Copper Development Association

Electrical Design

A Good Practice Guide

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Electrical Design

A Good Practice Guide

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Copper Development Association

Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and user industries and maintains close contact with other copper development associations throughout the world.

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Preface

This book is concerned with the design of electrical installations in buildings with particular reference to the growing incidence of power quality problems and energy efficiency considerations. It presents good practice design solutions to reduce the impact of power quality problems and explains how electrical efficiency can be improved.

Business and financial managers will find much of the material readily accessible despite it's technical bias and will gain a good understanding of the problems, risks and consequential costs that face their organisations.

Technical staff, including electrical designers and installation and maintenance engineers, will find detailed information on the causes of power quality problems and strategies for the reduction of their impact.

The cost of power quality problems can be very high and include the cost of downtime, loss of customer confidence and, in some cases, equipment damage. The recovery of lost data, including re-entry and re-verification can be very expensive indeed. The unpredictability of this disruption to business operations aggravates the problem and significant management intervention is often required to ensure that recovery operations are carried out logically and efficiently to restore essential business services as quickly as possible. It has been estimated that 70% of those companies who suffer a major computer disaster fail completely within 18 months.

Power problems arise primarily from two causes: interruptions in the public supply, and deficiencies in the customer's installation. On average, the public supply will be unavailable for about 100 minutes per year, but it is frequently blamed for the many other problems that really arise either in the customer's own installation or in a neighbouring installation.

This publication explains how to identify potential problem areas and design and maintain resilient power systems that are largely immune to both supply and installation problems.

Electricity is a very expensive fuel and as much as 8% of the electricity bought by industry is wasted by the use of inefficient plant and poor installation practices. Efficiency can be greatly improved at no cost by careful plant selection and good installation design. Happily, the measures required to improve resilience and those required to improve efficiency are complimentary.

The solutions presented are not difficult to implement, especially when introduced early in the design or refurbishment cycle. Well-planned installations, taking into account the types and numbers of loads, with due allowance for load growth, will have substantially reduced incidence of problems and lower running costs over the whole life of the installation. These benefits will be gained with little or no increase in initial installation cost.

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New problems are arising in electrical services installations in today's high-density commercial and industrial buildings, largely caused by quantity of electronic equipment in use. At the same time, the efficiency of electrical plant is being examined more carefully as concern over the release of greenhouse gasses grows. This publication examines the associated risks and costs and discusses how good design practices can reduce them.

The potential costs to businesses of power failures and disturbances can be very high indeed and managers need to understand the risks and know how they can be assessed and reduced.

The term 'good power quality' can be used to describe a power supply that is always available, always within voltage and frequency tolerances, and has a pure noise-free sinusoidal wave shape. 'Poor power quality' describes any supply that deviates from this ideal; whether or not the deviation is important depends entirely on the purpose of the installation, the design of the equipment and the design of the installation. Poor power quality may be apparent as supply interruptions, voltage dips, transients and noise, harmonic distortion or earth leakage.

Some risks, such as a failure in the supply distribution system, are outside the direct control of the user but it is important to realise that the impact of such a failure can be reduced if appropriate measures are taken in the design of the installation. Risk reduction may require the provision of an un-interruptible power supply, a local standby generator, a second redundant feed from the National Grid or a combination of any of these. The costs can vary over a wide range, and must be balanced against the potential risk. Many enterprises where data is central to the operation will find the extra investment worthwhile. In safety critical or data critical operations, where the cost of the potential disruption can be high in terms of human life or financial impact, even high cost solutions will be fully justified.

Other risks arise from the design of the user’s installation, the specification of the electrical plant or the type of equipment required by the nature of the business activity. The layout of the cabling and cross-sectional area of the conductors may not have been specified with harmonic generating loads in mind, so that interference and overheating may result. Separate circuits may not have been provided for heavy motor loads, so that switching produces transient spikes and the starting current causes voltage dips that can adversely affect other, more sensitive, equipment. Computer equipment, in common with most modern electronic equipment, makes use of switched mode power supplies. These are smaller, lighter and more efficient than traditional transformer units but have the major disadvantage that they generate high levels of harmonic currents in the mains supply. Where a number of computers is installed, these harmonic currents can reach high levels, especially in the neutral of three-phase supplies, leading to overheating and the risk of fire. Such equipment also produces earth leakage currents that have serious safety implications in many installations and may cause interference and data loss in communications systems.

A well-designed electrical system will also take account of energy efficiency. Not only should high-efficiency plant, such as energy efficient motors and transformers, be selected, but the best practice low loss installation standards should also be applied. Often this means using conductors that are two standard sizes larger than the minimum size for thermal safety suggested by national codes. Although the larger cable is more expensive to purchase, the total installation cost is only slightly increased, and the outlay is quickly recovered in lower fuel bills.

The publication is divided into the following sections:

- Overview of electricity supply and the cost of failure
- Reliability
- Power quality
- Harmonics
- Earth leakage
- Energy efficiency
- Future trends

Section 1 - Overview of electricity supply and the cost of failure

The structure of the electricity supply industry and the supply availability that can be expected is outlined and the financial impact of power failures and poor power quality are examined.

Section 2 - Reliability

This section discusses measures to ensure that the reliability of the supply is appropriate to the nature of the operation, for example by the provision of un-interruptible power supply (UPS) units, or by providing dual circuits in critical areas. Background theory and example calculations are presented.

Section 3,4, 5 and 6 - Power Quality, Harmonics, Earth Leakage and Voltage Dips and Transients

Power quality problems have become very important in recent years. The term is used to encompass supply defects, such as:

- harmonic problems
- earth leakage and noise problems
- transients, voltage dips and interruptions

The causes, symptoms and solutions are discussed in three separate sections.

Section 7 - Energy Efficiency

It is not generally realised that up to 8% of electricity bought by customers is wasted due to poor installation practice and poor selection of plant. Installation Standards specify minimum cable sizes consistent with thermal safety, i.e. such that the temperature is just low enough not to cause failure of the insulation. This means that many cables run at temperatures of up to 70°C or even 90°C and the energy to generate this heat is being paid for. When the cost of this energy is taken into account in a whole lifetime calculation it is apparent that the lowest overall cost is achieved by installing larger cables giving lower running costs.

Motors consume about £4 billion worth of electricity every year in the UK. The use of high efficiency motors, now available with no price premium, would reduce UK industrial electricity bills by about £300 million per year.

A complete publication on efficiency, ‘Electrical Energy Efficiency’, Publication 116, is available from CDA.

Section 8 – Future Trends

This section looks at factors influencing future installation practice, such as the age of building stock, load growth, flexibility and cost.

1. Overview of Electricity Supply and the Cost of Failure

1.1. Electricity supply in the UK

The electricity industry in England and Wales is logically split into Generators (who produce electricity) and Suppliers (who buy from the generators and sell to users) who trade electricity through the Electricity Pool. In reality, many companies are both suppliers and generators. The Pool is regulated by its members and operated by the National Grid Company who also own and operate the distribution grid. Commercial contracts between the generators and suppliers are used to hedge against the uncertainty of future prices in the pool. Electricité de France (EdF), Scottish Power and Scottish Hydro Power are external members of the Pool and each of these has a number of commercially negotiated contracts to sell electricity to the suppliers in England and Wales. The Regional Electricity Companies (RECs) supply electricity to customers in their own area but may also compete to supply customers nation-wide. The main generators also operate their own supply businesses, as do some other companies such as Scottish Power, Scottish Hydro Power, individual large users and trading companies.

Progressively since 1990, large customers, initially those with peak loads greater than 1 MW and now those over 100 kW, have been able to select their supplier. By early 1995, 75% of supplies to non-domestic customers were from a supplier other than the geographically appropriate REC. Of course, whoever supplies the electricity, it arrives at the customer's site over the distribution system belonging to the geographically local REC. As far as security of supply is concerned, it is the REC responsible for delivery of the power that matters as far as reliability is concerned.

Domestic and small industrial users buy their electricity from the local REC at controlled fixed prices. By contrast, the Pool price is set half-hourly to reflect the supply situation prevailing at the time.

Although the average industrial price in 1994 was 4.43p per kWh, the actual Pool price varies greatly; on two occasions in December 1995, poor weather conditions caused abnormally high demand resulting in a Pool price of over £1 per kWh. Several industrial users were forced to temporarily shut down their operations as a result.

In 1994 7% of the generated energy, amounting to over 24 TWh - worth £1 billion, was attributed to transmission losses (including measurement errors), while electricity imported via the Anglo-French sub-channel link made up 2% of the total available power. Short-term non-availability of this link, together with the longer-term failure of a relatively few items of equipment at UK power stations threatened large-scale power blackouts on at least four occasions in the first half of 1996.

1.2. Supply availability statistic for UK

In 1995/6, the Utilities in the UK achieved an average supply availability of 99.98%[1]. This seems very impressive, but to the average customer it represents unpredictable disconnections totalling 97 minutes per year with 90% of all customers experiencing one or more interruptions.

These performance figures are somewhat misleading because interruptions of less than one minute are not reported. To many commercial operations, an interruption of just 1 second is as disruptive as one of, say, ten minutes. For example, if a computer system loses power all the in-hand data will be lost and older data already stored may be corrupted. Recovery will require re-booting of the system, verification and restoration of older data and re-entry of recent data. The duration of the power cut is of little concern! Short interruptions (less than one minute) are very common and most are caused by auto-reclosers operating to clear transient faults that might otherwise have become longer duration interruptions. Such problems must now be seen as a fact of life and it is left to the customer to take steps to protect his operation.

As would be expected there are wide variations among the RECs; rural areas are more likely to experience power interruptions and it is likely that restoration will take longer. For 1995/6 average total disconnection rates ranged from 33 to 223 per 100 customers per year with total disconnection times from 54 minutes to 233 minutes per customer per year. Over the last ten years, the best and worst disconnection levels achieved were 20 and 285 disconnections per 100 customers per year with total disconnection times from 45 to 1300 minutes per customer per year.

There are no national statistics for other power quality defects, such as voltage dips, transients and harmonic pollution, but the number of customer complaints received by OFFER concerning the quality of supply rose by 23% in 1996 and has risen by 41% between 1991 and 1996. These figures include complaints relating to interruptions.

The susceptibility of the supply network to harmonic pollution is partly determined by the impedance of the lines - this is explained in Section 2.5.5. Since the UK has maintained a narrow voltage tolerance since 1937, the impedance of the system is generally lower than that found in other countries. The Table 1 below shows the phase to neutral impedance for consumers in various countries. (Note that tap changing is employed to maintain the voltage within tolerance – much lower source impedance would otherwise be required.) These are average figures; they reflect wide variations in the balance between rural and urban areas as well as differences in national policy.

Table 1 - Typical supply impedance in different countries

Country	**Impedance (Ω)**			
	98%	**95%**	**90%**	**85%**
Belgium		0.63 + j0.33	0.32 + j0.17	0.28 + j0.15
France		0.55 + j0.34	0.45 + j0.25	0.34 + j0.21
Germany		0.45 +j0.25	0.36 + j0.21	0.31 + j0.17
Ireland	1.47 + j0.64	1.26 + j0.60	1.03 + j0.55	0.94 + j0.43
Italy		0.59 + j0.32	0.48 + j0.26	0.44 + j0.24
Netherlands		0.70 + j0.25	0.41 + j0.21	0.32 + j0.17
Switzerland		0.60 + j0.36	0.42 + j0.25	0.30 + j0.18
United Kingdom	0.46 + j0.45		0.25 + j0.23	
USSR		0.63 + j0.30	0.50 + j0.26	

1.3. Financial impact of power supply failure

1.3.1. Introduction

The effect of power failure on the activities of an enterprise depends on many factors, not least on the nature of the business. Data processing activities are particularly susceptible, especially if data must be processed in real time such as stock trading and banking transaction processing. Current data will be lost, data storage devices may be corrupted and the whole network will have to be rebooted - a process which can take several hours. Lost data must be restored from backup and that which had not yet been backed-up must be re-keyed. As well as the cost of this recovery exercise and the break in customer service, there may be longer-term effects due to loss of customer confidence plus the possibility of introducing new errors.

In industrial processing, a power failure will halt production which, in a continuous process, may result in the waste of feed stocks and cause considerable expense in the removal and disposal of partially processed product. If the plant is producing manufactured items for stock, the business disruption may be tolerable, but if the product has a limited market lifetime, such as a national daily newspaper, the effect can be catastrophic. Following a missed edition, sales of daily titles remain depressed for an extended period of several weeks.

Hospitals are particularly at risk. Modern medicine relies heavily on electronic monitoring, and failure of the supply or equipment may result in loss of life. In a recent case in Honduras fourteen intensive care patients died during a power failure caused by rodent damage to the electrical installation.

The acceptable risk can be judged only by those responsible for running the enterprise, but decisions should be the result of careful assessment of the likely cost of failure and the identifiable cost of prevention. It must be borne in mind that protection has only to be bought once; disasters do strike twice.

Research in the United States [α] shows that only 43% of businesses that suffer a disaster ever resume business and only 29% of these are in business two years later. Of those businesses which lost their data centre for ten days or more 93% went bankrupt within one year.

No overall figures are available for the costs incurred as a result of power failures, possibly because many managements would find them acutely embarrassing. However, a recent study [β] has examined the incidence of problems associated with computer systems and this is discussed in the next section.

Computer Installation Losses

MACE (Management Accountancy Computer Education) estimate that in the UK there are 80,000 businesses with computer installations which report on average, 60 computer disasters per annum which are classified as 'advanced', 'critical' or 'intense'. These terms are defined as:

'Advanced' an interruption to the workload which will cause an extended but known delay in user's services

'Critical' an interruption which forces the computer site to shut down - some data loss due to the shutdown, but backups can be used to restore the missing data

'Intense' an interruption that will result in major financial loss or put the survival of the company at stake - the equipment is a total write off.

These 80,000 computer installations are made up of over 100,000 mainframe, mini-computers and workstations, together with a further 2.5 million PCs of which over 50% are networked.

The estimated annual losses from 1989 to 1995 are shown in Table 2.

Table 2 - Estimated annual losses to UK business from computer system disasters

Year	Annual Loss (£ Billion)
1989	3.87
1990	3.09
1991	2.73
1992	2.87
1993	2.90
1994	2.91
1995	2.94

The annual losses reported above can be attributed to a wide range of causes including:

Contamination (e.g. dust)	Fire/Smoke/High winds	Water (leakage/floods)
Abnormal heat/humidity	Infestation (insects/rodents)	Staff-related
Theft	Unreliable power supplies	System design failures

α National Archives and Records Administration, Washington, DC.

β Management Accountancy Computer Education study.

Effect of Power related failure

MACE estimate that up to 60% of computer system service calls are power related and that approximately 28% of computer system breakdowns are the result of power failure. This would imply that of the 1995 losses of £2.94bn, about £800m could be power related.

Typical effects of power failure and disturbance are: -

Blackout	Damage to storage drives, Data loss
Brownout	Overheating, Corrupted data
Transient Noise	Damage to storage drives, Component stress, Data interruption/loss
Frequency Variations, Surges, Sags	Component stress, Unreliable data, Data interruption/loss

Consequences of Power-related Failures

The main consequences of power failure impacting on computer systems can be categorised as follows:

- Costly computer system downtime - several hours to reconfigure a network.
- Corrupted data and keyboard lock-ups.
- Loss of operational data.
- Loss of communications.

1.3.2. Insurance industry statistics

Telephone discussions were conducted with a number of insurance companies as well as relevant organisations - Loss Prevention Council, Association of British Insurers, AIRMIC (Association of Insurers and Risk Managers) - to gauge the level of interest in, and importance attributed to, the issue of power quality.

The main organisation in the UK producing statistics on insurance claims is the Association of British Insurers (ABI). While the ABI does not produce statistics on claims resulting from problems with electrical installations, it does produce statistics on fire and business interruption. The statistics are based on information supplied by both members and non-members of the Association.

Table 3 - Business interruption and fire insurance claims statistics - gross incurred claims

Year	Fire Insurance	Business Interruption Claims		
	Commercial Claims (£m)	Following Fire Damage (£m)	Following Weather Damage (£m)	TOTAL (£m)
1992	**613**	139	2	**140**
1993	**423**	104	7	**111**
1994	**424**	188	17	**205**
1995	**492**	163	12	**175**
1996	**495**	179	26	**206**

Insurance industry sources suggest that the causal/contributory element attributable to inadequate electrical installations may be as high as 20% - about £100m in 1996 in the case of fire claims and up to £40m of business interruption.

Business interruption insurance makes good reduction in profit or increased costs incurred in keeping the business going following physical damage to the insured business or, in certain circumstances, that of neighbouring or supplying businesses. Business interruption insurance is available from general insurers against losses from, for example, fire and flood. However, it does not cover loss of profit arising from the breakdown of plant and machinery, as this specifically requires an engineering business interruption policy for which statistics are not available.

1.3.3. Insurers response

A small number of insurance companies, brokers and risk specialists in the UK do offer computer coverage. Awareness of the importance of power quality among insurers is low, although premium reductions are often attainable if the prospective insured has the following attributes:

- A comprehensive contingency plan in place and tested
- Uninterruptible power supplies installed
- Emergency power system capable of 10 minutes of sustained power.

1.3.4. Financial impact

This section has identified many of the costs associated with power failure and power disturbances. The magnitude of these costs will vary enormously across different industries depending on the type of activity and safety issues but most managers will be able to identify and quantify the risks facing their own operations. Once the risks have been quantified, an assessment of the appropriate preventative measures can be made using the following sections for guidance.

2. Reliability In Electrical Power Systems

The subject of reliability is perhaps less familiar to the building services engineer than to engineers in the telecommunications and electronics industry where reliability predictions are common practice. In this section, topics such as redundancy, resilience and parallel paths are introduced and the principles behind reliability in electrical power distribution systems are explained.

The concept of reliability became important in the mid-1940s when the complexity of systems began to increase rapidly as the electronic content grew. The development of advanced weapons systems and the early work on electronic computers stimulated the study of reliability. More recently, with the application of complex electrical and electronic systems in the telecommunications, nuclear and space industries, a complete new science of reliability has emerged. In the context of this publication we are concerned only with reliability as it is applied to the power distribution system and not with the equipment it powers.

The reliability expectations of power distribution systems have increased because of the critical nature of some of the systems supplied and the high costs associated with failures. For example loss of power to an air traffic control installation or a medical system could be life threatening and it is common for such sites to have a standby supply of some sort. Power loss to a computer data processing system can incur high costs due to loss of data and long recovery periods. The larger the computer system, the longer will be the recovery period after a power supply disruption and, for some of the larger installations, this can be 7 hours or more.

Data processing installations are now extremely important to commerce and industry and consequently feature strongly in the examples and illustrations given here. This is not meant to imply that they are the only important types of installation; production processes are also badly affected by power failure resulting in waste of raw materials, lost production time and wage costs. However, since computer systems are now central to almost every enterprise, they are used as an example to which most managers and engineers will easily relate.

Computer systems are notoriously sensitive to poor quality mains supplies and the Electric Data Processing (EDP) supply specification is much tighter than any mains supply specification. Tolerances for durations of less than 10ms are typically: -

Voltage	± 5%	
Frequency	50Hz ± 1%	i.e. 49.5 to 50.5Hz

For personal computer systems the requirements are: -

No deviation or break	>15ms
Spike free	>1kV
Total harmonic voltage distortion	<10%
Voltage, steady state	±1%
Frequency, dynamic	±1%
Slew rate (Rate of change of frequency)	<0.5Hz/s
Neutral-earth potential difference	<5V

No electricity supplier could provide a public supply meeting these specifications at an economic price level, so the user must install suitable power conditioning and distribution equipment to provide the required level of security. Of course, the extra equipment will contribute an unreliability of its own which must be taken into account.

Availability

A major consideration for system designers and users is service availability, that is, the proportion of time that an adequate service is provided. Availability must be carefully specified; the power supply availability may be 0.999886, equivalent to one hour total non-availability in one year, but the system availability will be less because of the time required to re-establish operations.

As an example, for a computer network requiring 7 hours to re-boot and restore, a single one hour interruption per year would result in a non-availability of 8 hours - an overall availability of 0.9991. If the power supply failed for 10 seconds every day - equivalent to one hour per year - then the non-availability would be seven hours per day, or 2,555 hours per year, an availability of only 0.71. The availability of the power supply has not changed, but that of the system has been seriously reduced by the frequency of supply interruption.

While the former scenario may be tolerable for some operations, the latter would certainly be totally unacceptable. Availability may be an important specification but it does not tell the whole story and must be interpreted carefully. This subject is discussed in more detail further on in this section.

Reliability, resilience and redundancy

Reliability is a measure of the probability that a component or system will remain operational for the required lifetime. Methods of calculating overall reliability from that of the individual components are given in Section 2.3.2.

Resilience is the ability of a system to remain operational after the failure of at least one of its components. Usually this is achieved by providing parallel paths so that failure of one of them does not cause the whole system to fail; i.e. at least one path is *redundant* in normal operation. Because a resilient system must experience more than one failure before becoming unserviceable, overall system reliability is improved. If good maintenance procedures are in place the failure in the redundant path should have been repaired well before a second failure occurs.

2.1. Examples of current trends in reliability

The objective of modern installation design is to provide a continuous supply to critical loads. In most situations, the steps taken to achieve this will include some of the following: -

- Provision of a separate, independent supply from the grid
- Provision of a standby generator
- Provision of an uninterruptible power supply
- Dualling of the distribution system, including any local transformers, busbars etc.
- Separation of critical and non-critical loads
- Provision of maintenance facilities to enable servicing without removing power from critical loads.

The implementation of some of these steps has been eased by two particular product developments; the static transfer switch and transistorised static UPS modules with digital control.

