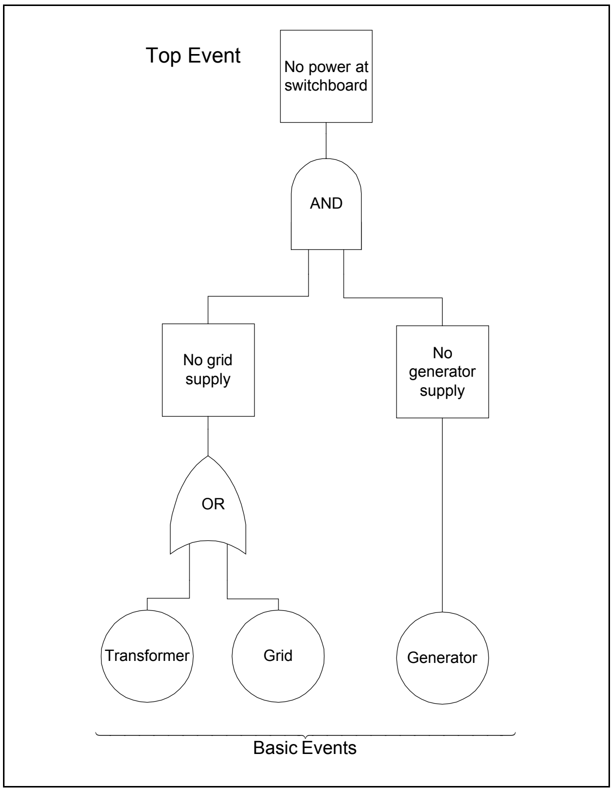

Figure 5: Fault tree of switchboard supplies.

Basic events at the bottom of the fault tree generally represent component and human faults for which statistical failure and repair data is available. Typical Basic Events might include grid supply failure, UPS battery failure, fire alarm failure, air-cooling unit failure.

When performing fault tree analysis the term minimal cutset is used to describe combinations of events, starting at basic events, that will result in the system failure. From Figure 5 a minimal cutset would be the simultaneous failure of the transformer and the generator, alternatively the failure of the grid and the generator.

Each cutset can be assigned a value in terms of the weight it carries in producing the top event. The weight if a percentage of the total unavailability can be used to assess which cutsets have greater criticality than others.

Fault trees are useful for analysing complicated or large systems, which would not be practical using manual calculation methods, and they are good at identifying system redundancy.

Reliability block diagram (RBD). This is a method of graphically representing a system through its components. It is a simple way of calculating the reliability of non-repairable systems or systems where the time to repair is of not as important as the failure itself.

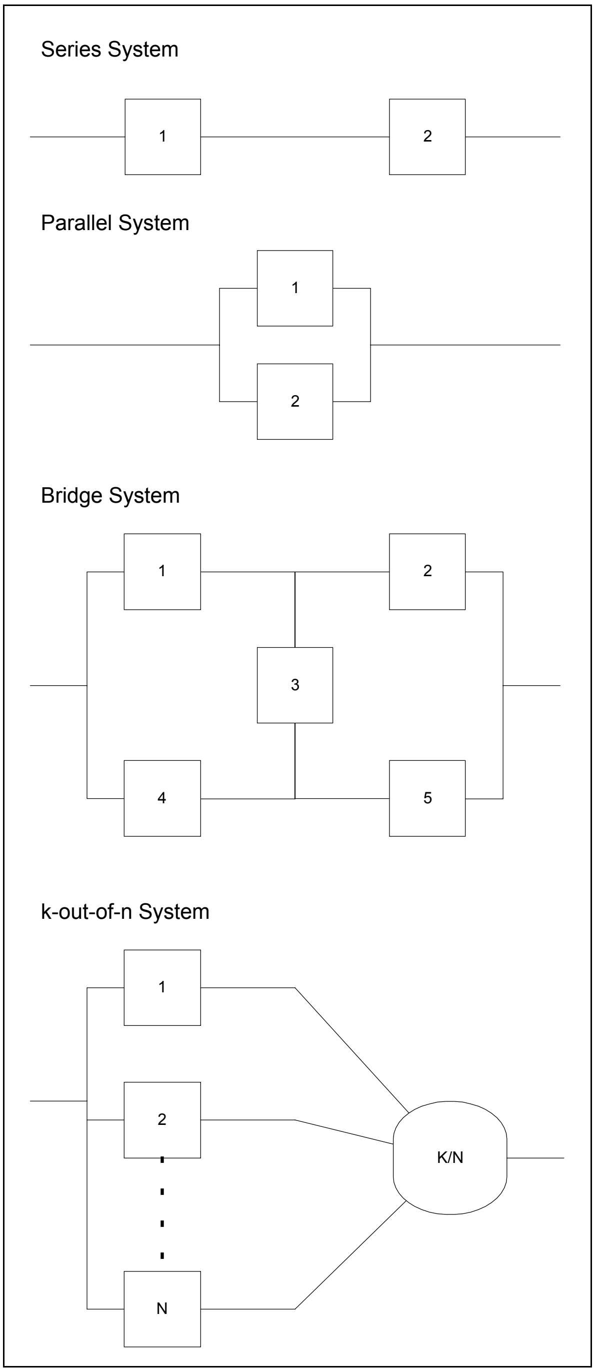

Figure 6: Reliability block diagrams.

The structure of a reliability block diagram defines the logical interaction of components and therefore failures within a system. Individual blocks may represent an individual component failure or sub-system failures. The logical flow of a reliability block diagram originates from an input node at the left hand side of the diagram to an output node at the right hand side of the diagram. Blocks are arranged in series, parallel, bridge or k-out-of-n configurations between the system input and output nodes.

The blocks of an RDB are independent, in that if one fails it should not cause the failure of another block. As power systems tend to be constructed in series and parallel configurations they are suitable for modelling with RDBs. For example a transformer is in series with the circuit breaker on the low voltage winding and with the cable connected to that circuit breaker, alternatively, generators and UPS systems frequently supply power in parallel arrangements.
A bridge configuration would be used for a system where two independently fed switchboards are connected via a bus coupler, the coupler forming the bridge. A k-out-of-n configuration would be employed for a system which required 2 out of 3 generators to function, with all generators being considered identical.

The calculations employed for simple series and parallel systems can be manually carried out quite easily but for more complicated systems and those with more than just a few components it is advisable to use software. Figure 6 depicts examples of these configurations.

Different reliability prediction methods are used for other types of systems, for example, electronic equipment can be modelled with the MIL-HDBK-217 method published by the US Department of Defence or with Bellcore published by AT&T Bell Labs. Mechanical equipment can be studied with NSWC published by the US Navy.

POWER SYSTEM COMPONENT SECTIONS

Earlier on in this paper certain sections of the power supply system were identified for individual study.

The first section is the primary power supply area or substation.

Substations

For the majority of installations the primary source of power is the regional electricity company (REC). Normally the REC will supply power at a voltage dependant upon the load requirement of the consumer. Typically in the UK, 400 volts three phase or 230 volts single phase for supplies up to 70kVA. For loads between 70kVA and 225kVA three phase supplies are usually used and for loads greater than 225 kVA a substation will often be required.

The power user does not have a great deal of influence on the reliability of the power supplies at this level, but there are sometimes certain options that can be selected which improve matters.

The substation consisting of one or more transformers and associated switchgear will transform voltages down from 11kV and higher voltages to 400 volts for use by the consumer. The substation is fed by one or more high voltage (HV) cables depending on the local availability and the required integrity of the substation.

In a recent study a comparison was made between having a connection to one or two independent 11kV supplies. The data in Table 1 shows the rates of failure in supply, that is breaks in power. A lower failure rate was expected for the case of two supplies, perhaps this anomaly was caused by a common cause failure at a higher voltage level.

TABLE 1 - Grid supply failure rates

Number of supplies	Failure rate per hour (λ)	MDT hours
1 HV ring	8.39 x 10-5	5.07
2 HV rings	6.13 x 10-5	0.59

From these figures it can be concluded that the MTBF of 1 HV ring is 11919 hours/1.36 years ($1/\lambda$), with 2 HV rings being 16313 hours/1.86 years.

The MDT of the single supply would certainly justify the provision of a back-up generator, as few UPS units would be expected to last for 5 hours.

Having a separate connection to 2 HV rings makes it possible to carry out any required maintenance on one, while maintaining supplies through the other. This principle obviously applies to all such parallel configurations.

To limit the possibility of common cause failure within a substation incoming supplies and transformers can be contained within separate substations or there can be a protective barrier within the common substation.