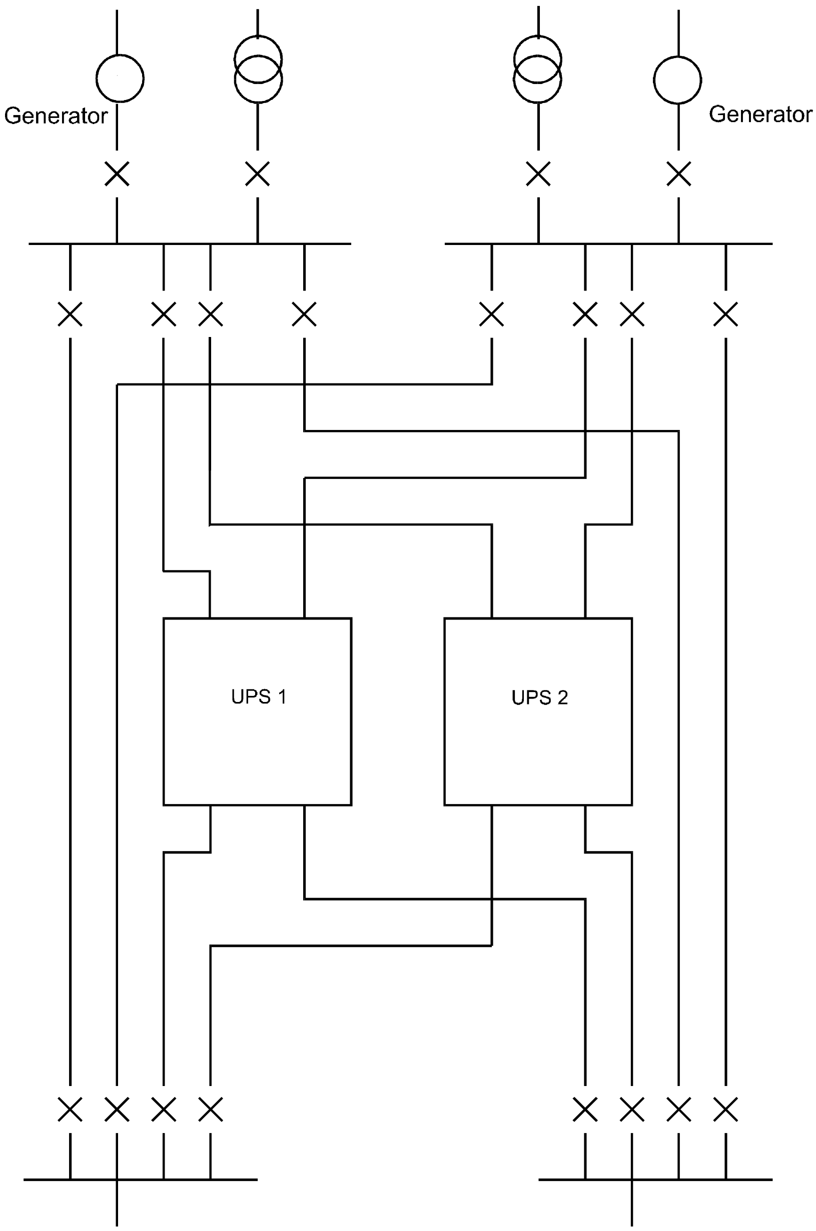
Two independent on-line strings in parallel

A dual string installation is shown in Figure 1. This design has two independent supplies from separate grid points backed up by two independent standby generators. Power from either input rail can be routed to either or both output rails directly or via either of two UPS units. Static transfer switches (STS) are used to connect and isolate equipment and paths as required. This example is symmetrical and assumes that the loads on each output are equally critical; in other circumstances, one output may be used to supply highly critical loads while the other supplies normal loads. In normal service power from one supply would be routed to both outputs via a UPS. In the event of a supply failure, connection would be made to the alternate supply with the UPS providing power during the short changeover period. If the alternate supply were unavailable, then a standby generator would be started and once up to speed, connected to the system; again a UPS would provide power during the start-up delay. If both supplies and both generators should fail, or be out of service for maintenance, then the UPS units would be used to supply the output rails independently. Load shedding would then be applied to extend the life of the supply.

This is an extreme example. It would be expensive to implement but may be justifiable in situations where loss of life or serious financial loss may result from failure. It is used to illustrate what can be achieved; a subset of this system would be appropriate in most cases based on a critical examination of the risks involved and the cost of protection.

It is worth noting that the control algorithm (which would probably be semi-automatic with manual intervention) for a scheme such as this would be somewhat complex and would itself require a careful reliability study.

Figure 1 - Two independent on-line strings



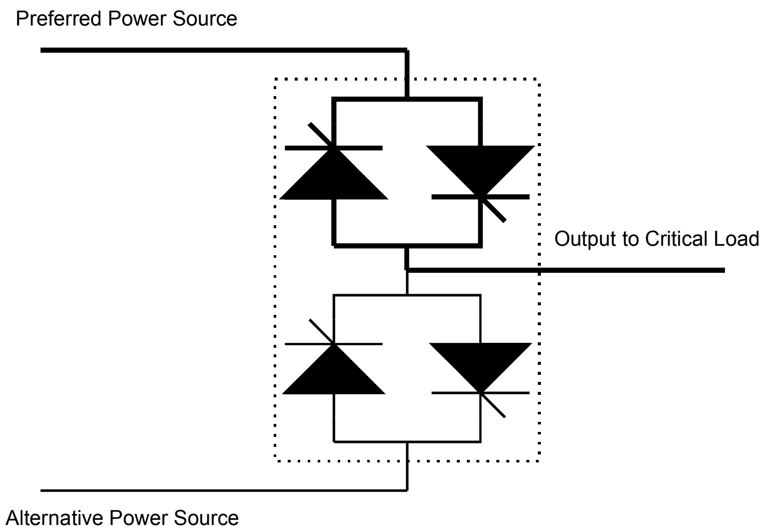
Static transfer switch

The primary purpose of the static transfer switch (STS) is to allow virtually uninterrupted transfer of the critical load from one AC power source to another. It can switch between two or more power sources or loads at high speed in response to a small control signal, has very low resistance when turned 'on' and very high impedance when switched 'off'. A fast break-before-make switching scheme is employed to avoid overlapping transfers (connecting together the two sources).

The STS is based on a solid-state device, the thyristor or silicon controlled rectifier (SCR). The thyristor is a rectifier (i.e. it conducts in only one direction) which can be controlled by a relatively small gate current. If the gate current is flowing, then the main load current will also flow. Once established, forward conduction will continue - even if the gate current is removed - and will only cease when the load current reduces to less than the minimum holding value for the device. This will happen at the end of each half-cycle when the applied voltage reverses, so the device must be turned on at the start of each half-cycle. Since the thyristor is unidirectional, two anti-parallel devices are required to conduct AC.

Figure 2 shows a single-phase two-way STS.

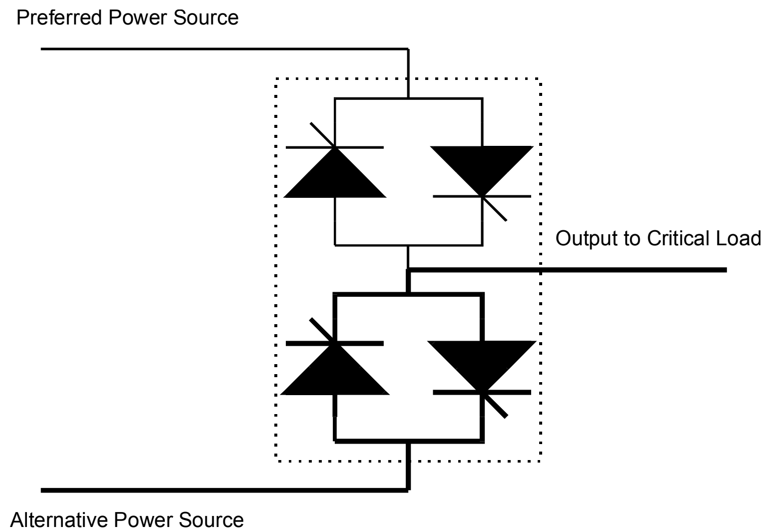
Figure 2 - Static transfer switch in normal position



During normal operation, the pair of thyristors associated with the preferred source are turned on at the start of each half-cycle, while those associated with the alternate source are not (in Figure 2, the bold lines denote conduction).

Sensing circuits constantly monitor the states of the preferred and alternate sources and feed the information to a supervisory microprocessor controller. Upon sensing the loss of the preferred source, the microprocessor control stops providing gate currents to the preferred-side thyristors and, when the preferred-side current is zero, provides gate current to the thyristors on the alternate side (denoted by the bold lines in Figure 3). The transfer from the preferred to the alternate source is so fast (normally less than ¼ electrical cycle), that even the most sensitive electrical or electronic loads are unable to determine its occurrence.

Figure 3 - Static transfer switch in alternate position



Since it is entirely based on solid state technology, the STS has no mechanical moving parts and thus requires minimal maintenance. It has an AC to AC efficiency between 98% and 99% and so does not require any dedicated air conditioning.

An STS coupled with two or more sources of power has been used instead of a UPS, the advantage being that there is no requirement for batteries or routine maintenance. For this approach to be effective the two power sources must be truly independent (i.e. they will not both fail as a result of a single failure either on-site or in the grid distribution system) and must be continuously available (there is no time to wait for a generator to start up!).

Transistorised static UPS module with digital control

Until recently, transistorised UPS modules have been limited to about 400kVA because of the size of transistors available. Now modules are available up to 1200kVA coupled with the digital control that allows fast reaction to load variations.

The advantages of the new transistorised UPS modules are as follows: -

1. Low output voltage distortion (providing the crest factor of the module is not exceeded).
2. Fast transfer to bypass.
3. Compact construction.
4. Ability to handle load disturbances.
5. Low cost.

Taken together, these developments have allowed engineers to design extremely robust power distribution systems for critical loads.

2.2. The importance of reliability assessment

Improving reliability will always involve some additional expenditure because, for example, redundant paths require additional cabling and equipment and high reliability equipment may attract premium prices. There will be many routes to achieving a particular level of reliability for an installation and each will have an associated cost. Selecting the optimum approach requires a careful analysis of the site requirements, the financial, business and safety risks posed by failure and the cost of each solution.

An understanding of reliability principles will allow systems to be designed for specific degrees of reliability and service availability by, for instance, using appropriate amounts of redundancy. System designers and planners can make informed decisions about the trade-offs between reliability and costs and can allocate the reliability requirements among the various elements of a system in order to minimise overall costs.

As technology advances and electro-mechanical devices are replaced by solid state devices, it is generally assumed that new systems will be more reliable than their predecessors. However, the increasing complexity of solid-state systems means that there are many more components involved, each of which has a finite reliability. The probability of failure must be minimised by careful design and by introducing redundant elements arranged so that they can take over until the faulty elements have been identified and repaired.

2.2.1. Purpose of reliability assessment

The principal purposes of reliability assessment, taken from BS5760: Part 2 1994, 'Guide to the Assessment of Reliability', includes the following:

(a) to provide an early indication of the potential of a system to meet a stated reliability requirement;

(b) to reveal aspects of the design that require particular attention to reliability or that present high risks in relation to the requirements;

(c) to provide as basis for reliability apportionment (*e.g. for use by sub-contractors whose subsystems are required to meet reliability requirements delegated to them*) and also to establish the reliability required of an item;

(d) to provide inputs to studies that may influence product design, such as design reviews, design evaluation, trade-off studies, life cycle costing, maintenance support, logistics studies and safety analysis. For example, assessment may highlight particular areas where an acceptable relaxation in performance could produce a major saving in life cycle costs;

(e) to establish whether the production process has adversely affected reliability;

(f) to establish whether an item in service has performed or is performing with the reliability required, and whether it is likely to continue performing adequately for the remainder of its generated life;

(g) to contribute to safety studies of an item (*it is necessary to distinguish between the operation and the safety requirements for reliability*);

(h) to estimate and control the effects of design changes on reliability;

(i) to provide input to logistic support analysis, spares ranging and scaling, hazard analysis and related maintenance studies.

In any assessment it is important to present the information results clearly with any limitations and assumptions clearly identified. Reliability assessments are an *aid* to good engineering but cannot function alone. The designer must carefully interpret the results to ensure that the optimum solution is achieved.

2.2.2. Benefits of reliability assessments

Reliability assessments enable system designers and planners to make informed judgements and decisions about the: -

- choice of system configuration
- manufacturer of the equipment
- type of components/equipment
- interface to other equipment
- trade-offs between reliability and cost
- choice of system that best meets the client's brief

The assessment provides a failure probability figure for the system based upon known or estimated statistical failure rates for each component. It does not indicate that the system will not fail more frequently - it is a guide to the *average* reliability. No manufacturer can provide a lifetime guarantee for the reliability of their products!

2.2.3. Assessing reliability

The following are some of the factors that contribute to the difficulty of assessing reliability accurately.

- Inconsistency in manufacture - not all components will have exactly the same lifetime
- Consequential damage (or over-stressing) of a component caused by partial or catastrophic failure of another
- Incomplete repair, e.g. components which may have been over-stressed by the failure of another were not replaced and may have shortened lifetimes
- Poor replacement, e.g. replacement components not of same quality as those originally fitted
- Failures not being accurately reported and therefore not included in statistics
- Environmental factors, e.g. systems run at higher temperatures will experience shorter lifetime
- Problems due to poor maintenance, e.g. failure to keep air vents clear will cause local hot-spots and result in earlier failure

2.2.4. Uncertainty in assessing reliability predications

It is important to appreciate that reliability predictions are subject to uncertainty. This arises from a number of factors:

- There is an inherent uncertainty in transferring failure (or success) data to different applications and environments.
- It may be unclear what constitutes a failure in various situations.
- The effect of human actions and interpretations may be uncertain.

- Predications are naturally based upon historical data. Differences in technology, changes in design team personnel and the changing specification of the product all introduce possible sources of error into predictions.
- The rate of occurrence of failure may not be constant with respect to time.
- Predication methods often have to be over simplified in order to make problems tractable.
- Confidence limits with respect to the statistical data being assessed.

2.2.5. Application of reliability assessments

Reliability assessments are an aid to good engineering and consideration should be given to the following: -

- Well-proven engineering practices.
- All statistical information is assessed to a common base.
- Previous designs and processes should be reviewed to determine the capability of the new product.
- Statistical analysis should always be tempered by engineering judgement. Parallel redundancy for example, can be introduced to improve the overall probability of successful operation of a system, but it may not be effective if the same inherent fault mechanisms exist within the parallel items.

Reliability is the product of the component count and the number of redundant paths that will allow the product or system to perform satisfactorily until the faulty elements have been repaired.

Therefore, the less complex the system you design, with fewer components and more redundant paths, the more reliable the system will perform without loss of power.

2.3. Basic concepts

2.3.1. Reliability and unreliability

The British Standard BS 4778 Section 3.1 1991 and Section 3.2 define reliability as "the characteristic of an item expressed by the probability that it performs a required function under required conditions for a stated period of time".

When assessing the reliability of a product there are four important elements to be considered as follows: -

(a) Function

(b) Conditions of use

(c) Time interval

(d) Probability

These elements are defined in to BS 5760 Part 2 1994, 'Guide to the Assessment of Reliability', Section 4.

Reliability is difficult and time consuming to measure. The accurate assessment of the reliability of a product in use requires a long time or a large number of samples in order to gain statistical confidence in the assessment.

During the design phase, when the product is largely conceptual, or during development, when only prototypes exist, reliability can be more difficult to assess. At this stage, reliability estimates are often made based on experience with similar products and earlier generations. Reliability data accumulates during development and the early phases of introduction to use.

Some failures may be obvious, such as the blowing of a light bulb, but in other cases, it may be much harder to determine that a failure has occurred. For example, a complex electronic circuit that must meet a detailed specification has failed if any of its parameters have moved outside their specified limits although this may not be apparent to the user. An electronic interface circuit may be required to have a certain immunity to noise voltage; failure to maintain this immunity would not be noticed under noise free conditions, but the symptoms would be apparent under more extreme conditions. It is likely to be difficult to localise the cause.

Failure may occur as a catastrophic failure, i.e. it is complete and sudden, like a light bulb failing, or as degradation, i.e. it is gradual or partial, like an electronic unit moving outside specification. In the case of an electrical supply, a complete loss of power would be catastrophic failure, while voltage or frequency deviation would be regarded as degradation. A failure is primary if it is not caused by failure in another part of the system, and is secondary if it is the result of the failure of another part of the system. Reliability data can only give information about primary failure.

2.3.2. Basic reliability formulas

If the number of components tested is N_o, the number of components which fail in time t is N_f and the number which survive is N_s, then

Reliability, $R(t) = \frac{N_s}{N_o}(t)$ Equation 1

where R(t) is known as the reliability function, and

Unreliability, $Q(t) = \frac{N_f}{N_o}(t)$ Equation 2

where $N_f(t)$ is the number of failures to time t. Q(t) is also called the failure probability.

Failure Rate

The probability density f(t) is probably the most fundamental function in reliability theory.

$$f(t) = \frac{\text{Failures during day}}{\text{Initial number of components } (N_o)}$$ Equation 3

We need to relate the number of components that failed on a particular day to the number of components that were exposed to failure on the same day, not the initial number of components. This is a conditional probability because it is the probability of failure on a given day, subject to the condition that the component has survived to that day and is known as the failure rate, or hazard rate λ(t), defined as: -

$$\lambda(t) = \frac{\text{No of failures in unit time}}{\text{No of components exposed to failure}}$$ Equation 4

Failure rate curves

Figure 4 shows the failure rate λ(t), plotted against time measured in days. It is often referred to as a 'bathtub curve' and is typical of that obtained for many electronic components. It has three distinct sections:

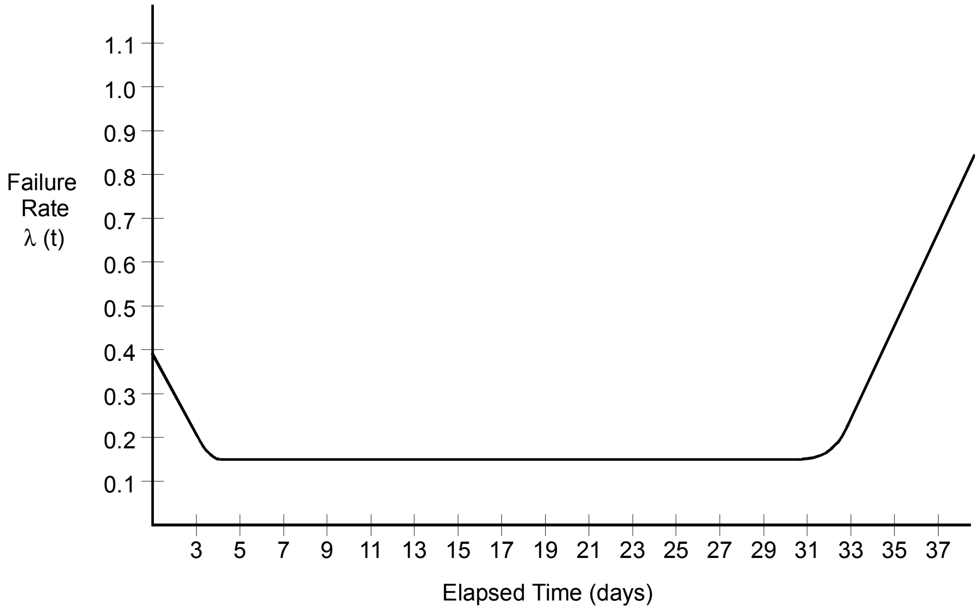
Early life or burn-in

This is the period (up to day 4 in this illustration), when λ(t) is decreasing as weak or substandard components fail. It is known as the early life, early failure, infant mortality or burn-in period. The reasons for the first three terms should be obvious. Burn-in is a process sometimes used in the final stages of manufacture of components in order to weed out early failures. It involves the components being run under normal conditions (or controlled conditions somewhat more severe than normal to accelerate the process) for sufficiently long to get through the early life period.

Useful life - normal operating period

This is a period of effectively constant, relatively low λ(t) (from day 5 to day 31 in Figure 4), known as the useful life or normal operating period. During this time, the failure rate is independent of the time for which the component has been run. In other words, the probability of failure of a component is the same throughout this period.

Figure 4 - Failure rate against time



Wear-out - old age

This is the period, when the failure rate increases steeply with time (beyond day 31 in this illustration), known as the wear-out or old age period.

The bathtub curve describes the behaviour that might well be expected for many types of component, or even for complex systems such as a UPS. Taking the familiar example of light bulbs, failures during early life might be due to filaments that have been badly attached to their supports, that have been locally drawn too thin or that have nicks in them. Another cause of early failure could be leaky glass envelopes, leading to filament oxidisation. During useful life the filaments gradually evaporate and become thinner until they break, usually under the thermal stress induced by current surges at switch on. If all bulbs were identical and were operated under identical conditions, they would all fail at the same time. However, since no manufacturing process will produce identical components, some will have serious faults leading to failure during early life, and the failure rate decreases as the weaker components are weeded out. Similarly, it is reasonable to expect a range of failure times during the wear-out period. In the case of light bulbs, filament composition, thickness, length and shape will vary slightly from bulb to bulb, thus leading to a spread in the time at which they finally break. As the bulbs get older, their probability of failure increases, giving a steep rise on the right-hand side of the bathtub curve.