Table 2 shows information published by some of the regional electricity suppliers with respect to the reliability of their supplies as required by the Office of Gas and Electricity Markets, OFGEM. Their figures are for customers supplied at high or low voltage.

TABLE 2 - Quality of primary electricity supplies

Supplier		Minutes lost per connected customer	Interruptions per 100 connected customers
A	LV	7.6	4.2
	HV	58.9	76.8
B	LV	8.6	6.3
	HV	54.2	52.3
C	LV	13.7	7.3
	HV	48.1	57.4

These chosen suppliers cover regions in the north, middle and south of the UK and broadly show a consistency of performance. Certain locations will have significantly degraded performance but these tend to be averaged out over large regions and therefore do not show up in the overall performance figures. It is always necessary to question the local supplier about the reliability of the exact connection point.

In terms of the duration of the interruptions it is interesting to note, from published electricity supply company figures, that the vast majority of interruptions have a short duration with very few lasting longer than 5 seconds.

Within the substation the transformers may be oil filled or dry type as there is little difference between the relative reliabilities, suitability and price being the dominant factors. Transformers along with the other equipment involved with distribution, as opposed to supply of power, are relatively reliable and have quoted failure rates of between 0.0059 and 0.0153 per unit year depending upon their rating, in other words once every 65 to 170 years. By having 2 transformers in parallel and assuming the worst case for failures, the overall failure rate becomes 0.000063 per unit year or once every 15877 years. From a reliability perspective 1 transformer is probably reliable enough for most installations but having 2 makes the job of maintenance much easier and it is only with proper maintenance that these low failure rates can be relied upon.

If the supply from the REC becomes unavailable then back-up supplies are required and this is usually provided by generators, either diesel or in some cases gas turbine depending on requirements and suitability.

Generators

Most installations have diesel generators and these tend not to be run constantly and so have 2 failure figures. Failures per start attempt, typically 0.0135, and failures per hour in use, typically 0.00536. This means that when modelling a generator installation it is necessary to calculate how often per year it will start and how long it will run for.

Generators often suffer from poor maintenance, which directly affects their reliability. If a generator fails to start it is more often than not due to poor or no maintenance. An often overlooked part of this required maintenance is the regular running of the generators on load.

In larger installations it is common to have generators arranged in an n+1 configuration, that is, 2 generators might be sufficient to supply the load, but 3 are provided so that 1 can be maintained while the other 2 remain available or if one fails to start then another is available as a standby.

Generators combined with electricity company supplies provide a high level of supply reliability. A single generator with a single electricity company supply, using the figures so far stated would, assuming the generator started, have a failure rate of 0.00108 or 924 years, not including failures of cabling and switchgear.

Not forgetting the generator starting, based upon the number of required generator starts due to local electricity company supply failures, there would be 0.0101 failures to start first time per year or 1 failure every 98.7 years.

These figures do not reflect the loss of power for the short periods of time that it takes the generator to start or supply disturbances of short duration. It is during these events that uninterruptible power supplies support the critical loads independently of the primary power sources.

Uninterruptible power supplies (UPS)

A UPS is typically the main power conditioner for the critical loads. The output from the UPS is automatically controlled by electronic monitoring circuits to make sure that it supplies high quality amps at the desired voltage levels. Modern UPS systems are designed to be intrinsically reliable and good performance data is available for most systems, as their reliability has been monitored for some time.

It is important that the UPS keeps the supply of power to the critical loads continuous within tight tolerances otherwise failure might occur. With this in mind, whichever UPS technology is employed, it is essential that the UPS can be maintained without disrupting the load it supports. To this end, installations should have some form of paralleling or redundancy built in to the system to facilitate this maintenance.

Parallel or dual redundancy are expressions used to describe two UPS systems connected in parallel each supplying up to 50% of their rated load, if either were to fail the other supplies the entire load without interruption.

Standby parallel is similar but with one UPS in standby mode. If the other UPS fails the UPS in standby mode comes on line to supply the load.

N+1 configurations, as in generator installations, are often used to allow maintenance of the system without critical load support degradation.

Dual Conversion. The most commonly occurring type of UPS found supporting critical electrical loads uses a rectifier to convert mains a.c. current to d.c., the d.c. current is used to charge batteries and to supply an inverter. The inverter converts the d.c. current back to an a.c. sine wave, or similar shape, hence the term dual conversion. If the supply to the rectifier fails or goes outside predetermined tolerances the load is switched to the batteries without interruption of service. Figure 7 shows a representation of a typical system.