Memory-less process or catastrophic failure

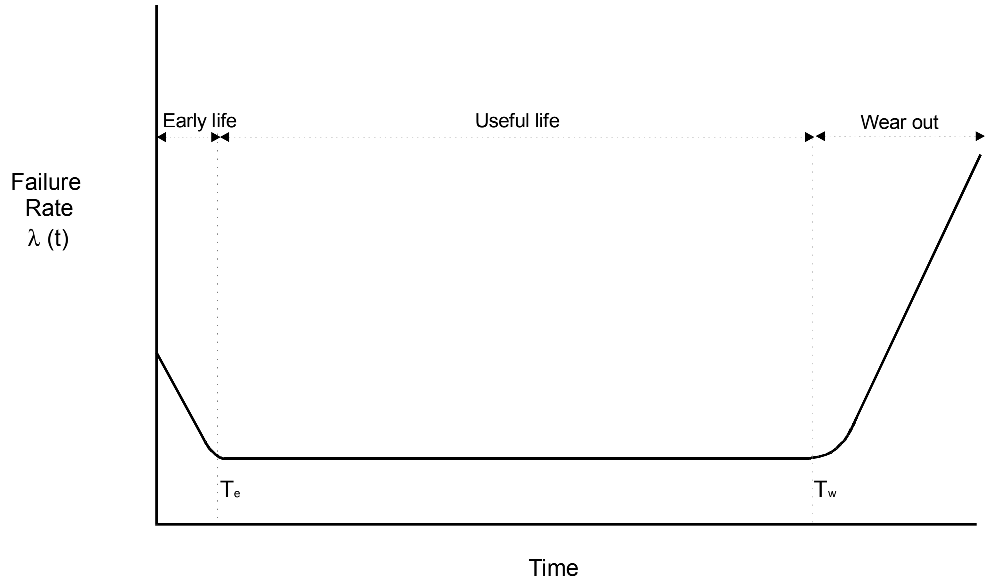
It is perhaps harder to see why there should be any failures at all during the normal operating period, once early failures have been weeded out and there has not yet been any significant wear. A detailed analysis of the numerous ways in which a light bulb could fail would be extremely complex because of the variety of mechanical, thermal and chemical processes that can take place. The wide range of possibilities, each with its own time dependence, averages out to produce a failure probability that is effectively independent of time. The process is referred to as memory-less, because the probability of failure is independent of previous history. These failures are also sometimes called catastrophic because they are unexpected.

Figure 5 shows a sketch of a typical bathtub curve. Useful life extends from T_e to T_w, i.e. after early life failures have occurred and before wear-out starts to be significant.

Failure rate during useful life

The manufacture of components and assemblies often involves a burn-in process so that those subject to early life failure can be removed from the supply chain. In many cases, electronic components do not reach their wear-out period during operational life - they may have useful lives that are much longer than the operational life of the system in which they are used. Routine maintenance procedures may be designed to ensure that components are replaced well before the onset of wear-out. Because of this, it is often possible to assume that components are run only during their period of useful life and that they have a constant failure rate, λ_u.

Figure 5 - Useful lifetime



2.3.3. Mean time to failure (MTTF)

The mean time to failure is a term that is applied to non-repairable parts such as light bulbs and is a measurement of the average time to failure of a large number of similar parts which operate under specified conditions. The conditions of test are important, for example an increase in the operating temperature of most components will reduce the MTTF. MTTF may be calculated from the equation: -

$$MTTF = \frac{\text{Sum of time to failure of each component}}{\text{No of components under test}}$$

In practice, the MTTF is often calculated from data taken over a period of time in which not all the components fail. In this case

$$MTTF = \frac{\text{Total operating time for all components}}{\text{No of failures at that time}} \qquad \text{Equation 5}$$

The relationship between MTTF and the parameter λ holds only for exponential distribution. The MTTF can be estimated from the results of reliability tests or from statistics by keeping records of component failures. This can form part of the servicing/maintenance procedures for equipment.

Example

The maintenance records for a large organisation show that during a period corresponding to 1,000,000 operating hours for a particular piece of equipment, 80 of these failed and had to be replaced.

If 80 units fail in 1,000,000 hours, the MTTF of one piece of equipment is

$$\frac{1{,}000{,}000}{80} = 12{,}500 \text{ hours}$$

2.3.4. Mean time between failures (MTBF)

In the case of components or system elements that can be repaired, failure rates are often expressed in terms of the mean time *between* failures (MTBF) rather than mean time to failure (MTTF). This is a measure of the average time that a piece of equipment performs its function without requiring repair (although it may require routine scheduled maintenance).

Many components cannot be repaired; they can fail only once in their lifetime after which they have to be replaced. However, in more complex systems, elements can usually be repaired: faulty components on circuit boards or faulty boards in equipment racks can be replaced and breaks in cables can be repaired.

Example

A television rental company operates their sets for an average of 900 hours per year. The company records show that during one year 26,300 of its 210,000 rented televisions had to be repaired.

Total number of operating hours = 210,000 x 900 = 189 x 10^6 hours.

The estimated $\text{MTBF} = \frac{189 \times 10^6}{26300}$ = 7,200 hours.

Because MTBF is a statistical quantity, a large number of faults must be recorded in order to establish confidence in the result. Testing one piece of equipment for a very long time is impracticable. It is usual to test a large number of samples simultaneously for a shorter period, and to determine the total number of faults in the total operating time for all of the equipment. This method assumes that burn-in and wear-out failure modes are not involved.

2.3.5. Availability and mean time to repair (MTTR)

The average time needed for repairs is known as the mean time to repair (MTTR). It must be taken into account when calculating availability. Repair times need to be considered when using MTBFs to estimate the effective reliability of the system.

In practice the MTTR can depend on a whole range of factors including: -

- Time needed to learn about the fault.
- Time needed to locate the fault.
- Time needed to isolate the fault.
- Time needed to gain access to the fault.
- Access to the service engineer and time needed to reach site.
- Availability of (and delivery time of) spare parts.
- Time needed to repair the fault and to make any necessary adjustments and perform tests.

The availability of a system or of a component is the proportion of time for which it is operating correctly. It is the ratio of operational time to total time, which is the sum of the operational and repair times.

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$ Equation 6

System users are sometimes more concerned with the availability rather than the reliability of such systems. It is usually important to maximise the proportion of time a system is available, and this can involve trade-offs between component reliability and repair time. For instance, hard-wired components are usually much more reliable than plug-in ones, because of the relatively high failure rates of connections. On the other hand, the repair times of plug-in components may be much shorter than those for hard wired ones because they can simply be replaced. The use of plug-in components can result in higher availability, but with a higher failure rate. The optimum balance depends on the absolute values of MTBF and MTTR.

2.4. The reliability of system and system elements

2.4.1. Reliability block diagrams

It is useful to represent the system undergoing analysis in the form of a reliability block diagram (RBD). The main purpose of producing reliability assessments is to enable the user to: -

(a) Compare one product against another.

(b) Compare the merits of different distribution systems.

(c) Compare the difference in the magnitude of the reliability assessment between the different systems under evaluation.

The principle benefits[2] are as follows: -

(a) The pictorial representation means that models are easily understood and therefore readily checked.

(b) Block diagrams are used to identify the relationship between elements in the system. The overall system reliability can then be calculated from the reliability of the blocks using the laws of probability.

(c) The block diagrams can readily be interpreted in the case of elements that are, in reliability terms, in series.

(d) Block diagrams can be used for the evaluation of system availability provided that both the repair of blocks and failures are independent events, i.e. provided the time taken to repair a block is dependant only on the block concerned and is independent of repair to any other block.

The main limitations of the RBD technique are as follows: -

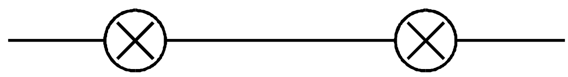
(a) This method cannot model systems in which the sequence of failures affects the outcome (*i.e. order dependant failures*).

(b) This method cannot model maintenance strategies.

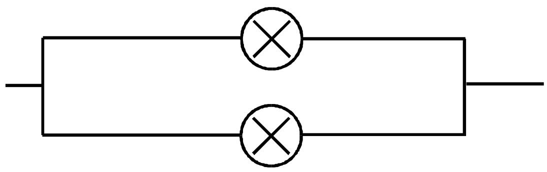
(c) For a given system, each failure or success definition needs a separate block diagram.

Figure 6 shows two warning lamps that form part of a control panel.

Figure 6 - Example of RBD



(a) In Series



(b) In Parallel

They are in series in diagram (a) and in parallel in diagram (b). As a warning system, (a) fails at the first failure of a lamp whereas (b) fails only when both lamps have failed. Arrangement (b) is more resilient and so is clearly preferable to (a). If it were not possible to have two bulbs in parallel, it would be better to have just one, rather than two in series. Although the failure of one or the other bulb is more likely with two bulbs than with one, the parallel combination increases the availability of the warning system.

In terms of reliability, the components of (a) are in series because the system fails if either of the components fails and those of (b) are in parallel because the system fails only if both its components fail.

Figure 7 shows two RC elements which could each form part of a filter. From an electrical point of view, (a) is a series and (b) a parallel circuit. However, both circuits fail if *either* of their components fail, so in reliability terms the components are in series in both cases.

Figure 7 - RC circuit in series and parallel

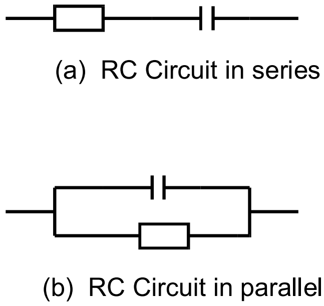


Figure 8 - Two switches in series

Two switches in series

Whether the switches in Figure 8 are in series or parallel (in reliability terms) depends on their intended function. If they are to close on command in order to energise an item of equipment, then they are in series (because if one fails the action does not take place). If they are safety switches fitted to interrupt current flow when, say, a door of an equipment cabinet is opened, then they are in parallel in reliability terms because only one is required to operate to achieve the design objective. This example illustrates the need for careful analysis of the function of each element.

When drawing reliability block diagrams it is usual to represent each element by a box, possibly characterised by an appropriate parameter such as the failure rate or MTBF in hours. Each series or parallel combination is progressively reduced to a single equivalent element until the whole system has been reduced to one single equivalent element.

2.4.2. Series reliability

Components are considered to be in series, in reliability terms, when failure of any one of them causes total failure of that system or part of a system undergoing evaluation. If a failure of any part is independent of the operation of the other parts then the reliability of the system is given by the product of the reliability of the parts: -

$$R(t) = R_1(t) \times R_2(t) \times R_3(t) \times .... \times R_k(t) \times ... \times R_n(t) \qquad \text{Equation 7}$$

where R(t) is the system reliability and $R_k(t)$ is the reliability of the k th part at a time t.

If the failure rate, λ, is constant then the system failure rate R(t) is given by: -

$$R_k(t) = e^{-\lambda_k t}$$

$$R(t) = e^{-\lambda_1 t} \times e^{-\lambda_2 t} \times e^{-\lambda_3 t} \times ..... \times e^{-\lambda_k t} \times ....e^{-\lambda_n t}$$

$$R(t) = e^{-(\lambda_1 + \lambda_2 + \lambda_3 + ... + \lambda_k + ... + \lambda_n)t}$$

$$R(t) = e^{-\lambda t} \quad \text{where } \lambda = \lambda_1 + \lambda_2 + \lambda_3 + ... + \lambda_k + ... + \lambda_n \qquad \text{Equation 8}$$

$$MTBF = \frac{1}{\lambda_1 + \lambda_2 + \lambda_3 + ... + \lambda_k + ... + \lambda_n} \qquad \text{Equation 9}$$

2.4.3. Parallel reliability

Components are considered to be in parallel, in reliability terms, if failure of any one component does not cause the total failure of that system or part undergoing evaluation. This can be referred to as in-built redundancy, i.e. the inclusion of additional equipment in such a way that a failure of one part does not cause a failure of the whole system.

If the reliability of each part is independent of the other parts then the probability of a system failure is

$$Q(t) = Q_1(t) \times Q_2(t) \times Q_3(t) \times .... \times Q_k(t) \times .... \times Q_n(t) \qquad \text{Equation 10}$$

Where Q(t) is the system unreliability and $Q_k(t)$ is the part unreliability. Since R(t) = 1 - Q(t) the system reliability is easily calculated.

2.4.4. Calculation examples

The following examples illustrate how the calculations are carried out in practice.

Example 1

A sub-system element consisting of 12 identical components is required to have a reliability of at least 0.95. Failure of any component results in failure of the system.

In terms of reliability, the components are in series, because the system fails if any one of them fails. If *R* is the component reliability function, then the requirement is that R^{12} should be equal to 0.95, or greater. Thus the minimum acceptable value for *R* is given by $R^{12} = 0.95$, so *R* must be at least 0.9957, say 0.996.

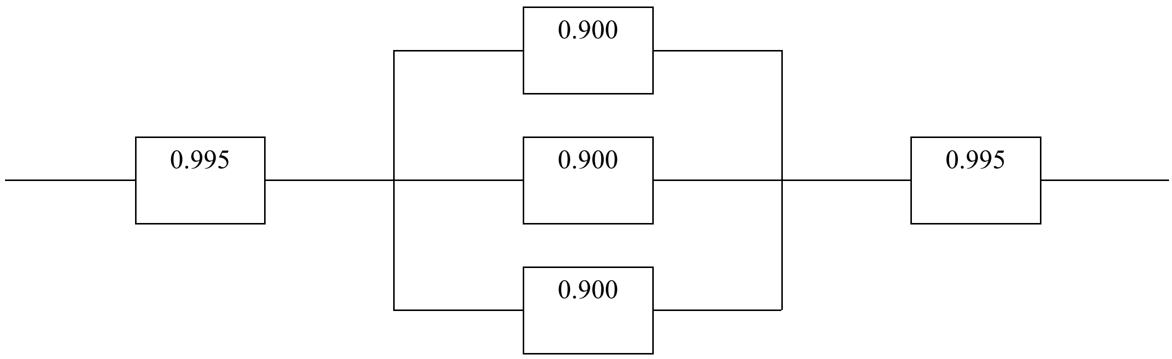
Example 2

A communication system uses two exchanges, each with reliability *R* = 0.995, linked via three trunk routes, each with a reliability of 0.900. If the selected route fails, the exchanges automatically switch to another route.

The reliability diagram for the system is shown in the

Figure 9. The three routes are in parallel because any one of them can be used on its own. The reliability of this parallel combination is $1 - (1 - 0.0900)^3 = 0.999$ and this is in series with two exchanges, each with reliability 0.995. So the overall system reliability is 0.995 x 0.999 x 0.995 = 0.989.

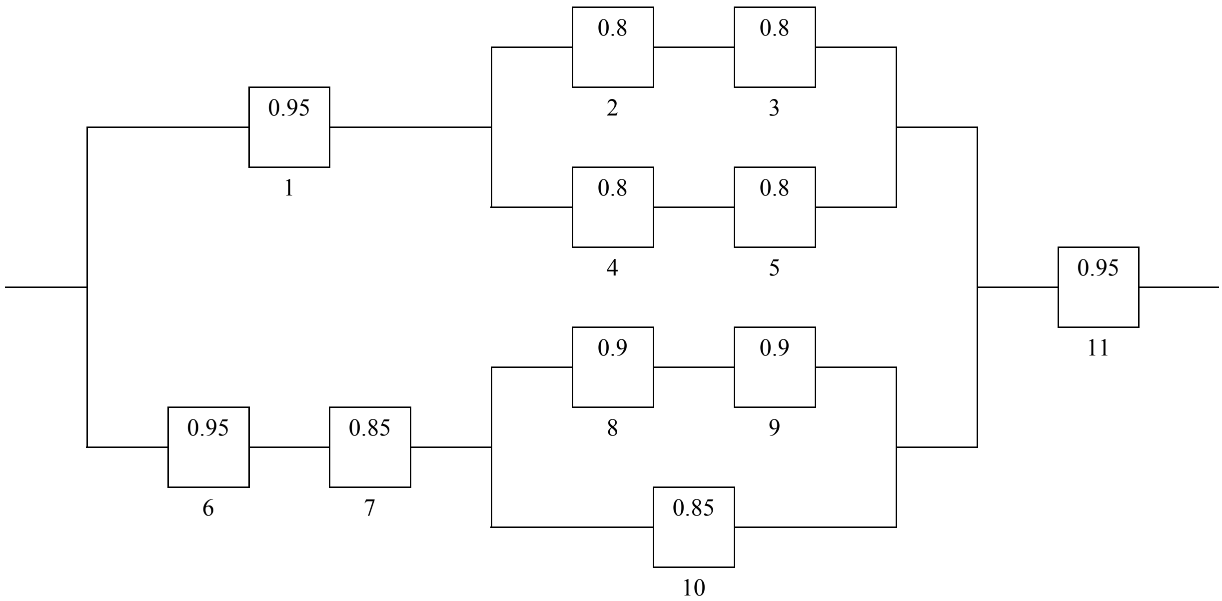
Figure 9 - Reliability diagram



Example 3

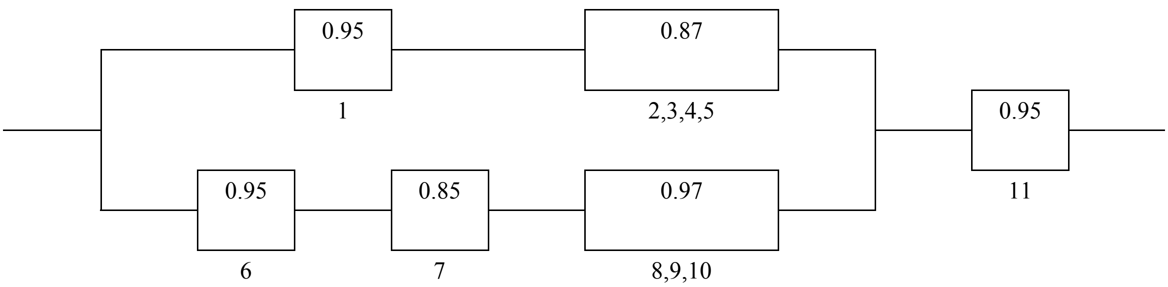
Figure 10 shows the RBD of a system in which component 1 has a reliability of 0.95, component 2 a reliability of 0.8, and so on.

Figure 10 - Reliability block diagram



The reliability of the whole system is calculated by first merging simple series and parallel combinations. Thus, components 2 and 3 have combined reliability of 0.8 x 0.8 = 0.64, as have components 4 and 5. The reliability of these two parallel groups is $1 - (1 - 0.64)^2 = 0.87$. Similarly, components 8 and 9 have combined reliability 0.9 x 0.9 = 0.81, and they are in parallel with component 10, so the reliability of this group is 1 - (1 - 0.81) (1 - 0.85) = 0.97. At this stage, the reliability diagram has been reduced to that shown in Figure 11.

Figure 11 - Reduced reliability block diagram



The upper, 2-component, branch in this figure has reliability 0.95 x 0.87 = 0.827, while the lower, 3-component, branch has reliability 0.95 x 0.85 x 0.97 = 0.783. The reliability of the parallel combination of these two branches is 1 - (1 - 0.827)(1 - 0.783) = 0.96, and this combination is in series with component 11, so that the overall system reliability is 0.96 x 0.95 = 0.91.

2.5. Application of reliability

2.5.1. Power system design philosophy

In designing any power distribution system the following fundamental elements should always be addressed: -

1. Reliability
2. Resilience
3. Maintainability

4. Capacity
5. Flexibility
6. Interface with Existing Infrastructure

The parameters for providing a reliable electrical system include the following: -

- The use of modular standby equipment rather than large central plant.
- Individual power supplies rather than shared power supplies to the critical load.
- Dual feeds (parallel paths) throughout the electrical distribution system with automatic changeover on failure.
- The power distribution, standby generating equipment and the UPS concepts employed should include redundancy and no-break switching.

With information available regarding reliability, capacities, maintainability and costs, a suitable scheme can be selected to meet the specification parameters.

In general, the overall reliability of a system is dependent upon the number and reliability of individual components; a more complex system impairs reliability as more components are involved leading to a greater number of failure points. Therefore, the use of high quality reliable components based on "tried and tested" technology that has undergone an appropriate service period is essential.

2.5.2. Parallel redundancy and standby modes

Redundancy is a useful method of increasing reliability and optimising the balance between operation effectiveness and expenditure. In the context of reliability, redundancy signifies that a system will continue to function satisfactorily in spite of the failure of some of the component parts. This resilience to failures is obtained by providing alternative paths of operation, by arranging selected elements of the system in parallel.

Standby Redundancy

Standby redundancy means that an alternative means of performing the function is provided but is inoperative until needed. It is switched on upon failure of the primary means of performing the function. An example of standby redundancy would be the use of a standby generator in a building to ensure continuity of supply in case of a mains failure. The generator is not called for until it is needed when the power supply fails.

Such a scheme would not be suitable for a computer system, because data would be lost during the relatively long period required to start the standby generator.

Active or Parallel Redundancy

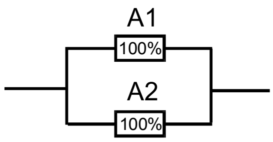
In active or parallel redundancy, all redundant units are operating simultaneously rather than being switched on when needed. The most obvious approach is to use two components, each capable of carrying the full load, so that if one should fail the other will take over - this is referred to as 1+1 redundancy. An alternative approach is to split the load among a number of units, each capable of carrying only a fraction of the load, and provide just one additional redundant unit - this is referred to as N+1 redundancy. For very critical loads, more than one fully rated redundant unit may be provided. For example, a 1+2 redundancy scheme would have two fully rated redundant units supporting the single operating unit and would require all three units to fail before the system fails. Because there is no interruption, active redundancy is suitable for computer installations.

N+1 and 1+1 Redundancy

As discussed earlier, the theory of redundancy is that should a component within a system fail, the system will continue to function because alternative paths are available for the system to operate.

In Figure 12 the system will function with either A1 or A2 operating. Should component A1 fail, the system will continue to function. This type of redundancy is termed 1+1, as there is 100% redundancy available.

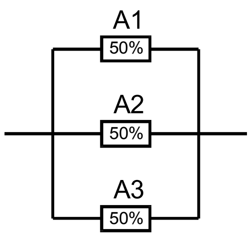
Figure 12 - 1+1 Redundancy



In the system shown in Figure 13 two out of the three components are required for the system to function and there is one redundant component. In this scenario, the system would be called 2+1.