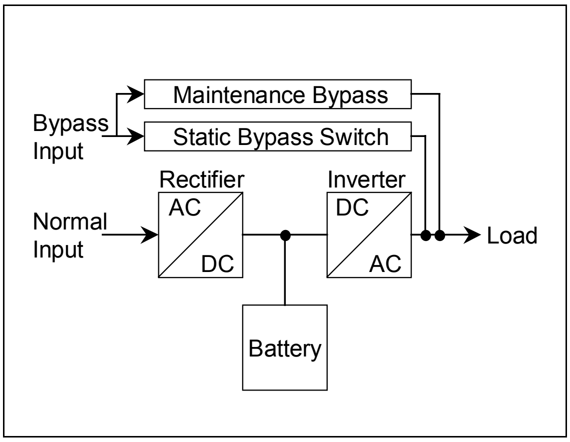

Figure 7: Dual conversion UPS schematic.

If there is a fault such as an overload then the UPS automatically switches to the static bypass and if required the UPS can be manually bypassed completely by using the maintenance bypass. The voltage and current supplied to the load is controlled by the inverter.

TABLE 3 - UPS configuration reliability data

Configuration	MTBF (hours)	Availability
1. UPS x 1 with a common Normal and Bypass Input supply	87000	0.9998851
2. UPS x 1 with separate Normal and Bypass Input Supply	310000	0.9999677
3. UPS x 2 with parallel redundancy configuration	400000	0.9999750
4, UPS x 2 with standby parallel configuration	500000	0.9999800

Reliability figures obtained from a reputable manufacture for various combinations of dual conversion installation are given in Table 3.

To put these figures in to perspective, the MTBF for configuration 3 is more than 45 years. These figures are rather pessimistic as they are based on a mains interruption or disturbance once every 100 hours with restoration within 0.1 hours, the majority would cease within one second.

Delta Conversion. Developed in Norway and currently available from a single manufacturer, due to patent restrictions, is a form of UPS similar in size and cost to an equivalent rated dual conversion system.

The delta conversion principle is based around the use of two invertors connected to a common battery.
The benefits of this system are that it has unity input power factor, draws sinusoidal current so does not create harmonic currents or voltages and is claimed to have an efficiency of greater than 95% for loads between 50% and 100% of rating.

The reliability of these systems, stated as 282000 hours for a single unit, is comparable with dual conversion systems.

Rotary and Hybrid Rotary. Rotary systems are based around the principle of an electric motor driving a shaft connected to an alternator, which supplies the critical load. With no electrical connection between motor and alternator the output is of a high quality, conditioned and separated from any mains supply disturbances. The shaft also drives a flywheel, which provides stability, and momentum should the mains supply fail, thereby maintaining the output of the alternator. This stored kinetic energy is also used to start a diesel engine connected to the same shaft via a clutch, which, once run up, takes over driving the shaft. This is an inherently reliable way of starting a diesel engine/generator, as there is no reliance on starting batteries. The UPS and generator are effectively combined in one unit. A schematic diagram of a simple rotary system is shown in Figure 8.

Hybrid systems are essentially the same but have no flywheel or attached diesel motor. They rely instead on batteries and require an additional generator if the load is to be supported for any prolonged period of time following mains failure.

Rotary units are often only cost effective for UPS loads of greater than 1.0MVA, they normally cost 10-15% more than static systems and have the installation constraints normally associated with generators such as noise, vibration, heat removal, air supply, exhaust flues, fuel supply etc. Rotary systems provide very high quality output power, are self-contained so no cabling or switchgear between generator and UPS need occur, are tolerant to higher temperatures than typical static systems and can be paralleled to provide redundancy. Rotary systems typically require less space that static UPS systems when battery installation and generator are taken in to account.

From a reliability perspective, rotary systems are very good with at least one manufacturer quoting MTBF figures of 1,380,000 hours for a single system.

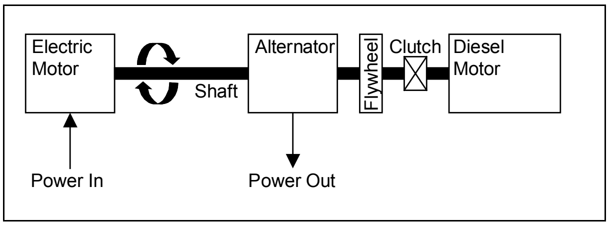

Figure 8: Rotary UPS schematic.