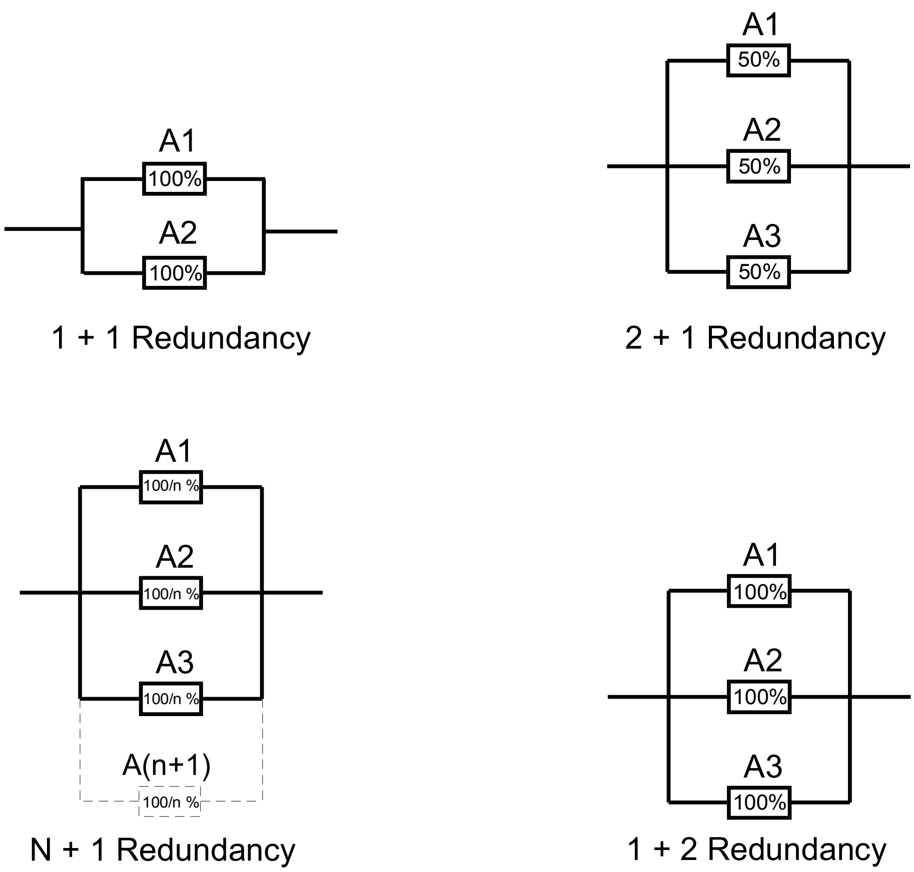
In each case, the first number refers to the number of components required for the system to function correctly and the second number refers to the number of standby components available.

Figure 13 - N+1 Redundancy



It is possible to have many redundant components that would significantly improve the reliability of the system. However, this would also be expensive and in most applications a balance is achieved between reliability and economics.

Figure 14 - Examples of redundancy



2.5.3. Maintainability

Maintainability is the probability that a device will be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures[3].

There are generically four parts to achieving good reliability.

Detecting that a problem or defect exists - catastrophic failures are obvious, gradual failures may not be noticed for some time.

Locating quickly and identifying the defective component - the solution to this problem includes:

- Good training
- Good instrumentation panels
- Appropriate test apparatus

Rectifying the defective component which may include finding replacement parts.

Verifying that the repaired system functions correctly.

2.5.3.1. Designing for maintenance

A survey among building services engineers revealed that in less than 50% of projects were maintenance requirements addressed prior to the detailed design stage, although 88% of engineers agreed that it should have been.

Maintenance may be preventative or corrective. Preventative maintenance, also called time based maintenance, requires a defined routine of activities such as cleaning, lubricating, replacement of filters, etc. Measurement of critical parameters may also be performed to detect early signs of component failure.

Corrective maintenance may be either planned or un-planned. Planned corrective action would be initiated following the discovery of a defect during a routine inspection. Un-planned maintenance results from failure of the equipment; it is often referred to as a 'run to failure' policy. This strategy is more difficult to manage because manpower and spares requirements are very difficult to predict and can result in excessive downtime and poor equipment availability.

For an electrical installation that supplies critical loads, it is essential that the system is designed with maintainability in mind and that the maintenance strategy is well planned. Individual items of equipment will need to be serviced, tested and calibrated, or even replaced entirely, without disturbing the load. This will be possible only if redundant units and/or bypass links have been provided.

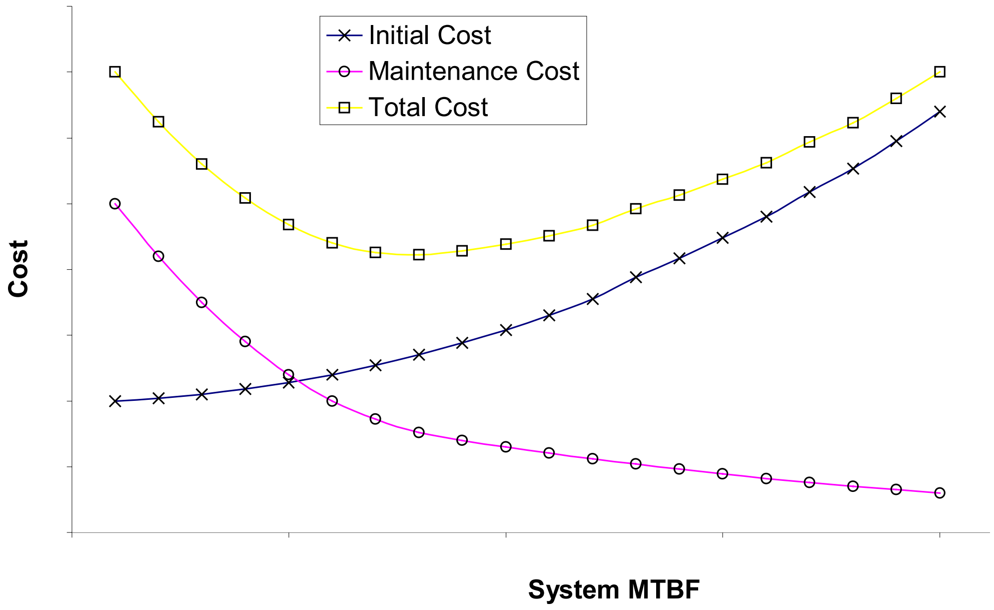
2.5.4. Cost versus reliability

Introducing increased reliability and maintainability into a design will increase the initial capital costs, but this increase will be offset against savings from reduced maintenance costs and reduced costs of failure. Savings arise not only from a reduction in the man-hours required for maintenance but also because of a reduction in the on-site spares stocks required. The graph in Figure 15 shows typical costs against reliability.

The graph shows that the capital cost rises and the cost of maintenance falls as the target system MTBF increases. The optimum design, from a purely economic point of view, occurs when the total of capital and maintenance costs is a minimum.

When there are other risks associated with the loss of power, the potential cost of a power failure can be extremely high, for example in the case of a critical data centre, dealing floor or safety critical application. The likely costs can be several times the capital cost of the installation so the cost of providing an installation with increased reliability and resilience becomes insignificant in comparison.

Figure 15 - Cost of unreliability



2.5.5. Reliability and safety

When designing any power system under the new Construction Design and Maintenance (CDM) Regulations, safety will be an important factor. It is worth acknowledging that safety and reliability can conflict. This can happen when safety considerations require the introduction of additional complexity, such as the provision of safety interlocks, which reduces reliability.

Safety must always take precedence and additional steps will be required to maintain the required reliability.

3. Power Quality

3.1. What is poor power quality?

Most electrical and electronic equipment is designed to operate from a power supply with a particular specification that usually defines the minimum and maximum limits for RMS (root-mean-square) voltage and frequency. There is an expectation on the part of the user that the supply will be available and within tolerance for 100% of the time. This is not guaranteed by the supplier and would be practically impossible to realise at an economic price level.

Electricity is unlike any other product in that quality cannot be assessed before delivery. It is used at the time of production but some distance away from the point of production having passed through several transformers, many miles of transmission lines and having been mixed with the output of other generators. Suppliers, the Regional Electricity Companies (REC) in the UK, can only measure the quality of supplied electricity in retrospect and therefore take measures that can reasonably be expected to maintain an appropriate minimum average quality. It is not possible to withdraw poor quality electricity from the supply chain! In the UK, the suppliers' success is monitored and the results reported annually by the Office of the Electricity Regulation[1], OFFER.

The term 'good power quality' can be used to describe a power supply that is always available, always within voltage and frequency tolerances, and has a pure noise-free sinusoidal wave shape. 'Poor power quality' describes any supply that deviates from this ideal; whether or not the deviation is important depends on the purpose of the installation, the design of the equipment and the design of the installation.

The major causes of poor power quality fall into two categories that are discussed in the following sections.

- Supply system quality problems
- Installation and load related problems

As later sections will make clear, the separation between these categories is never complete because disturbances caused by equipment on one site may result in damage or disruption to equipment on another site. For example, a heavy load, such as an arc furnace, in a factory unit on a small estate may cause a voltage dip to several neighbouring users when it is switched on. The result may be complete shutdown of a computer network causing disruption far greater than would be expected by the operator who pushed the button.

3.1.1. Supply system quality problems

Supply interruption: - Complete loss of power lasting more than one minute.

Caused by generation or distribution plant failure, transmission line faults, or load shedding during system overload. The obvious effect is complete shutdown of all electrical plant.

Transient interruption: - Complete loss of power for less than one minute.

Usually caused by auto-reclosers restoring power after transient faults. Computers and communications equipment will shut down with loss of data. Restart times may be several minutes: data recovery times will be much longer.

Transients: - Fast rise-time high voltage pulses superimposed on the supply voltage.

Can be caused by a number of factors, including the residual effects of lightning strikes, power factor correction capacitor switching and inductive load switching.

Under/over voltage: - Long term excursion outside statutory limits.

Caused by failure of tap changers. Under voltage ('brownouts') may be introduced deliberately by the supplier to reduce demand and can cause unreliable equipment operation, including repeated re-booting of computer systems, solenoid drop-out and overheating of squirrel cage motors. Over-voltage may cause permanent damage to a wide range of electrical and electronic equipment.

Voltage dip/surge: - Short term voltage disturbance outside statutory limits.

Caused by starting and shutting down heavy loads such as large motors. In extreme circumstances, dips can cause equipment shutdown and surges can cause equipment damage.

Voltage imbalance: - Asymmetry of phase voltages of a three-phase supply.

Caused by differential loading of phases. Results in circulating current (and excess heating) in transformers and reduced efficiency of three-phase motors.

Flicker: - Periodic fluctuations in supply voltage.

Caused by presence of cyclical load variations, e.g. from a cyclo-convertor drive system. Results in visible flicker in lighting systems.

Harmonic distortion: - Distorted voltage waveform.

Caused by non-linear loads. Causes overheating due to increased eddy and hysteresis loss in transformers, overheating and reduced torque in motors and overheating in neutral conductors and power factor correction capacitors.

Some of the defects, such as interruptions or flicker, will be obvious to the user, while others may only be apparent by their effects on equipment and plant. The electricity customer has no control over supply problems, but the resilience of an installation can be improved in a number of ways.

Although classified as supply problems, sometimes the root cause may lie within the user's own premises; in these cases the design guidelines in later sections will provide a solution.

3.1.2. Installation and load related problems

There are three major installation related problems:

- Harmonic currents
- Earth leakage currents
- Voltage dips and transients

Harmonic current

Harmonic currents arise from the increasing prevalence of non-linear loads now in use and cause problems in cabling, transformers and motors. Drawing harmonic currents from the supply imposes distortion on the voltage waveform that, if unchecked, could cause problems for other users of the supply and so limits are imposed on the permitted magnitude of the major harmonics. Harmonic currents, their causes and effects are discussed in detail in Section 4.

Earth leakage currents

Earth leakage currents arise from most modern electronic equipment. For individual units the current is quite small - usually less than 3.5 mA - but in large installations of computers for example the combined current can be quite large. In addition, there is a significant high frequency component in the leakage current resulting from the filtering of switching transients in power supply units. Most earthing systems have been designed to function as safety earths (i.e. to provide a safe low impedance path for fault current to allow the overcurrent protection to operate) and not to cope with continuous leakage currents especially at high frequency. The high sensitivity to noise of modern computer and communications equipment has placed further requirements on the earthing system. Earthing and earth leakage are discussed in Section 5.

Voltage dips and transients

Most voltage disturbance defects are attributed to the supply, but this is not always the case. Switching of heavy loads, such as large motors and arc furnaces, causes voltage dips and if the load is inductive, transient over-voltages. Dips may last for several seconds as machinery runs up to speed, causing problems for voltage sensitive equipment. Transients can cause damage to electronic equipment and, via inductive coupling to data lines, data errors in computer and communications equipment. In circumstances where there are power factor correction (PFC) capacitors resonance with the supply inductance can occur causing damage to the PFC capacitors. Good practice solutions include circuit separation, such as proposed for control of harmonic problems in Section 4.2.1.1, and using generous conductor cross-sectional areas, as is proposed for improved efficiency in Section 7.3. Specific solutions are discussed in Section 6 and will be found useful when the source of the problem is outside the customer's control. Wherever possible, prevention, by the application of good practice, is the better path.

3.2. Power quality survey

In order to gauge the nature and extent of power quality problems in the UK commercial and industrial sector, a survey of end-users has been carried out[4]. The survey has focussed on problems resulting in downtime caused by harmonic currents, earth leakage currents and voltage disturbances (i.e. disturbances from the supply).

A sample of 45 end-user electrical engineers in the commercial, public and industrial sectors was surveyed. Analysis of the data is presented in the following section.

3.2.1. Power quality survey findings

Power quality survey findings are presented in the tables below:

- Frequency of occurrence
- Scale of occurrence
- Sources of problems

Table 4 - Frequency of occurrence of power quality problems

Sector	Harmonics			Earth Leakage			Voltage Disturbance		
Frequency of occurrence	**High**	**Med**	**Low**	**High**	**Med**	**Low**	**High**	**Med**	**Low**
Commercial	71%	20%	9%	20%	31%	49%	51%	27%	22%
Public	60%	20%	20%	31%	31%	39%	31%	49%	20%
Industrial	60%	31%	9%	40%	31%	29%	40%	31%	29%

High *greater than twelve incidents resulting in down-time a year*
Medium *one to twelve incidents resulting in down-time a year*
Low *up to one incident resulting in down-time a year*

Analysis of the data in Table 4 shows a high incidence of problems caused by harmonics, with over 60% of respondents across all sectors reporting more than twelve incidents per year and over 80% of respondents reporting at least one incident a year.

Reported incidence of problems caused by earth leakage is less common, with just over 30% of those surveyed reporting more than twelve incidents per year and 60% of end-users reporting at least one incident. Frequency of occurrence of voltage disturbances is also high with 76% of end-users reporting at least one incident a year. The scale of occurrence of the problem is summarised in Table 5 below.

Table 5 - Scale of occurrence of power quality problems (at least once per year)

Sector	Harmonics	Earth Leakage	Voltage Disturbance
Commercial	91%	51%	78%
Public	80%	62%	80%
Industrial	91%	71%	71%
Total	87%	61%	76%

From those respondents reporting at least one problem per year the survey attempted to elicit the probable primary cause and the results are presented in Table 6 below.

Analysis of Table 6 shows that the main source of both harmonics and earth leakage quoted by respondents in both the commercial and public sector is computer systems. Respondents in the industrial sector also quoted process control equipment, inductive load switching and switched-mode power supplies as prime sources of these problems.

Voltage disturbances were primarily attributed to the utility although in reality many are caused within consumers' sites, for example, by the starting of large motors.

Table 6 - Reported main sources of power quality problems

Problem	Source(s)	Commercial	Public	Industrial
Harmonics	Computer systems	71%	78%	34%
	Inductive load switching	5%	-	22%
	Switched mode power supplies	10%	17%	22%
	Combination of factors	14%	5%	22%
Earth Leakage	Computer systems	100%	100%	41%
	Process control equipment	-	-	59%
Voltage Disturbance	Lightning	-	-	-
Transients	Inductive load switching	12%	31%	43%
Dips	From the utility	88%	69%	57%
Ripple	Heavy load switching	-	20%	40%
	From the utility	100%	80%	30%
	Large cyclic loads	-	-	100%

Inductive load switching: e.g. motors, transformers and lighting ballasts

Large cylic loads: e.g. Arc furnaces, spot welders

3.2.2. National extent of power quality problems

No comprehensive survey of the extent of power quality problems in UK commercial, industrial and public properties has ever been undertaken, nor is any information on the issue routinely collated. One reason for this is the difficulty in defining what constitutes a 'power quality problem'.

There has been a recent survey on the financial impact to UK businesses from computer downtime resulting from power-related failures (see Section 1.3).

The estimates in Table 7 below are based on the survey of end-users and on Department of the Environment Construction Market Intelligence statistics. The estimates are derived by applying the survey figures from Table 5 to the Department of the Environment figures for total building stock to give the number of buildings likely to experience a problem at least once a year.

Table 7 - Potential extent of power quality problems in the UK

Sector	Commercial	Public	Industrial Other	Total
Total stock of Buildings	1,139,400	139,500	274,040	1,552,940
- subject to harmonic problem	1,036,854	111,600	249,376	1,397,830
- subject to earth leakage problem	581,095	86,490	194,568	862,153
- subject to voltage disturbance problem	888,732	111,600	194,568	1,194,900

4. Harmonics

Harmonic currents have been present in the electricity supply system for many years. Initially they were produced by the mercury arc rectifiers used to convert AC to DC current for railway electrification and for DC variable speed drives in industry. More recently the range of types and the number of units of equipment causing harmonics have risen sharply, and will continue to rise, so designers and specifiers must now consider harmonics and their side effects very carefully.

This section describes how and why harmonics are generated, how the presence of harmonics affects the electrical system and equipment and how to minimise these effects.

4.1. Types of equipment which generates harmonics

Harmonic load currents are generated by all non-linear loads. This includes:

- Switched mode power supplies (SMPS)
- Electronic fluorescent lighting ballasts
- Variable speed drives
- Uninterruptible power supplies (UPS)
- Magnetic-cored devices

Switched mode power supplies (SMPS)

The majority of modern electronic units use switched mode power supplies (SMPS). These differ from older units in that the traditional step-down transformer and rectifier is replaced by direct controlled rectification of the supply to charge a reservoir capacitor from which the required direct current is derived by a method appropriate to the output voltage and current required. The advantage – to the equipment manufacturer – is that the size, cost and weight is significantly reduced and the power unit can be made in almost any required form factor. The disadvantage – to everyone else – is that, rather than drawing continuous current from the supply, the power supply unit draws pulses of current which contain large amounts of third and higher harmonics and significant high frequency components. A simple filter is fitted at the supply input to bypass the high frequency components from line and neutral to ground but it has no effect on the harmonic currents that flow back to the supply. The earth leakage effects of these filters are discussed in Section 5.

For high power units there has been a recent trend towards so-called power factor corrected inputs. The aim is to make the power supply load look like a resistive load so that the input current appears sinusoidal and in phase with the applied voltage. It is achieved by drawing input current as a high frequency triangular waveform that is averaged by the input filter to a sinusoid. This extra level of sophistication is not yet readily applicable to the low-cost units that make up most of the load in commercial and industrial installations.

Fluorescent lighting ballasts

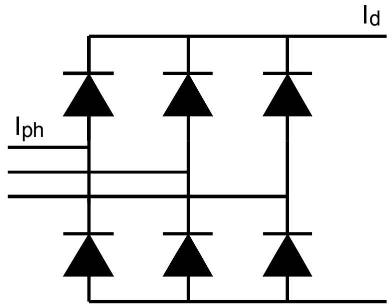
Electronic lighting ballasts have become popular in recent years following claims for improved efficiency. Overall they are only a little more efficient than the best magnetic ballasts and in fact, most of the gain is attributable to the lamp being more efficient when driven at high frequency rather than to the electronic ballast itself. Their disadvantage – and an important one in large installations – is that the inverter generates both harmonics in the supply current and electrical noise. Power-factor corrected types are becoming available which reduce the harmonic problems, but at a significant cost penalty.

Magnetic ballasts also generate harmonics but levels are generally lower than those produced by electronic units. They often incorporate a local power factor correction capacitor which act as a low impedance shunt for the harmonic currents. Consequently, the level of distortion that propagates into the distribution system is lower and fewer problems arise.

Variable speed DC drives

Variable speed controllers for DC motors are usually based on the three-phase bridge, which is also used in D.C. transmission links and uninterruptible power supplies. It is also known as the six-pulse bridge because there are six pulses per cycle (one per half cycle per phase) on the D.C. output.

Figure 16 - Three-phase, or six-pulse, bridge



The current is described by the series: -

$$I_{ph} = \frac{2\sqrt{3}}{\pi} I_d \left(\cos \varpi t - \frac{1}{5}\cos 5\varpi t + \frac{1}{7}\cos 7\varpi t - \frac{1}{11}\cos 11\varpi t .... \right)$$

The bridge will therefore produce harmonics of the order

$n = 6k \pm 1$ where k is an integer

and the magnitude of each harmonic current will be

$I_n = \frac{I_1}{n}$ where I_1 is the 50 Hz component.

These equations are valid only when the source impedance is low and the supply voltage is a pure sinusoid. In theory, the controller produces 30% total harmonic currents distributed as follows:

Harmonic number	5	7	11	13	17	19	23	25
Magnitude (%)	20.0	14.3	9.1	7.7	5.9	5.3	4.3	4.0

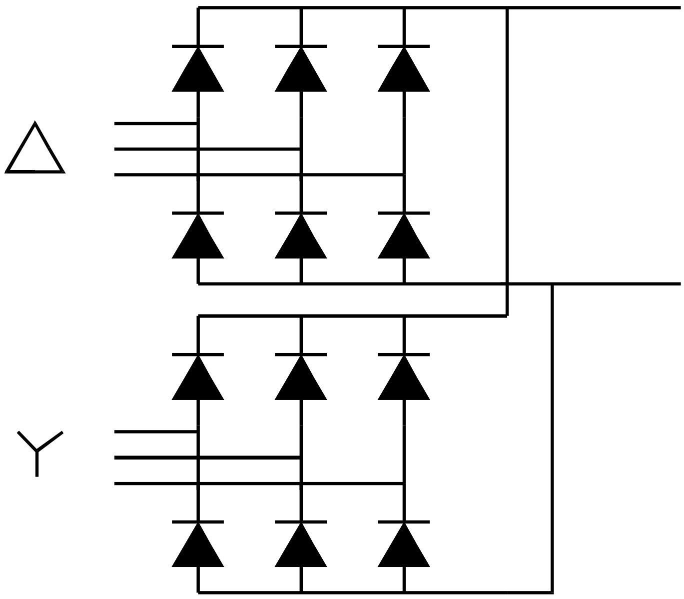
In practice, DC motors have finite inductance so there is a 300 Hz ripple (i.e. six times the supply frequency) on the DC current. This changes the harmonic profile of the supply current and fifth harmonic currents of up to 50% have been encountered with some motors. There is a trend towards using motors with lower inductance to reduce cost, but this can prove to be a false economy; the higher levels of harmonics are more difficult to deal with and harmonic filters, often designed for the theoretical case, may be damaged.

The magnitude of the harmonics[5,6] is significantly reduced by the use of a twelve-pulse bridge. This is effectively two six-pulse bridges, fed from a star and a delta transformer winding, providing a 30 degrees phase shift between them. The fifth and seventh harmonics are theoretically removed, but in practice, they are only reduced by a factor between 20 and 50. The higher harmonics remain unchanged, reducing the total harmonic current to about 12%, again assuming zero source impedance. Not only is the total harmonic current reduced, but also those that remain are of a higher order making the design of the filter much easier.

Further increase in the number of pulses to 24, achieved by using two parallel twelve-pulse units with a phase shift of 15 degrees, reduces the total harmonic current to about 4.5%. The extra sophistication increases cost of course, so this type of controller would be used only when necessary to comply with the electricity suppliers' limits (discussed in Section 4.2.2).

The figures for harmonic current distortion given above assume that the source impedance is zero. If it were, the level of harmonics would be irrelevant because no voltage distortion would result and other consumers would not be affected. In reality, the source impedance is finite (see Table 1) and, under these conditions, the current distortion is considerably reduced. Of course, since the distorted current is flowing through the source impedance, voltage distortion results.

Figure 17 – Twelve-pulse Bridge



Variable speed controllers for AC motors use similar converters to produce DC followed by an inverter to produce AC at the required frequency for the drive. As well as the harmonics that would be expected for the converter, other components of current are produced which are related to the operating speed of the drive. These components are referred to, somewhat confusingly, as inter-harmonics or non-integer harmonics but they are more akin to the sidebands found in any modulation process. The harmonic current profile is dependent on the precise design of the converter and inverter. Because of the large size of drives of this type, local filtering is normally provided but the design of filters for these systems is often very difficult.

Uninterruptible power supplies (UPS)

UPS are available in many different forms depending on how the power conversion is achieved and how the change over from external to internal supply takes place. Most units up to a few MVA use solid state inverters (termed static) to generate the output power, very large units use motor generators (rotary). Typical configurations include:

An **on-line** UPS converts AC line power to DC to keep a battery charged and inverts DC battery power to produce AC. The load is continuously fed from the constant battery power, regardless of supply conditions. Because the whole of the supply is converted twice, this type of UPS is relatively inefficient and is used only for small units.

An **off-line** UPS feeds the load from the mains supply when it is available. The inverter/converter is normally inactive until a disruption occurs, when the battery delivers power to the inverter, which converts the DC power back to AC power for the load. The drawback is that the time needed to transfer from AC to battery can present a problem for some sensitive equipment such as computers and servers.

A **line-interactive** design combines the characteristics of on-line and off-line designs. The inverter in this design performs a dual function. Under normal operation, it keeps the battery fully charged. When a power supply failure is detected, the inverter is disconnected from the supply and power is provided from the battery through the inverter to the load. Similar to an off-line UPS, line-interactive technology is efficient because power is normally supplied directly from the line. Heat and stresses are minimised because the line-interactive UPS delivers only incremental power, compensating for line voltage sags via the output transformer. Like the on-line UPS, it also provides continuous power. However, the line interactive UPS does not provide the complete isolation between the line and load that is offered by the on-line UPS.

The input converter of a UPS is very similar to that for the variable speed drive discussed above and results in similar harmonic distortion. During normal operation the off-line and line interactive designs draw a relatively low input current, having only to maintain the battery charge, but the installation design must take account of the effect of the full load current which will flow when recovering from a blackout.

The load on the output of the UPS is invariably composed of IT equipment and is therefore non-linear and rich in low order harmonics. The output transformer of the UPS must be adequately rated to cope with the excess heating that will result.

In three-phase systems the 'triple-N' harmonics (i.e. harmonics which are an odd multiple of three) add in the neutral. All neutral conductors within the UPS and in the rest of the distribution circuit should be adequately rated to carry these increased currents, which can approach twice the phase current (see Section 4.2.1.3).

Provision of a third harmonic filter on the UPS output is desirable, but will often require very large and expensive components.

When specifying a UPS care should be taken to ensure that the true nature of the load is understood and properly communicated to the supplier.

Magnetic cored devices

The relationship between the magnetising current and the resulting flux density in an inductor with a magnetic core is inherently non-linear. If the current waveform is constrained to be sinusoidal, i.e. the series *resistance* in the circuit is high, then the magnetic field will contain harmonics. This is referred to as forced magnetisation. If the voltage across the coil is sinusoidal, i.e. the series resistance is low, the flux density will also be sinusoidal but the current will contain harmonics – this is free magnetisation.

Transformers typically introduce a small amount of *voltage* distortion, about 1.5%, into the output waveform. Fluorescent light fittings using chokes generate some harmonics due to the non-linear behaviour of the lamp itself (it has a negative dynamic resistance) and the non-linear behaviour of the core. Levels are generally lower than those produced by electronic ballasts.

4.1.1. Theoretical background – How harmonics are generated

In an ideal clean power system, the current and voltage waveforms are pure sinusoids. In practice, non-sinusoidal *currents* result when the current flowing in the load is not linearly related to the applied voltage. In a simple circuit containing only linear circuit elements - resistance, inductance and capacitance - the current which flows is proportional to the applied voltage (at a particular frequency) so that, if a sinusoidal voltage is applied, a sinusoidal current will flow, as illustrated in Figure 18.

The load-line is the relationship between the voltage applied and the current that results in the load; that shown in Figure 18 corresponds to a linear load. Note that where there is a reactive element there will be a phase shift between the voltage and current waveforms; the power factor is reduced, but the circuit can still be linear.

Figure 18 - Current waveform in a linear load

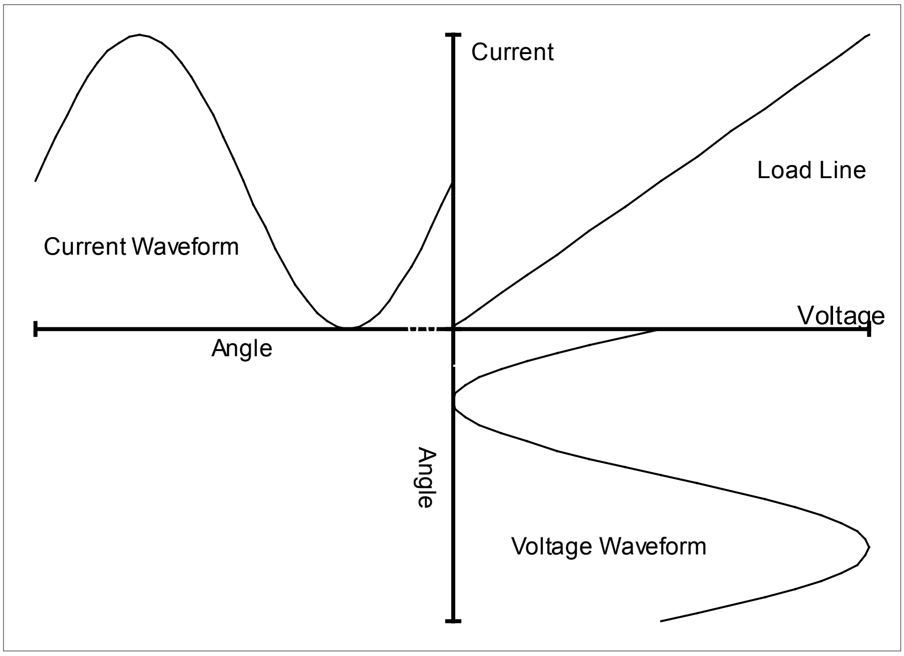
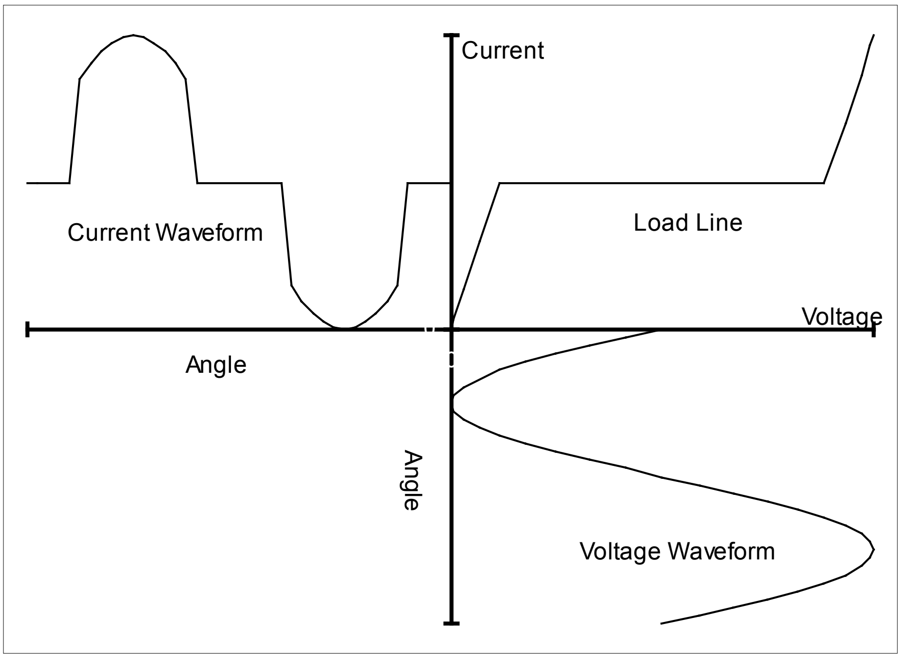


Figure 19 shows the situation where the load is a simple full-wave rectifier and capacitor. In this case, current flows only when the supply voltage exceeds that stored on the reservoir capacitor, i.e. close to the peak of the voltage sine wave, as shown by the shape of the load line.

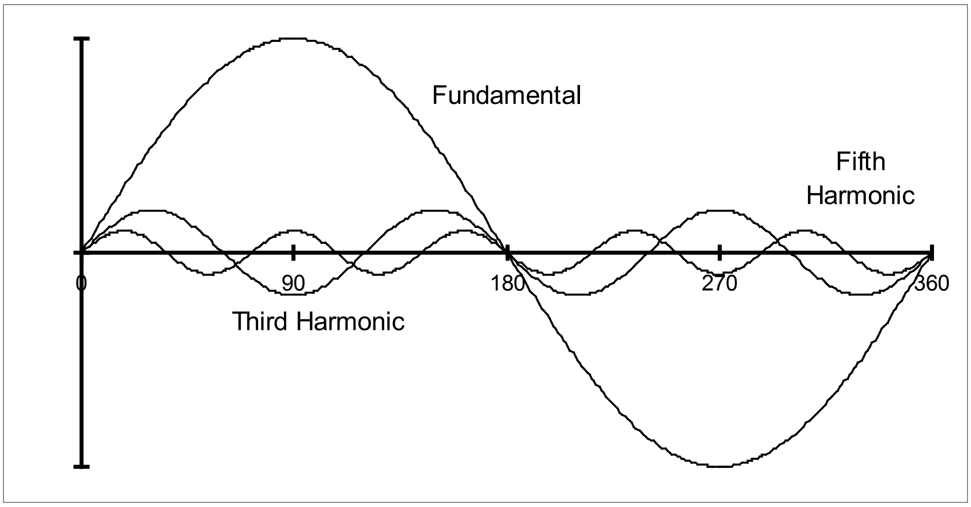
Figure 19 - Current waveform in a non-linear load



In practice, the load line (and hence the current waveform) is likely to be much more complex than shown in this illustrative example; there may be some asymmetry and hysteresis and the breakpoints and slopes will change with loading. Note that this case represents a typical SMPS.

Any cyclical waveform can be de-constructed into a sinusoid at the fundamental frequency plus a number of sinusoids at harmonic frequencies. Harmonic frequencies are integral multiples of the fundamental, e.g. for a fundamental of 50 Hz, the second harmonic would be 100 Hz and the third harmonic would be 150 Hz. Figure 20 shows a fundamental sine wave with third and fifth harmonics.

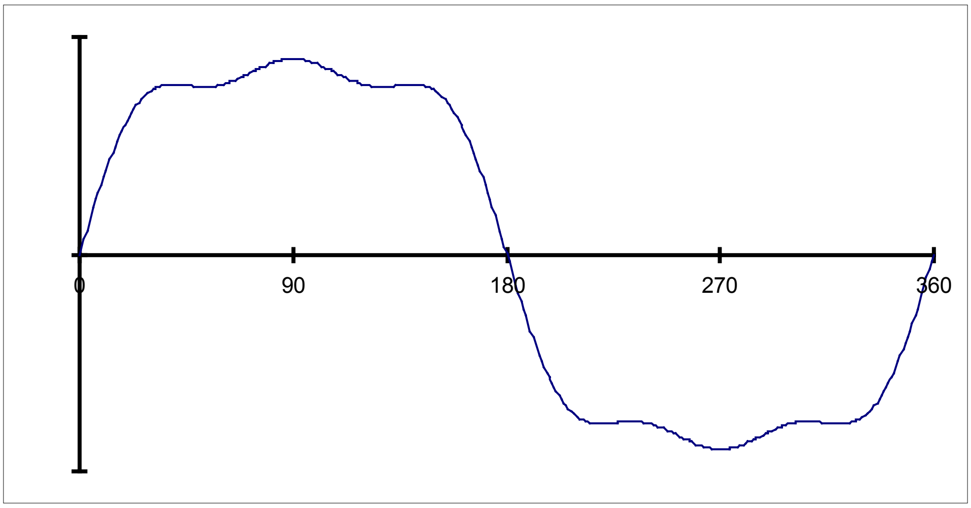
Figure 20 - Fundamental with third and fifth harmonics



Thus the distorted current waveform in Figure 19 can be represented by the fundamental plus a percentage of second harmonic plus a percentage of third harmonic and so on, possibly up to the thirtieth harmonic.

Figure 21 shows a fundamental with 20% third harmonic and 10% fifth harmonic added. Note that in practice most distorted current waveforms will be much more complex than this example.

Figure 21 - Distorted current waveform



4.2. Problems caused by harmonics

Harmonic currents cause problems both on the supply system and within the installation. The effects and the solutions are very different and need to be addressed separately; the measures that are appropriate to controlling the effects of harmonics within the installation will not reduce the distortion caused on the supply and vice versa.

4.2.1. Harmonic problems within the installation

There are several common problem areas caused by harmonics: -

- voltage distortion
- zero-crossing noise

- overloading of neutrals
- overheating of transformers and induction motors
- nuisance tripping of circuit breakers
- over-stressing of power factor correction capacitors
- skin effect

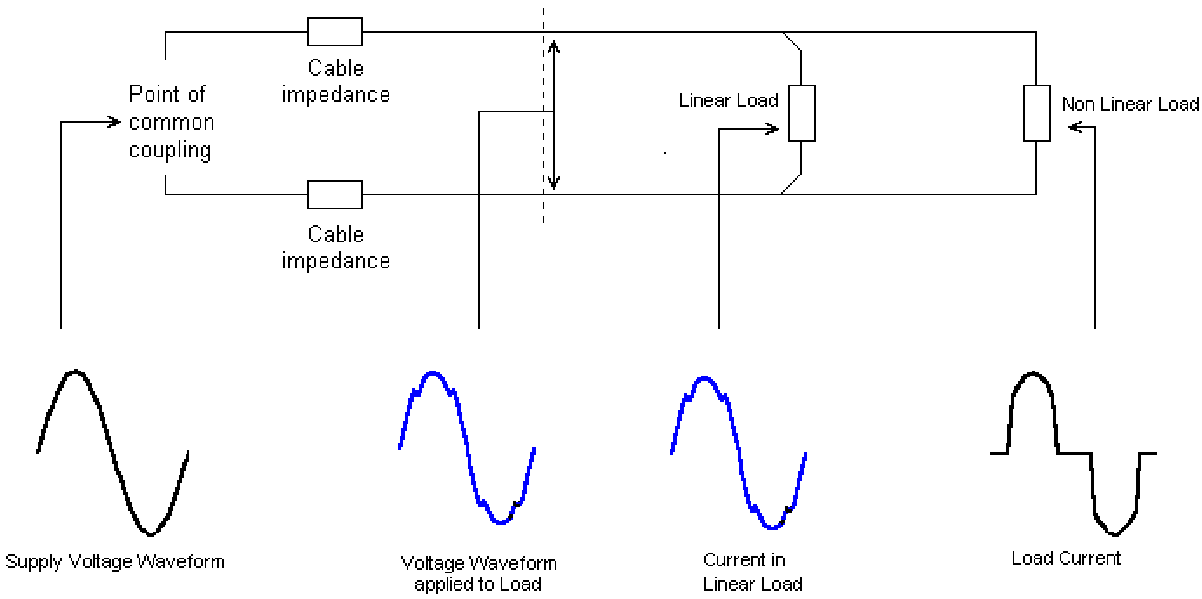
Each of these areas is discussed briefly below.

4.2.1.1. Voltage distortion

Because the supply has source impedance, harmonic load currents give rise to harmonic voltage distortion on the voltage waveform (this is the origin of 'flat topping'). There are two elements to the impedance: that of the internal cabling from the point of common coupling (PCC), and that inherent in the supply at the PCC, e.g. the local supply transformer. The former is illustrated in Figure 22.

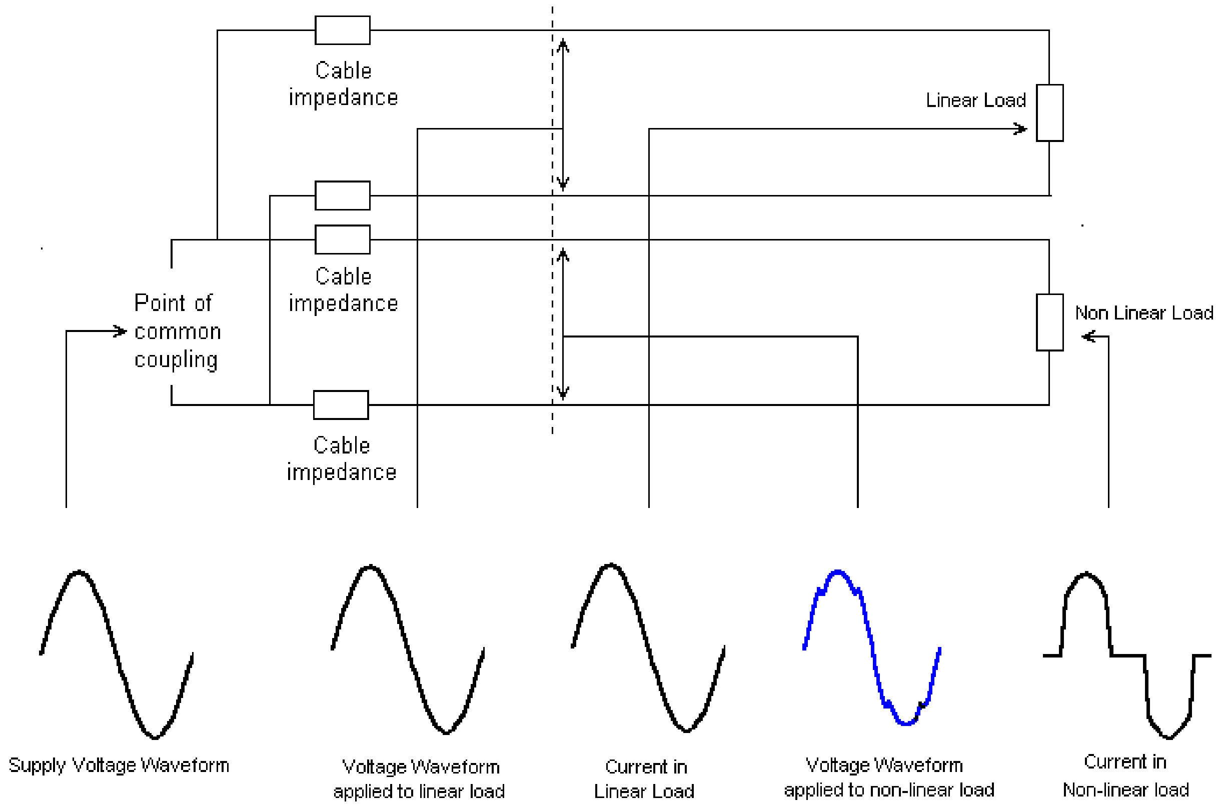
The distorted load current drawn by the non-linear load causes a distorted voltage drop in the cable impedance. The resultant distorted voltage waveform is applied to all other loads connected to the same circuit, causing harmonic currents to flow in them - even if they are linear loads.

Figure 22 - Voltage distortion caused by a non-linear load



The solution is to separate circuits supplying harmonic generating loads from those supplying loads which are sensitive to harmonics, as shown in Figure 23. Here the linear and non-linear loads are fed by separate circuits from the point of common connection, so that the voltage distortion caused by the non-linear load does not reach the linear load.

Figure 23 - Separation of linear and non-linear loads



For simplicity, these examples assume that the source impedance at the PCC is zero. In reality the source impedance is low but finite and has an inductive component that increases the harmonic voltage distortion resulting from the harmonic currents.

Where local transformers are installed, they should be selected to have sufficiently low output impedance and to have sufficient capacity to withstand the additional heating, in other words, by selecting an appropriately oversized transformer. Note that it is not appropriate to select a transformer design in which the increase in capacity is achieved simply by forced cooling – such a unit will run at higher internal temperatures and have a reduced service life. Forced cooling should be reserved for emergency use only and never relied upon for normal running.

4.2.1.2. Zero-crossing noise

Many electronic controllers detect the point at which the supply voltage crosses zero volts to determine when loads should be turned on. This is done because switching inductive loads at zero voltage does not generate transients, so reducing electromagnetic interference (EMI) and stress on the semiconductor switching devices. When harmonics or transients are present on the supply the rate of change of voltage at the crossing becomes faster and more difficult to identify, leading to erratic operation. There may in fact be several zero-crossings per half cycle.