Flywheels. Various battery-free ‘compact’ flywheel systems are available, mainly as yet for the US market it would appear. These systems store energy in an integral rotating flywheel which is sufficient for short duration interruptions, up to 25 seconds at 50% load, for longer interruptions a diesel engine powered generator is started and the UPS load smoothly transferred to the generator. The advantages of this system are that it has approximately the same footprint as a traditional dual conversion UPS unit but without the battery racks, no batteries also means better tolerance to higher temperatures, less maintenance and less weight. The system is also reported to be efficient to the order of 97% at full load and have a low harmonic current impact. The manufacturer states that the MTBF figures for this system are similar to that of conventional double conversion units with lead acid batteries.
As most disturbances have a duration of less than a couple of seconds this type of system would be suitable for many applications, although doubts over the support generator starting for longer outages might hold back some users.

Batteries. All static UPS systems and some of the rotary systems require batteries to provide power to the critical loads once the energy stored internally in their circuits has been expended.

These batteries are usually housed in racks or cabinets in close proximity to the UPS systems themselves to minimise the lengths of d.c. cabling between UPS and battery.

The majority of battery installations for UPS usage are of the sealed lead acid or valve regulated lead acid type. These batteries are heavy, take up a lot of space and are relatively expensive. Under ideal conditions the individual cells, which make up the battery installation, often have a stated design life of up to 10 years, which means in effect that many cells will have failed before the end of the ten year period, therefore regular testing or monitoring equipment is required to identify failed cells for replacement, otherwise the support period of the UPS can not be relied upon. It is important that the battery cells are maintained at their optimum temperature of 15 - 25 °C otherwise their operational life will be significantly shortened.

In some instances it might appear advantageous to share a common battery between two UPS or to have a manual switch to connect two batteries together. This is not normally recommended as a potential common cause failure is being introduced to the installation, degrading the benefits of having 2 UPS.

Normally the battery installation should support the critical loads for the period of time it takes to safely shut down those loads, plus a reasonable period of time to allow the generator with several re-start attempts. It is not normally practical to expect the batteries to support the critical loads for prolonged power outages.

RELIABILITY IMPROVEMENT & MAINTENANCE

If the system is being designed from scratch, then the designer has some luxury in being able to make selections within a budget to achieve a predefined estimation of reliability.

The level of reliability required varies between applications. A measure of the requirement, sometimes referred to as '9s of reliability', has been quoted as 99.99% for factories, 99.999% for hospitals, 99.9999% for banks and 99.99999% for online markets.

Apart from back up supply generators and UPS systems there are some steps that the designer can take to mitigate risk and improve reliability.

To minimise common cause failures there should be diversification of supply cables from power sources to critical loads and if a component is part of the critical path, then if possible, it should be duplicated and staying with cables, their lengths should be as short as possible as the reliability of a cable is proportional to its length.

Maintain up to date protection grading records of all circuits to ensure that protection devices co-ordinate properly.

Evaluate and remove if possible the potential risks to the critical supply components, such as mechanical damage and corrosion, fire and heat, flooding and humidity, vandalism and theft, lightning and other weather occurrences such as wind.

Keep the design as simple as possible so that others can easily understand its operation and there is no likelihood of misunderstanding.

Maintenance, regular and thorough, is one of the most significant aspects. The majority of systems failures experienced by this author have been attributable to problems with maintenance.
Keeping spares on site and having a quick response time from the local service provider can also help.

Surge suppression devices on the main distribution board will protect electronics, such as UPS systems from most surges.

Harmonic loads are endemic in modern installations, so double sized neutral cables for the high currents should be used for all 3 phase circuits with regular monitoring of the harmonic profile. Permanent monitoring equipment might even be considered. Active harmonic filtering devices should be allowed for at the time of system conception even if not actually installed.

Power factor correction equipment is not normally worthwhile with modern equipment unless its main purpose is as an harmonic filter. It will need regular maintenance particularly with harmonic loads, could be a source of failure and needs setting up properly or can resonate with active compensation units.

If fuses can be used to protect circuits then they require less maintenance than circuit breakers although both have low failure rates.

When carrying out reliability studies it must be remembered that any results obtained are usually only valid if all the equipment is maintained, to the level prescribed by the equipment manufacturers.

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