4.2.1.3. Neutral conductor over-heating

In a three-phase system the voltage waveform from each phase to the neutral star point is displaced by 120° so that, when each phase is equally loaded, the combined current in the neutral is zero. When the loads are not balanced only the net out of balance current flows in the neutral. Installers (with the approval of the standards authorities) have taken advantage of this fact by installing *half-sized* neutral conductors. However, although the fundamental currents cancel out, the harmonic currents do not - in fact those that are an odd multiple of three times the fundamental, the 'triple-N' harmonics, add in the neutral. A recent case study found a neutral current of 150 Amps while the phase currents were only 100 Amps. The neutral current can easily approach *twice* the phase currents in a *half-sized* conductor!

Neutrals should have a cross-sectional area which is 200% that of the phases and this is most easily achieved using five core cable; one core for each phase and two for the neutral, all of equal cross-sectional area. Five-core cable is readily available from some European manufacturers.

If it is not possible to source a suitable five-core cable, it is best to use a separate double sized cable for the neutral. The alternative of adding a separate parallel neutral cable to an existing four-core installation is less satisfactory - because it is physically separated, the mutual inductance between it and the phases is lower than between the integral neutral and the phases. This has the effect of increasing the apparent impedance of the external conductor, which consequently carries a lower share of the neutral current.

4.2.1.4. Effects on transformers and induction motors

Transformers

The way in which a three-phase transformer responds to harmonics depends on the connection configuration used.

For a star-star configuration, any imbalance in the phase currents results in the star point being electrically displaced and the phase to neutral voltages unequal. Triple-N harmonic currents cause harmonic voltages to appear on both primary and secondary phase-to-neutral voltages and as ripple on the star point voltage. If the primary is fed by a four-wire system, i.e. star point is connected to neutral, the voltage distortion is removed, but a harmonic current flows in the primary neutral, so exporting the distortion onto the supply system. This can be overcome by adding a delta tertiary winding, rated at about 30% of the transformer rating, which provides a path for circulating unbalanced and triple-N harmonics, and thus prevents them propagating back into the supply distribution system.

In the delta-star configuration, the unbalanced and triple-N currents circulate in the delta winding of the primary and do not propagate onto the supply system. This configuration is the one most commonly used for distribution transformers.

Note that all other harmonics do propagate back onto the supply and can be widely distributed as a result. As would be expected, the lower harmonics are the most troublesome because they are larger, less attenuated by the system impedance and more difficult to remove at source.

All harmonics, whether propagated or not, cause increased losses in the transformer winding and core. Circulating currents do no useful work, but cause excess loss and increased temperature in the winding. Magnetic and eddy losses are increased at the higher harmonic frequencies; the transformer eddy current loss increase can be calculated by:

$$P_{eh} = P_{ef} \sum_{h=1}^{h=h_{\max}} I_h^2 h^2$$

where:

P_{eh} is the total eddy current loss

P_{ef} is the eddy current loss at fundamental frequency

h is the harmonic order

I_h is the RMS current at harmonic h as a percentage of rated fundamental current

and the stray losses by:

$$P_{sh} = P_{sf} \sum_{h=1}^{h=h_{max}} I_h^2 h^{0.8}$$

where:

P_{sh} is the total eddy current loss

P_{sf} is the eddy current loss at fundamental frequency

h is the harmonic order

I_h is the RMS current at harmonic h as a percentage of rated fundamental current

The factor $\sum_{h=1}^{h=h_{max}} I_h^2 h^2$ is also referred to as the K-Factor; transformer rating plates frequently state the maximum K-Factor. Where no rating is stated, it must be assumed to be one.

These equations give accurate results for low order harmonics up to the ninth but tend to over estimate losses for higher harmonics. They also assume that the source impedance is constant for all harmonics which is not so in practice.

Large transformers often have parallel windings in which it can be difficult to achieve good load sharing. This problem is compounded when harmonics are present because generally they will not share in the same proportion as the fundamental. Computer modelling techniques are now available to assist in transformer design but transformers that are required to supply harmonic generating loads need to be carefully and completely specified so that the manufacturer can take appropriate measures to control losses.

Induction Motors

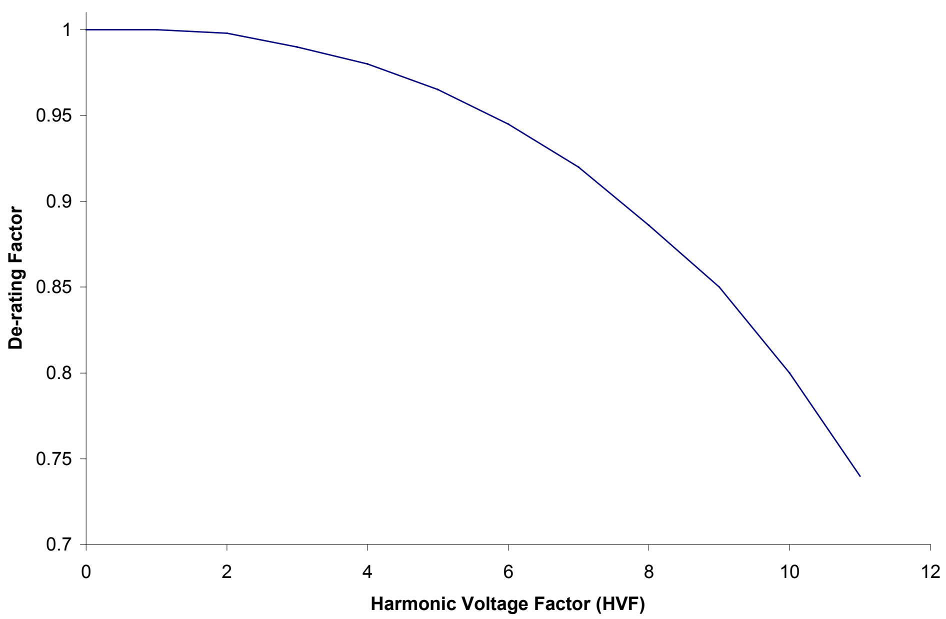
Harmonic distortion causes increased losses in motors in the same way as in transformers. However, additional losses arise due to the production of harmonic generated fields. Each harmonic has a sequence, positive, negative or zero, which indicates the direction of rotation that would result if it were to be applied to an induction motor relative to the positive rotation of the fundamental.

Harmonic Number	1	2	3	4	5	6	7	8	9	10	11	12
Phase sequence	+	-	0	+	-	0	+	-	0	+	-	0

Zero sequence harmonics, the third and multiples of third (the so-called ‘triple-N’ harmonics) , produce a stationary field, but since the harmonic field frequencies are higher, the magnetic losses are greatly increased and the harmonic energy is dissipated as heat. Negative sequence harmonics result in a counter-rotating field (with respect to the fundamental) which results in reduced torque and, as for zero sequence harmonics, higher losses. Positive sequence harmonics produce a forward rotating field that adds to the torque; this, together with the negative sequence torque components can result in vibration and reduced service life of the motor.

Where harmonics are present motors should be de-rated according to the curve[7] in Figure 24.

Figure 24 - Motor de-rating curve for harmonic voltages



The Harmonic Voltage Factor (HVF) is defined as:

$$HVF = \sqrt{\sum_{n=5}^{n=\infty} \frac{V_n^2}{n}}$$

where

V_n is the RMS voltage at the nth harmonic as a percentage of the fundamental

n is the order of odd harmonic, excluding triple-N harmonics.

This sensitivity to harmonics underlines the need to provide dedicated circuits to isolate motors from problem loads. (See also Section 7.2.1 regarding the effects of unbalanced phase voltages on three phase motors.)

4.2.1.5. Nuisance tripping of circuit breakers

Residual current circuit breakers (RCCB) operate by summing the current in the phase and neutral conductors and, if the result is not within the rated limit, removing the power from the load. Nuisance tripping can occur in the presence of harmonics for two reasons. Firstly, the RCCB, being an electromechanical device, may not sum the higher frequency components correctly and therefore trip erroneously. Secondly, the current flowing in the circuit will be higher than that expected from calculation or simple measurement due to the presence of harmonic currents. Most portable measuring instruments do not read true RMS values; instead, they measure the average and then apply a correction factor that assumes that the waveform is a pure sine wave. When harmonics are present this results in a reading that can be much lower than the true one and this can mean that over-current trips are set at too low a value. True RMS measurement requires a wide frequency response and accurate high-speed multiplication, making it difficult to implement in low cost portable instruments until recent progress in digital signal processing techniques. Modern hand-held instruments are capable of measuring waveforms with a crest factor greater than three with an accuracy (including the current transformer) of 5%. The crest factor is the ratio of peak value to RMS value; for a sinewave it is 1.41.

Circuit breakers are now becoming available which sense the RMS value of the current: these, together with true RMS measurement should provide reliable operation.

4.2.1.6. Over-stressing of power factor correction capacitors

Power-factor correction capacitors are provided in order to draw a current with a leading phase angle to offset lagging current drawn by an inductive load such as induction motors. The impedance of a capacitor is inversely proportional to frequency, so the impedance to harmonic currents is very low and tends to 'hog' the harmonic current. Unless the capacitor is specifically designed to handle these high harmonic currents, serious damage can occur, often resulting in the catastrophic disintegration of the unit.

A second problem is that the capacitor and the leakage inductance of the supply transformer can resonate at or near one of the harmonic frequencies leading to very high currents or voltages.

Resonance can be avoided by adding an inductance in series with the capacitor such that the combination is just inductive at the lowest significant harmonic. This solution also limits the harmonic current hogging that can occur in the capacitor. The physical size of the inductor can be a problem, especially when low order harmonics are present.

4.2.1.7. Skin effect

Alternating current tends to flow on the outer surface of a conductor. This is known as skin effect and is more pronounced at high frequencies. Skin effect is normally ignored because it has very little effect at power supply frequencies but above about 300 Hz, i.e. the seventh harmonic and above, skin effect will become significant, causing additional loss and heating. Where harmonic currents are present, designers should take skin effect into account and de-rate cables accordingly.

Multiple cable cores or laminated busbars can be used to help overcome this problem and design guidance is given in CDA Publication 22, ‘Copper for Busbars’.

4.2.2. Harmonic problems affecting the supply

The Electricity Supply Regulations 1988 states that no customer should interfere unduly with the supply to another. However, since the supply system has impedance, the harmonic load currents drawn from it by one customer will cause voltage distortion on the supply to all others on the same distribution circuit. Worse, some of the harmonic distortion will be fed back through the distribution transformer to higher voltage networks and be distributed very widely. ‘Unduly’ is an imprecise word!

It has been reported[8] that the level of harmonic voltage distortion on the low voltage network closely reflects television viewing patterns, reaching 2.5% during weekday evenings and 3.5% during weekend evenings. This distortion is also measurable on the 11kV system where distortion levels rise significantly during weekend evenings due to the high level of television usage and the low level of the base resistive load.

The G5/3 standard sets limits for harmonic voltage distortion, and a supplier may refuse to supply power to a site that exceeds these limits. There are three stages of G5/3. Stage 1 defines the size of equipment in terms of kVA that can be connected without further consideration. This applies to all premises where the REC would not have detailed knowledge of the load. There is some evidence that these limits are too generous since some types of equipment, such as television receivers and personal computers are connected in very large numbers, causing the harmonic voltage distortion limits of G5/3 to be reached or exceeded throughout the network. There is a clear correlation between television viewing patterns and the level of harmonic distortion.

Stage 2 sets a limit for each harmonic current that the customer may draw. These limits assume that the supply is not of higher than average source impedance, and that the level of distortion is not already excessive. It follows that conformance with Stage 2 does not guarantee that the distortion limits set in Stage 3 will not be breached, and that it is not possible for an equipment manufacturer to claim compliance with G5/3 – the manufacturer cannot know where the equipment will be installed!

Stage 3 limits the permitted total and individual harmonic voltage distortion. Compliance requires detailed measurements to be made.

The voltage distortion that results from a distorted current depends on the source impedance; the higher the impedance, the higher the voltage distortion resulting from a particular current distortion. The supply network is generally inductive for harmonics up to the tenth order, so the source impedance is proportional to frequency and the higher the harmonic the more distortion will result. It is not normally possible to reduce the supply impedance so other steps are required to ensure that the limits on voltage distortion are not exceeded. The appropriate measure depends on the precise nature of the cause. Possible solutions include:

- Harmonic filters
- Isolation transformers
- Active harmonic conditioners

In the case of a motor controller, where the harmonic profile is well defined, a filter can be used to reduce the harmonic current. For a six-pulse controller the filter must remove the 20% fifth harmonic and all the higher harmonics while having little effect at the fundamental. To avoid a gain peak close to a harmonic a de-tuned filter must be used, and it may be necessary to use a number of filters. The situation is somewhat simpler in the case of twelve-pulse bridges where the lowest harmonic is the 11^{th}.

When the harmonic profile is unpredictable or where substantial third harmonics are present filtering is not practical. Typically, such situations might include:

- Single phase UPS supplies (significant third harmonic)
- Computer installations (significant third harmonic)
- Converter/inverter drives (non-integer harmonics)

Propagation of balanced third harmonic currents back onto the supply can be reduced by using a Delta/Star isolating transformer. Where such a transformer is used, it is usual to provide a bypass circuit around it so that maintenance can be performed without necessitating a long-term disconnection of the load. In this case, a conventional four-wire feed must be provided to make the neutral available, which must be adequately oversized. In critical systems, local isolation transformers are sometimes installed at each distribution unit: this effectively establishes a new local neutral so that the triple-N currents are isolated from the distribution system. The temptation to downsize the neutral feed conductor should be resisted – when the transformer bypass is in use the neutral will have to carry the full triple-N and unbalanced currents. The transformer must be appropriately rated for harmonic currents of course, otherwise voltage distortion and overheating will result.

The side-bands and harmonics produced by converter/inverter controllers cannot be adequately removed by conventional filters because the side-band frequencies change with drive speed and are often very close to the fundamental. Active harmonic conditioners are now becoming available that operate by actively injecting a current to exactly compensate for the harmonic current drawn by the load so that a pure sinewave results. The operation of the equipment relies on digital signal processing (DSP) techniques to control fast insulated-gate bipolar transistors (IGBT). Since the equipment operates in parallel with the supply, only harmonic current is controlled; the fundamental supply current does not have to pass through the conditioner. If the harmonic current required is greater than the capacity of the conditioner, it simply limits, leaving the waveform partially corrected. It follows that the conditioner can be disconnected for maintenance and, as with the isolation transformer, the distribution cabling on both source and load sides of the conditioner must be capable of carrying the full uncorrected harmonic load and should therefore employ double-sized neutrals.

4.3. Maintenance and measurement

4.3.1. True RMS metering

When voltage and current figures are given for AC circuits they are always assumed to be RMS (root mean square) values unless otherwise defined. The RMS value of a current is that which has the same heating effect as a direct current of the same magnitude. Mathematically, it is the square root of the integral over one complete cycle of the square of the instantaneous value, hence the name root-mean-square. For a pure sinewave, the RMS value is 0.707 times the peak value. The mean value is the area under the waveform (for a complete cycle) divided by the cycle time: for a sinewave is this 0.636 times the peak value. The *form factor* is the ratio between the RMS and mean values and is 1.11 for a pure sinewave.

Measuring RMS values has historically been very difficult. True measurement can be achieved broadly in two ways, either by thermally based devices (which are slow and inaccurate in general use) or by relatively sophisticated electronics (which have been expensive). Most older hand-held instruments arrived at their RMS readings by measuring the *mean* value and then applying a correction factor that is valid only for a pure sinewave.

Over the last few years true RMS reading multimeters have become practical at economical price levels and this type of instrument should always be used when harmonics may be present. Care is still required however - true RMS meters have a maximum limit to the *crest factor* for which accurate results are produced so very highly distorted waveforms will still be misread. The crest factor is the ratio of peak value to true RMS value and a meter with a crest factor rating of three or greater should be used.

More recently, hand held Power Harmonic Meters have become available which measure the harmonic content of the current. These instruments provide useful diagnostic information.

4.3.2. Identifying harmonic problems

A periodic site survey should be carried out to check on the circuits feeding personal computers and printers, adjustable speed motors, solid-state heater controls and dimmers, and fluorescent lighting fixtures equipped with electronic ballasts.

Using a Power Harmonic Meter (PHM), or a true RMS meter, the current in each phase and neutral should be measured at each distribution board and the reading compared to the rating for the wire size used. The presence of harmonics will be clearly indicated by the PHM, while a multimeter may indicate a frequency other than the fundamental. In three-phase circuits the neutral current should be compared to that expected from the imbalance of the phases - any difference indicates the presence of harmonics.

Similar measurements should be made on all feeders and busbars and at any local transformers to check for harmonics and excess imbalance and to make sure that adequate de-rating factors have been used.

5. Earthing and Earth Leakage

Earthing of electrical systems is required for a number of reasons, principally to ensure the safety of people near the system and to prevent damage to the system itself in the event of a fault. The function of the protective conductor, or earth, is to provide a low resistance path for fault current so that the circuit protective devices operate rapidly to disconnect the supply. The resistance of the earth path must be low enough so that the potential rise on the earth terminal and any metalwork connected to it is not hazardous; a value of 50 volts is often quoted, but some locations and circumstances require a lower limit.

With the massive increase in the use of electronic equipment in commercial and industrial premises, especially personal computers and their related communications equipment, the situation has changed. Safety under fault conditions is now just one of the functions of the protective conductor; it must also carry the leakage currents from electronic equipment and must provide a noise-free ground reference required by the equipment. There are now three aspects to consider in the design of the earthing system:

- Safety
- Leakage currents
- Noise

5.1. Earthing for safety

The primary purposes of the earthing system of a building are to ensure that a safe environment is maintained for the occupants and to protect equipment from damage in the event of a fault. This is achieved by:

- providing a safe low resistance path to earth for fault currents so that protection equipment can operate swiftly
- establishing an equipotential platform on which equipment can be safely operated
- bonding metalwork to earth

BS 7671:1992, 'Requirements for Electrical Installations' gives detailed regulations covering earthing within buildings, and BS 7430:1991, 'Code of Practice for Earthing' gives detailed guidance on the design and specification of the earthing system. CDA Publication 119, 'Earthing Practice' gives an overview of the subject as a whole.

5.1.1. Typical earthing systems

Earthing systems are referred to by a letter code indicating their characteristics.

The first letter indicates

T one or more points of the supply are directly earthed (e.g. the neutral at the supply transformer)

I either the supply is not earthed at all, or it is earthed through a deliberately inserted impedance to limit the fault current. This system is **not permitted** for public supplies in the UK.

The second letter indicates

T all exposed metalwork and conductive metalwork is connected directly to earth

N all exposed metalwork is connected directly to an earthed supply conductor provided by the electricity supply company.

The third and fourth letters indicate

S neutral and earth conductor systems are quite separate

C neutral and earth conductors are combined.

Combinations of types are common; in the TN-C-S system the earth and neutral conductors are combined in the supply but are separated at the point of common connection and remain separate throughout the installation. On the supply side, there may be multiple connections between the combined neutral/earth and the mass of the earth - referred to as protective multiple earth (PME) - or a single connection - referred to as protective neutral bond (PNB). The majority of systems in the UK are TN-C-S systems with PME.

5.1.2. Ground connections

In earlier practice, it was considered sufficient merely to provide a suitably low impedance connection to the mass of the earth. This was often achieved by providing a single earth rod or a buried horizontal conductor of sufficient length to give the required resistance value. This is no longer adequate, and consideration must now be given to the potential field that arises around the earth connection when a large fault current flows into it. A brief outline of the principles follows; a fuller discussion can be found in CDA publication 119, 'Earthing Practice'.

If a single rod is used, electrons will flow in all directions into the mass of the earth (assuming that the resistivity of the earth surrounding the electrode is homogeneous). As the current spreads out, the area through which the current flows increases as the square of the distance from the rod, and the voltage gradient reduces similarly.

A person standing near the earth rod is standing on the voltage gradient, and will be at the voltage appropriate to his position - the closer to the rod, the higher the voltage. If our person stands as far as possible from the rod while he can just reach the earth rod (or any metal work connected to it), then the voltage difference between the two will be a maximum. This is called the *touch voltage*. If he were to stand with one foot next to the rod, and the other foot a pace away, radially, then there would be a voltage difference between his two feet, and this is called the *step voltage*. There will be a voltage between his feet wherever he is standing, but it will be highest closest to the rod.

The *transfer voltage* is the voltage difference between the earth rod (and any metalwork connected to it) and an insulated cable connected to a remote earth. It applies equally to the complimentary condition of an insulated cable from the earth rod taken to the vicinity of a remote earth.

Modern earthing practice aims to reduce these voltages by careful design of the earthing system.

The transfer voltage simply depends on the size of the fault current and the resistance of the earth connection - it is in fact the traditional consideration of earlier practice - and the lower the earth resistance, the better. The factors that affect resistance are the physical dimensions and form of the earth electrode and the soil condition. For example, the resistance of the earth contact will reduce as the length of the rod (and to a lesser extent as the radius of the rod) increase, as the side length of a square plate increases, or as the length of a horizontal conductor increases. Several formulae are available to calculate the effective resistance from the resistivity of the soil and examples can be found in BS 7430 and in CDA Publication 119. Obviously, there are limits to the real benefits that can be gained merely by increasing size, and careful calculations need to be made.

The touch voltage depends not only on the earth resistance but also on the physical positioning of the earth point and the equipment. By installing a buried perimeter conductor around the installation, connected to the earthing system, an equipotential area is established covering the whole of the area within the conductor loop. Now any person who can reach out and touch the enclosure metalwork must be standing within the perimeter conductor and is therefore at the top of the voltage gradient where the touch voltage is low. The larger physical size of the earth electrode system has two additional advantages; the current density in the mass of the earth is reduced, making the voltage gradient much less steep, lowering the step voltage, and the earth resistance is also lower, reducing the maximum fault voltage.

National regulations regarding the use of structural and utility metalwork for earthing vary greatly from country to country. The use of gas and fuel pipes *as earth electrodes* is generally prohibited, while some codes (but not the UK) allow the use of water pipes with permission of the owner of the pipe. The use of structural steelwork is generally permitted, but there may be special limitations attached. It is generally required that all such metalwork is bonded to the earthing system whether or not use as an electrode is permitted.

5.1.3. Bonding

Bonding is the practice of connecting all accessible metalwork - whether associated with the electrical installation (known as exposed-metalwork) or not (extraneous-metalwork) - to the system earth.

When a fault occurs in the electrical system in a building an elevated voltage results on the system earth and hence on exposed metalwork connected to it such as equipment housings. This voltage is higher than that of the mass of the earth because the earthing system has resistance and the fault current is flowing through it. Much of the extraneous metalwork in a building, such as water and gas pipes and structural steelwork, is connected to the mass of the earth by default. If it were not bonded to the system earth, a voltage would exist between this extraneous metalwork and the system earth. Anyone in simultaneous contact with extraneous metalwork and the external metalwork of electrical equipment would be exposed to a potential shock hazard. Bonding of extraneous metalwork to the system earth removes this hazard and provides a so-called equipotential environment.

Typically, metalwork such as water and gas mains, radiators, building framework, metal stairways and handrails, metal floors and racking, etc. must be bonded.

The bonding must be installed in such a way that the removal of a bond for maintenance of equipment does not break the connection to any other bond. This can be achieved for example by using one continuous conductor looping into each service connection in an area, so that removal of a clamp does not break the connection to further points. Because some metalwork may not be electrically continuous - for example, there may be joints in pipework and cable trays - supplementary bonding must be provided to bridge non-conducting sections. Again, these supplementary bonds must be installed in such a way that maintenance work does not disrupt the bonding to further sections.

Bonding of metalwork that is not permitted for use as an earth electrode by the local regulations must be carefully controlled to avoid normal earth currents flowing. For example, a gas supply pipe should be bonded to the earthing system at the point where it enters the building and nowhere else, although there must be a supplementary bond across each joint. If multiple bonding were used then the pipe would act as a part of the earthing system in contravention of the regulations.

In the UK, BS 7671 requires that the cross-sectional areas of the bonding conductor must not be less than half that of the main protective earth conductor subject to a minimum of $6mm^2$. For TN-C-S systems, the maximum cross-section is $25mm^2$. Supplementary bonds must be of at least $2.5mm^2$ copper if mechanically protected or $4mm^2$ copper if unprotected.

Naturally, it is essential that all bonding be maintained over the whole lifetime of the building, during which there may be many changes of use and considerable change in equipment and facilities. Management policies must ensure that adequate records are retained to ensure that future work can be carried out without disturbing existing bonding. This applies as much to the removal of existing plant as it does to the installation of new plant.

5.2. Earthing in a high leakage current environment

Most modern electronic equipment uses switched mode power supplies (SMPS) which draw pulses of current from the mains supply rather than a continuous sinusoidal current. The fast rise time edges of the current waveform contain high frequencies that can cause serious radio frequency interference (RFI) to other equipment in the vicinity. To prevent propagation of this interference on to the supply each SMPS incorporates a filter on the input consisting of a small series inductor in both the phase and neutral lines with a small capacitor to ‘earth’ from each.

Since the filter capacitor provides a path from phase to the protective conductor, current will flow. This current is made up of a small current (permitted by regulation to be up to 3.5 mA) at the fundamental frequency, a small fraction of each harmonic frequency present and high frequency transients caused by switching.

Because of the high population of electronic equipment in a modern office leakage currents can be significant; typically each desk will have at least a personal computer and monitor, each contributing to the leakage current. This amounts to a change of function for the protective conductor system; while it used to be provided only to carry current in the event of a fault it is now required to carry a continuous leakage current as well as serving as a sink for high frequency noise currents. (The latter is often referred to as functional earthing).

Now that the protective conductor has both safety and functional requirements to fulfil, the designer must take many more factors into consideration during design, and the services manager must be vigilant to ensure safe use. For example:

- Integrity – to ensure the safety of operators and the public
- Impedance – to improve reliability and prevent data loss
- Residual current circuit breakers
- Maintenance and Housekeeping

5.2.1. Integrity

Since the protective conductor is now carrying a leakage current, any break in the 'earth' side connection to it will mean that the isolated section will rise to a potentially lethal voltage – half of the supply voltage - as will all the exposed metalwork connected to it. The current available to flow will depend on the total leakage current of the equipment connected to that section. In a typical modern office a final ring circuit could serve up to 16 operators (an area of 100 m^2), each with at least a PC and monitor, so that the possible earth-leakage current for the ring is 112mA. This is likely to be fatal.

BS 7671 attempts to improve the integrity of such circuits by requiring that a final circuit in which the leakage current is expected to exceed 10 mA must meet either of the following two requirements:

Either

(a) A high integrity earth must be provided by one of the following methods:

(i). A single protective conductor with a cross-sectional area of not less than 10 mm^2.

(ii). Separate duplicate protective conductors with a cross-sectional area of not less than 4 mm^2, independently connected.

(iii). Duplicate protective conductors incorporated in a multi-core cable with the live conductors of the circuit if the total cross sectional area of all the conductors is not less than 10 mm^2. One of the conductors may be formed by metallic armour, sheath or braid incorporated in the construction of the cable.

(iv). Duplicate protective conductors formed by conduit, trunking or ducting and a conductor having a cross-sectional area of not less than 2.5 mm^2 installed in the same enclosure and connected in parallel with it.

(v). An earth monitoring device which, in the event of a discontinuity in the protective conductor, automatically disconnects the supply of the equipment.

(vi). Connection via a double wound transformer where the input and output circuits are electrically separated. The protective conductor between the equipment and the isolating device must be provided by one of the methods (i) to (v) above.

Or,

(b) The final circuit must be a ring connecting single socket-outlets with no spurs. Each end of the protective conductor ring must be individually terminated (i.e. separate connections, individually screw clamped) to the distribution board.

These regulations are designed to ensure that the protective connection is as robust as possible so that the risk of shock to users is minimised. They apply specifically to final circuits, but the same considerations apply to the whole of the cabling from the point of common connection through to the final equipment.

One serious problem is that these regulations apply to final circuits in which the leakage current is *expected* to exceed 10 mA. Often, the use of the circuit is not known to the installer, and indeed changes over the lifetime of the building, so the above requirements are not implemented. This means that many circuits do not have the required protective conductor integrity to safely supply IT and other electronic equipment.

5.2.2. Impedance

If the earth is to be effective, it must be designed to have low impedance at all frequencies, otherwise the high frequency noise voltages will build up on the earth and will be distributed as interference throughout the installation.

The methods given in the BS 7671 Regulations are designed to ensure safety and vary considerably in their suitability for high frequencies noise currents.

Method (a)(v) and (a)(vi) are designed to provide safe operation where the path to earth cannot be guaranteed and are not appropriate where electrical noise is likely to be a problem.

Methods (a)(i), (a)(ii) and (b) all require protective conductors with substantial cross-sectional areas, so these methods are likely to provide a good low impedance path at high frequencies with good noise performance. (See section 5.3)

Methods (a)(iii) and (a)(iv) rely on a relatively small conductor backed up by either metalwork or armouring. The use of these methods can cause problems.

> At high frequencies, the impedance of cable armouring is significant so almost all the noise current will flow via the alternative protective conductor path. However, should the alternative conductor, or one of the connections to it, fail, then a significant noise voltage will result between the ends of the armouring. This is likely to cause interference with local data cabling and computer networks.
>
> Impedance at higher frequencies is less of a problem for conduit or trunking used as an earth path than for armoured cable. However, should the alternative conductor, or one of the connections to it, fail, the safety hazards of large earth leakage currents flowing in frequently unlabelled, exposed metalwork is significant. In particular, the problem may arise of a high impedance primary earth route causing combined earth leakage currents to flow back into a building infrastructure. In such instances, several amps may flow in conduit where negligible current is expected.

5.2.3. Residual current circuit breakers (RCCB)

The residual current circuit breaker (RCCB) is designed to trip if the currents in the phase and neutral conductors differs by more than a pre-set amount. It can be used to ensure that the total leakage current on a final circuit does not exceed a pre-determined (safe) value.

An RCCB with an operation time of less than 40 ms at a residual current of 30 mA is generally accepted as providing adequate protection against electric shock. This applies to the situation where an accidental contact has been made between the phase conductor and the protective conductor, but is also appropriate as a limit when the contact is between a temporarily disconnected protective conductor and true earth. RCCBs should be used to protect all high earth leakage final circuits so that the potential shock hazard from a floating protective conductor is restricted to a safe level. This approach protects personnel by ensuring that too many high-leakage loads cannot be added to final circuits.

RCCBs have often been criticised for so-called nuisance tripping, that is, the supply is disconnected as a result of the normal leakage current rather than as the result of a fault. This is unfair criticism; if the final circuit use is properly managed to ensure that the earth-leakage current is constrained within safe limits then nuisance tripping should not occur.

5.2.4. Maintenance and housekeeping

A full earthing schematic should be produced during the design of the installation, and upon completion, all earthing and bonding conductors should be clearly labelled to show:

- origin
- destination
- that it should not be disconnected without appropriate precautions having been taken

The system should be tested routinely and the method, period and results recorded.

It is particularly important that protective conductors carrying leakage currents are never disconnected while power is connected to the load because all connected equipment (whether turned on or not) will rise to half the supply voltage. When it is essential that tests on the earth be carried out without removing power from the load then an alternative protective path must be provided before disconnection of the normal paths.

If for any reason the connection to earth is poor, then the impedance of the primary earth route will be high and earth leakage currents will seek alternative routes to earth. This may result in current flowing in unexpected places with consequent risk should the system be disconnected.

The common practice of using extension boards and cables to serve several loads from a single power point should not be permitted. Earth leakage currents of the attached equipment summate and are connected to the hardwiring of the building installation by one conductor in a flexible cord that is very easily damaged. In the event of an earth fault, the following situations may develop:

- exposed metalwork goes live at a potentially lethal voltage
- equipment is earthed via the data leads of peripheral equipment. If the mains plug of this remote equipment is unplugged, the earth pin will be live.

In either case, the risk to human life is significant.

If extension boards are necessary, they should be wall-mounted above a height at which they might be kicked and the flexible cord should be trimmed to length and clipped to the wall. Preferably, a secondary protective connection should be provided. Extension cables should *never* be cascaded under any circumstances. Maintenance procedures should be established to ensure that extension cables remain safe.

Wire Managed Desks are simply extension boards built into the office furniture and all the precautions outlined above apply.

An alternative is to use a track distribution system. These systems provide greatly increased flexibility in the positioning of sockets, enabling non-skilled people to make changes and avoid the use of extension leads. The danger is that too many socket outlets are fitted on a ring circuit, leading to overloading and excessive earth leakage current. Maintenance and inspection routines must be established to ensure that these dangers are avoided.

5.3. Noise - functional earthing for sensitive equipment

Noise can cause serious interference to electronic equipment resulting in the corruption or complete loss of data that can require time-consuming procedures for recovery. Many devices, such as communications and IT equipment require a connection to a so-called clean, or quiet, earth in order to function correctly and reliably. This earth is correctly referred to as a functional earth (FE), but is frequently referred to as 'telecom earth' or 'communications earth'.

To be effective it must have low impedance at all frequencies from DC up to several megahertz. A traditionally installed protective conductor is never a good functional earth because it does not have low impedance at high frequencies and is contaminated by high frequency noise currents, such as those produced by the power supplies in modern electronic equipment.

The importance of a clean earth can be seen by considering the case of interconnected units in a traditional 'protective earth' environment.

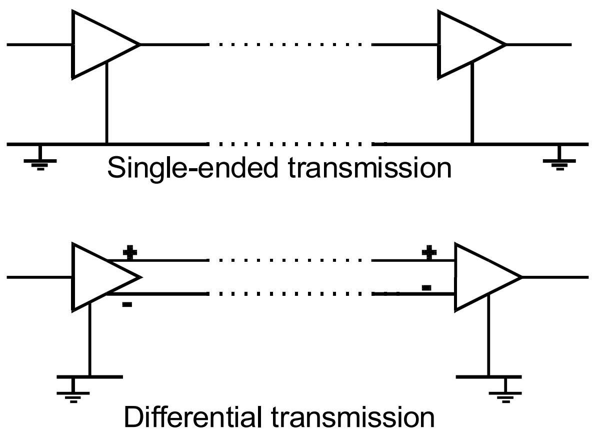
5.3.1. Data interconnection problems

IT equipment interconnects with other equipment over data lines which may be ‘single-ended’ or ‘differential’. Single-ended signals are sent as a voltage level on a single line that is referenced to a ground line carried with the signal line. One ground wire may serve as the reference for several signals and may or may not be bonded to the safety earth at each unit.

If the ground reference is connected with the safety earth at each end, then the signal wire, perhaps only 0.1 mm^2, is connecting the safety earths in different parts of the building. Under normal conditions, such a conductor may carry a circulating current (because the earths will be at slightly different potentials) and will couple noise into the signal. In the event of a fault at one location, fault earth current will flow via the reference to the remote unit presenting a shock hazard and almost certainly damaging the cable and both units before the circuit protection has time to operate. If the ground reference is disconnected from the safety earth one end, then the fault voltage will appear across the disconnection, with similar catastrophic results.

Sometimes the reference wire is connected to safety earth through a resistance of about 100 ohms, so that fault current, equipment damage and shock hazard are all reduced. The reference then has a high impedance to earth, and will therefore be subject to inductively and capacitively coupled noise. Signal voltages are small, often only 2 volts, so noise is very important; single ended signal connections are often limited to very short distances for this reason.

Figure 25 - Single-ended and differential transmission



Differential signals are transferred as a voltage *difference* between two lines without a ground reference. The advantage is that, since the two lines run together (often they are twisted together), noise affects each in the same way so that the differential signal is not changed. The noise is *common-mode* noise because it is the same on each line and any difference between the ground references of the two units appears as a common-mode voltage. In theory, the receiver is sensitive only to the differential signal and immune to common mode noise. Practice is not quite so simple because the ability of the circuits at the receiver to discriminate between the differential signal and the common-mode noise – the common-mode rejection ratio (CMRR) - is finite, and decreases further at high frequencies. Transmission errors will be introduced if the common mode noise is too high. Excessive common-mode voltage can permanently damage the transmitter or receiver circuits. It usual to run a signal ground reference line between the two units, typically tied to the safety ground at each end through a resistance of the order of 100 ohms to reduce circulating and fault currents. Clearly, if communications are to be reliable, all the equipment must operate in an environment where the earth impedance, and therefore the noise on the earth, is low.

Where the distances between units are great, e.g. in different buildings, it is often not possible to guarantee a low-impedance low-noise earth between them. In such a case it is preferable to use a fully isolated system so that voltage differences between the different earths does not cause errors. The obvious way to do this is to use optical fibre to carry the signals, but this is quite expensive and uses relatively fragile cable.

Figure 26 - Optically isolated data transmission

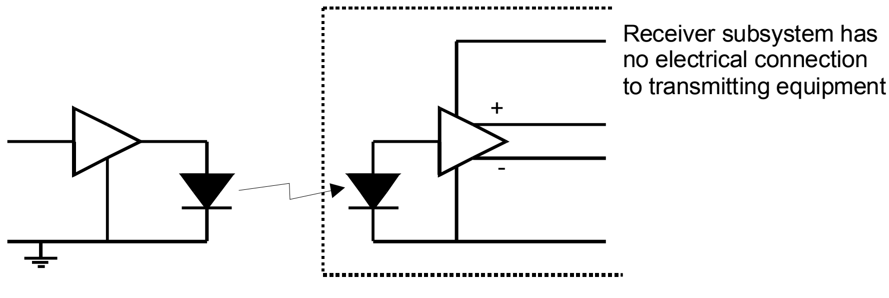


Figure 26 shows an alternative, more economical approach using a short length of optical fibre to feed the signal to a receiver subsystem that is powered from the remote site and is completely electrically isolated from the originating site.

Note that the commonly available semiconductor opto-isolator devices will not provide sufficiently high voltage isolation in most cases.

Isolation up to several thousand volts is easily achieved. It must be remembered that a remote earth is being brought into the zone of another and adequate precautions must be taken to protect operators against the shock hazard that may arise.

5.3.2. Star earth configurations

One method that has been used to attempt to provide a clean earth is the star arrangement. In this scheme, dedicated insulated copper earth conductors from each unit are run directly back to the main earth terminal. This ensures low impedance at the supply frequency and ensures that earth leakage currents of one unit do not flow in the earth path of another, but it is rarely satisfactory at high frequency, because;

- The conductor lengths are long
- When the length of the conductor is close to a quarter wavelength of a noise frequency the impedance will approach infinity i.e. there are resonance effects
- Circulating currents will flow in loops formed by the ground wires of data cables causing induced interference.

Another significant problem is that of maintaining isolation of the clean earth from protective earth (except at the common MET) throughout the extent and life of the installation. The standard colour for insulated earth wires in such a system is cream.

5.3.3. Mesh earth configuration

Within electronic equipment, earth current noise problems are dealt with by providing a continuous ground reference plane. Every circuit board and back-plane has at least one internal layer that is connected to the system ground and is continuous except for necessary feed-through holes. Because there are an infinite number of paths in the plane, there are no quarter-wave resonances and the impedance remains low at all frequencies. It would be ideal if this concept could be extended throughout the building installation; it is obviously not practical to provide a solid plane, but the effect can be simulated by a using a copper mesh, or grid, of suitably small spacing. A mesh provides multiple parallel paths and so does not exhibit resonance and can have very low impedance. The mesh should be made from wide, thin copper strip conductors to reduce skin effect and inductance and it is important that the mesh conductors are properly jointed, preferably by welding, where they cross. There are several methods of fitting the grid, for example: -

- Embedded into or attached to a concrete floor
- Fitted above a suspended ceiling
- As the supporting grid of a raised floor

It is important to maintain the mesh concept throughout the inter-floor connections and the connections to the main earthing terminal (MET). In particular, vertical connections should be short, straight and taken from several points around the floor mesh. They should be cross-connected to form a vertical mesh. Connections to the MET should again be taken from several points on the mesh with cross-connections as appropriate.

To some degree, the bonding of exposed and extraneous metalwork contributes to the mesh, but rarely to such an extent that it is sufficient in itself.

6. Voltage Dips and Transients

Voltage dips and transients are usually blamed on the supplier, but this is often unfair. There are many potential on-site causes; for example, starting of heavy loads may cause voltage dips and switching of inductive loads will generate transients.

Voltage dips

Heavy loads, such as large motors, draw very high starting currents for several seconds as the rotor accelerates causing a voltage drop in the wiring feeding it. This voltage drop will be much greater if the wiring has not been carefully rated to account for the magnitude of the starting current. If other equipment is fed from the same feeder, it will be subject to the same voltage drop, and may fail as a result.

Good installation practice is the key to reducing this problem; large loads should have dedicated feeders of adequate cross-section right back to the point of common coupling (PCC) so that the heavy load is separated from other, more sensitive, loads. Maintenance procedures should ensure that this circuit separation is not destroyed during system extension.

Modern low power electronic equipment is often specified as operating over a very wide supply voltage range – indeed many units are claimed to operate over the 100V to 250V range without adjustment. This can be misleading. Most equipment uses a switched mode power supply (SMPS) unit that draws pulses of current from the supply, once per half cycle, to charge an internal capacitor. Load power is drawn via a regulator, discharging the capacitor that is recharged by the next supply pulse. If the charge on the capacitor is sufficiently high, then a stable output will still be available for a short period in the absence of a supply. This period is known as the hold-up time and, for a high quality unit at nominal supply voltage, is usually greater than one supply cycle at full load. However, since the energy stored in the capacitor is proportional to the square of the supply voltage, a 10% reduction in supply voltage results in a nearly 20% drop in stored energy. Lower cost units have more limited hold-up times and may fail to supply the required load during a voltage dip. In particular, wide supply voltage range units may have very low hold-up times at the lower end of the input range. It is important to remember that many computer peripherals, such as backup tape drives and communications modems, use this type of supply.

Where the electricity supply is the source of voltage dips it will be necessary to provide voltage regulation, either for the whole site or for selected sensitive equipment.

Ferroresonant transformers, sometimes called constant voltage transformers, operate with a saturated core and resonant circuit to maintain the output voltage as the input voltage varies, the primary current varying to compensate. The device operates satisfactorily over a narrow range of output loadings.

Older variable transformer regulators employed a servo motor driven brush tap around a toroidal autotransformer winding. Response time was slow – several seconds – control resolution poor and maintenance requirements high. The modern equivalent uses a multi-tapped transformer and a solid state tap changer and is fast, accurate and maintenance free. The transformer may be an autotransformer, but in this case noise isolation is poor and dual-wound shielded transformers are preferred. It is important that the control circuitry for such devices is true RMS sensing, otherwise distortion on the supply will be mis-interpreted as a change in voltage.

Transients

Transients are most frequently caused by switching of inductive or capacitive loads. Wherever possible, suppression should be applied at the source to prevent the transient propagating and coupling to other circuits. When the source of the transient is off-site, the suppression techniques outlined below should be used.

Low magnitude transients are unlikely to result in damage but will cause noise and can be reduced by the provision of line filters or isolating transformers. Typical small equipment line filters (6 Amp rating) have attenuation figures of 22dB for differential and 8dB for common mode noise at 150 kHz, rising to a maximum of 70dB at 30 MHz.

Isolation transformers provide good noise isolation providing that adequate electrostatic shielding is provided between the windings. Single, double and triple shielded types are available with increasing levels of noise attenuation.

Transients can reach several thousand volts[9] and can seriously damage equipment but, fortunately, protection is achieved easily and economically by the use of transient voltage surge suppressers. Typically metal oxide varistors (MOV) are used; these devices have very high resistance at normal voltage but above their breakdown voltage the resistance becomes very low, so clamping the transient to the breakdown voltage of the device. The clamp effect requires the voltage of the transient to be dropped in the impedance of the supply so a high transient current must flow and this often results in noise coupling to adjacent wiring, including signal and network cabling. For this reason, it is better to fit suppressers near the source of the problem rather than at every other device that may be affected. Note that the transient is not completely removed, it is reduced to the breakdown voltage of the MOV, which, to prevent unduly frequent operation and to cater for manufacturing tolerances, is likely to be around 120% of the peak (170% of RMS) voltage. It will often be found necessary to follow the suppressor with a filter to further attenuate the transient. MOVs can pass very large currents of short duration but, because their power handling capability is quite low, they are not suitable for clamping repetitive spikes.

7. Energy Efficiency

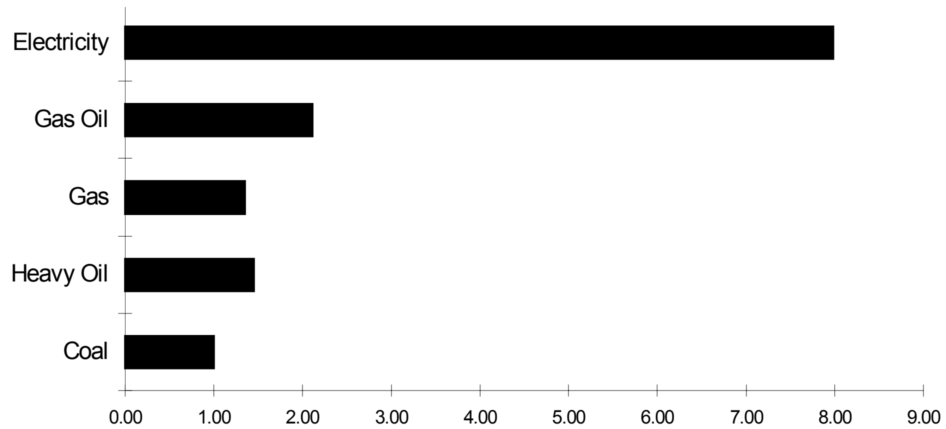
This section presents a brief overview of electrical energy efficiency. It is based on CDA Publication 116, 'Electrical Energy Efficiency'[10], which contains information on financial appraisal as well as a full technical background to the subject.

- More than 8% of the electricity you buy is probably wasted due to the design of your equipment and the way it has been installed! This is in addition to the energy wasted by running equipment for longer than necessary.
- Electricity is the most expensive form of energy available - about eight times the cost of coal and six times the cost of gas - this expensive fuel must be used wisely!
- The average cost of industrial electricity in the UK has risen by 8% in the last five years despite the very strict regulatory environment. In future, it may rise even faster.
- Motors use 64% of industry's electricity in the UK - worth around £4 billion per year. Using high-efficiency motors, properly selected and installed, could save industry up to **£300 million** per year.
- A motor consumes electricity to the equivalent of its ***capital cost in just three weeks*** of continuous use - high efficiency motors save money over the whole of their long life.
- Energy is lost in all cables. Using the minimum regulation size means greater losses and hotter running. Using larger sizes saves energy and costs less over the lifetime of the installation - the energy saved is worth many times the slightly increased cost of larger cables.
- Energy lost still has to be generated. A reduction in losses brings about not only a reduction in fuel costs, but also in plant capacity needed to provide the losses at times of peak generation.

7.1. The cost of energy in UK.

Electricity is by far the most expensive form in which an organisation buys power. Figure 27 shows the relative costs of different fuels, in terms of price per kilowatt-hour, and Figure 28 shows the change in costs between 1990 and 1995[11]. Not only is electricity the most expensive, but it is also increasing in price while the prices of many other fuels are falling.

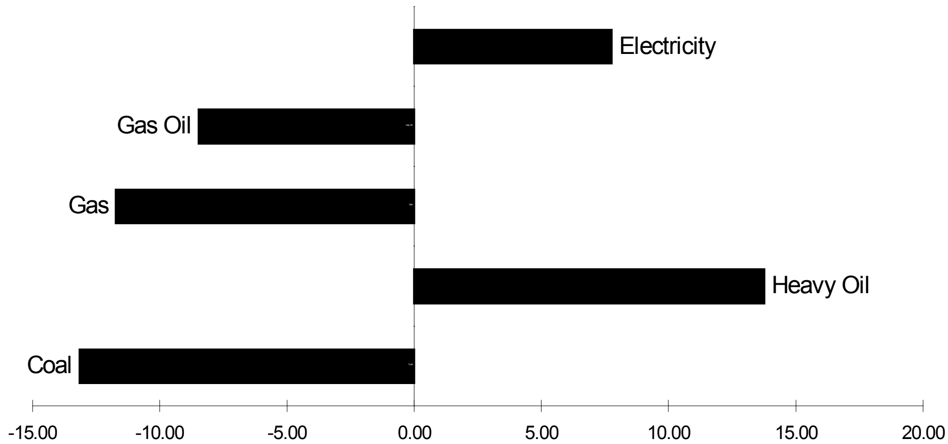
Figure 27 - Relative fuel costs per kWh (1995)



The use of electricity is justified because it is often the only practical form of energy for many purposes, for example, for lighting and for the provision of local power for rotating machinery. It also has the advantage of being pollution-free at the point of use.

The fact that electricity is the only practical form of energy does not mean that it should be used without proper consideration. The average industrial customer uses 350 MWh per year, at a cost of 4.43 p/kWh, resulting in an average bill for £15,500 (1994 figures). While thermal savings are keenly monitored and can readily be measured, much less attention has been paid to the money that can be saved by attention to the design, specification and installation of electrical plant and power systems. The efficiency of electrical equipment has always been assumed to be high and the amount of electrical energy that is wasted in commercial and industrial environments is usually greatly underestimated and has been assumed to be unavoidable. In fact, the efficiency of electrical equipment can be further improved easily at low cost, and, because of the quantity of electrical energy used, this will yield very substantial savings. Once high-efficiency equipment has been selected, it is equally important to ensure that it is correctly rated and installed using the best practice. For example, motor efficiency is highest *above* 75% of full load, so over generous rating will increase both capital and running costs. On the other hand, cables are *least* efficient when fully loaded, so generous rating of cables can substantially reduce running costs.

Figure 28 - % Change in energy costs 1990 to 1995



Power losses in electrical equipment are due to the electrical resistance in conductors and losses in the magnetic material and occur primarily in motors, transformers and in all cabling. The conductor losses are proportional to the square of the current and the resistance (I^2R losses) and can be minimised by using the optimum size of conductor for the application. Later sections demonstrate that the lowest overall life cycle cost is achieved by specifying larger conductors than the safe thermal minimum, so saving energy costs with only a marginal increase in installation cost. Magnetic losses can be reduced by the use of better materials and production methods.

The available savings in energy costs are substantial and accrue over the whole of the life of the installation.

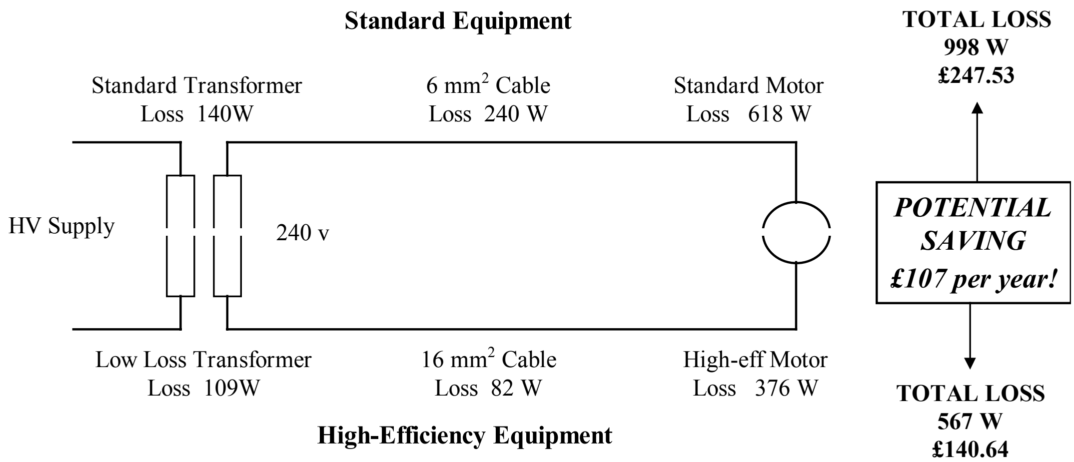


Figure 29 shows the losses for a hypothetical installation using both typical standard efficiency and high-efficiency equipment. This is based on a 7.5 kW motor, operating for 5,600 hours per year (two-shift day) at 5.0 kW loading, with a cable run of 30 m. Because a transformer would supply many loads of this type, the illustrative losses shown here are scaled from a larger transformer. The figures are tabulated in Table 8 for reference.

Figure 29 - Comparison of losses for a single motor installation

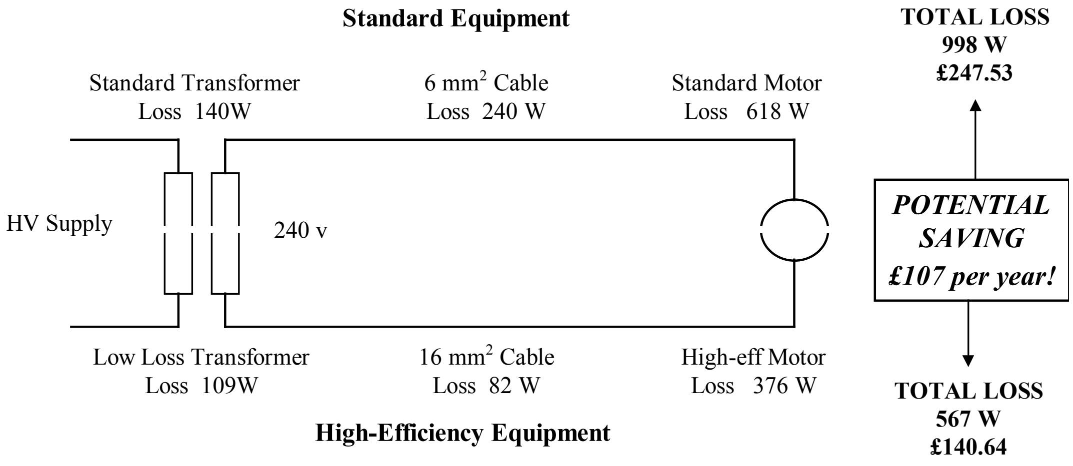


Table 8 - Comparison between a standard and high-efficiency installation

	Standard Equipment, 6 mm^2 cable			High-efficiency equipment, 16 mm^2 cable		
	Efficiency (%)	Loss (W)	Cost of loss/ annum (£)	Efficiency (%)	Loss (W)	Cost of loss/ annum (£)
Motor	89	618	153.30	93	376	93.28
Cable	96	240	59.50	98.5	82	20.34
Transformer	97.6	140	34.73	98	109	27.02
Totals	83.3	998	**247.53**	90	567	**140.64**

Total Bill **£1,488** **£1,381**

<u>Saving</u> **<u>£107</u>**

The annual saving of £107, i.e. 7.2% of the bill, achieved on this small sample installation will payback the extra cost of high-efficiency equipment in about 18 months, and go on producing savings over the equipment life, on average 13 years for the motor, and 30 years for the cable and transformer. The lifetime savings total over £4,800 even if the cost of electricity does not rise! The saving attributable to the use of a High-Efficiency motor is particularly significant since 64% of the electricity bought by industry in the UK is used to power motors. If this improvement were achieved over the whole of an average industrial user's motor load, electricity costs would fall by £700 pa, and for the whole of industry and commerce in the UK, total savings would amount to over £300 million pa.

Interactive Software

Interactive software has been produced to facilitate the choice of the most cost-effective high-efficiency electric motors, optimum cable sizes and busbar designs.

The motor selection software[12] allows the designer to compare the cost of operating both standard and high-efficiency motors, taking account of load factor, duty cycle and different energy tariffs. Overall savings and payback period are calculated.

The cable size optimisation software[13] determines the most cost-effective size of power cable to install. Most popular types of cable and cable configuration are considered together with termination costs where appropriate. Calculations are based on varied utilisation at different tariffs by day and night and include allowances for electricity demand costs together with the variables mentioned above. This results in a significant simplification of the work needed to calculate the most economic size of conductor to specify.

Two programs have been developed to enable designers to specify busbars in the most cost-effective manner, one by CDA (UK)[14] and the other by CDA Inc. (USA)[15]. The former enables designers to carry out many of the calculations included in the standard book on busbar design[16], the latter enables designers to use a standard or variable set of costings to establish the most cost-effective installation design.

In co-operation with ETSU (Energy Technology Support Unit), two videos[17] have been produced encouraging management to extend energy-efficient considerations to the purchase of electric motors or installation of power cables.

7.1.1. Electricity generation in the UK

Since the oil crisis of the 1970's, energy prices have risen dramatically and there has been increasing public awareness of the need to save energy in order to reduce both the consumption of fossil fuels and the environmental pollution which results from their use. There is increasing resistance to planning applications for large scale infrastructure projects including both conventional and nuclear power generation stations and distribution networks, and the opposition is becoming increasingly sophisticated. Although planning applications are normally allowed, the delay and expense involved have an impact on energy costs and availability. Effective management of the efficient use of energy has never been more important, from both an economic and a public relations standpoint.

The organisation of the electricity generation and supply industry was discussed in section 1.1. This structure, which has evolved over the last decade, has led to an increase in the use of natural gas as a primary fuel, which has resulted in much lower pollution levels. This process, colloquially known as the 'dash for gas', was initiated by the RECs need for low capital-cost short lead-time generating plant to cover peak demand so that they could avoid the purchase of peak price electricity from the pool. This type of plant is ideal for peak lopping, but is expensive for high duty-cycle use, so it is unlikely that the very high growth rate will be maintained in the long term. Attention must now return to the problem of reducing pollution from coal fired power stations, both by better environmental control and by promoting the more efficient use of electricity.

The primary fuels used for the production of electricity in the UK are shown in Figure 30, and Figure 31 shows the percentage of electricity used by various market segments.

Figure 30 - Primary fuels used for electricity generation in the UK.

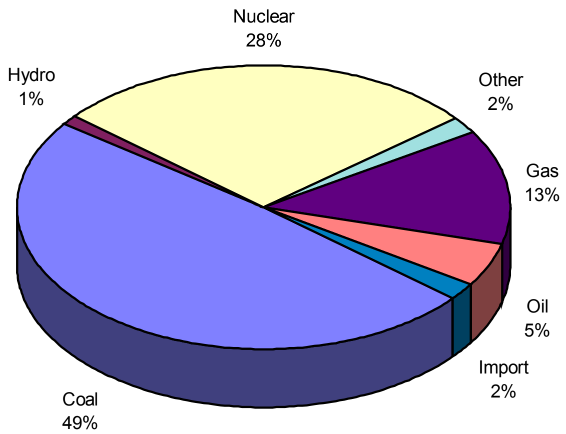
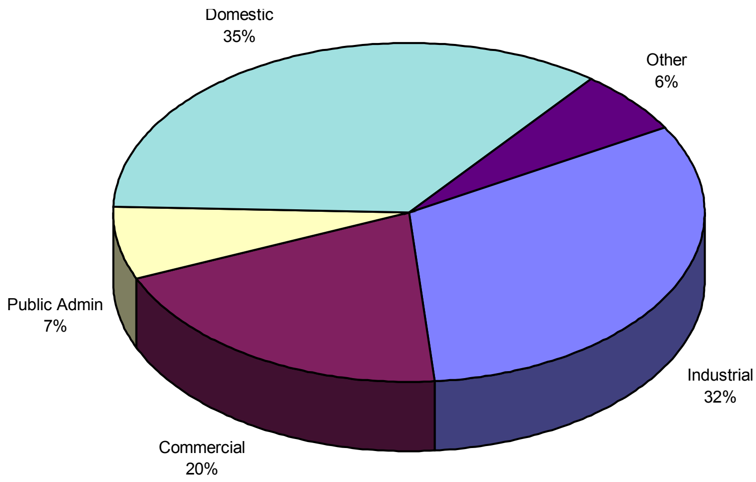


Figure 31 - Electricity consumption by market segment.



In the UK (in 1994), the total annual industrial and commercial usage was 160 TWh (1 TWh = 10^9 kWh). To help to put this enormous figure into perspective, it is equivalent to the continuous full load output of 15 power stations of the size of Sizewell B, or just over double the total UK nuclear capacity. The price industry pays for this energy is approximately £7 billion per annum, so an overall increase in efficiency of only 3% would reduce the cost by £220 million per annum and would save a great deal of pollution. Table 9 shows the total UK production of some pollutants and the amount attributable to electricity generation in 1992. An improvement in efficiency of 3% would reduce the carbon dioxide emission by 1.5 million tonnes - 60% of the UK's Rio Summit Meeting target.

Table 9 - Annual production of pollutants in the UK (1992)

Pollutant	Total Annual Production	Contribution from Power Stations
Carbon dioxide	156 x 10^6 tonnes	51 x 10^6 tonnes
Sulphur dioxide	3.5 x 10^6 tonnes	2.5 x 10^6 tonnes
Oxides of Nitrogen	2.75 x 10^6 tonnes	0.69 x 10^6 tonnes

7.2. Energy-efficient motors and transformers

7.2.1. Motors

The electric motor has a long history of development since its invention in 1887, with most early effort aimed at improving power and torque and reducing cost. The need for higher efficiency became apparent during the late 1970s and by the early 1980s, at least one British manufacturer had started to market a premium range of motors with improved efficiency.[18] Now the trend is towards marketing all motors with improved efficiency at little or no premium. However, because improved efficiency requires more precise manufacture, only the higher quality manufacturers are supplying high-efficiency units. There is therefore still a price difference, but one that applies between manufacturers rather than between ranges from the same manufacturer. There is still a choice to be made, and the following sections illustrate that paying for the high-quality high-efficiency motor is an excellent investment.

The UK industrial motor population[19] is estimated at about 10 million units, while the new market is about 3,000 units per day, mostly rated at less than 150 kW. Of the electricity supplied to power industrial motors, one third is consumed by motors rated at 1.1 to 15 kW, and a further third by motors rated from 15 to 150 kW, suggesting that there are very large numbers of small motors among the installed base. Clearly, it is important to consider energy efficiency for all sizes.

Most motors operate at less than their design loading. Safety margin, selection of preferred sizes, and starting torque requirements mean that most motors are operating at between 60% and 80%

of full load, and many will run at very low load for a substantial part of their working life. It is important that high-efficiency motors retain their energy efficiency at these typical load factors and the leading manufacturers typically optimise efficiency at about 75% full load.

An electric motor can consume electricity to the equivalent of its capital cost within the first 500 hours of operation - a mere three weeks of continuous use, or three months of single shift working. Every year, the running cost of the motor will be from four to sixteen times its capital cost. Over its working life, an average of thirteen years, it may consume over 200 times its capital cost in energy. Clearly, the lowest overall cost will not be achieved unless both capital and running costs are considered together.

7.2.1.1. Energy losses

It must be emphasised that the standard electric motor is already a very efficient device with efficiencies above 80% over most of the working range, rising to over 90% at full load. However, because of the high energy consumption, and the very large number of installed units, even a small increase in efficiency can have a major impact on costs.

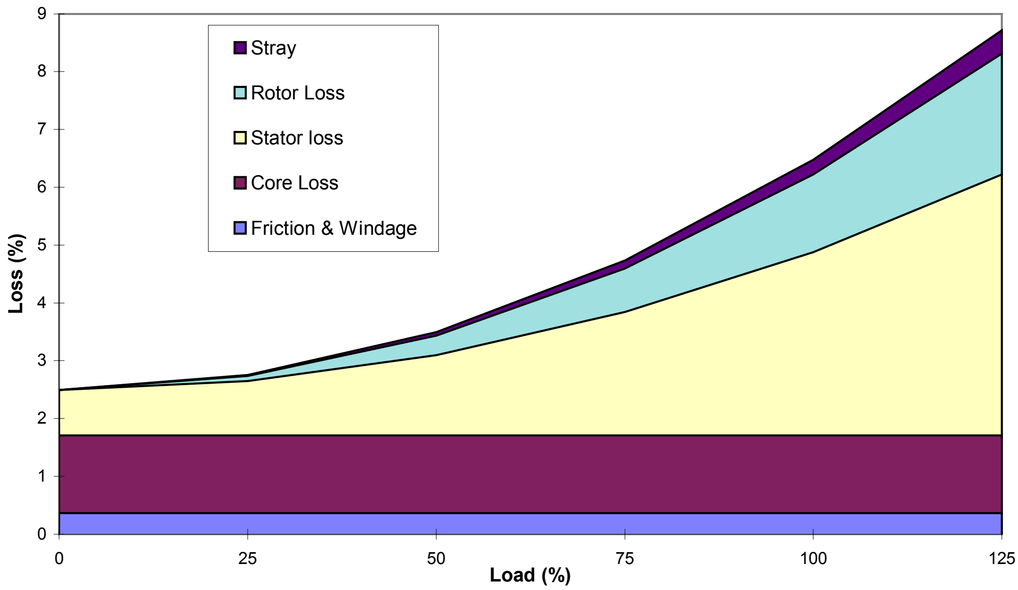
The efficiency of an electric motor depends on the choice of materials used for the core and windings, their physical arrangement and the care and precision with which they are handled and assembled. Losses can be categorised into two groups; those that are relatively independent of load (constant losses), and those that increase with load (load dependent losses). The factors that affect efficiency are:

Conductor content	(load dependent)
Magnetic steel	(mainly constant)
Thermal design	(mainly load dependent)
Aerodynamic design	(constant)
Manufacture and quality control	(constant)

Conductor Content

Resistive losses in the windings increase with the square of the current (which increases with the load) and normally account for around 35% of the total losses. These resistive losses can be reduced by putting more copper into the windings - using a thicker gauge wire - and improving manufacturing techniques to shorten the end windings (which do not contribute to output power but do contribute to loss). Since more copper requires more space, both for the endwindings and in the stator slots, the volume of material in the magnetic circuit would be reduced, leading to earlier saturation and increased iron losses. Consequently, it is necessary to increase the length of the magnetic core, and sometimes the diameter as well. Normally, the increased length is accommodated by increasing the overhang at the non-drive end of the unit. Because copper losses are load-dependent, the benefit of increasing the copper content is most apparent at high loading. Since the coefficient of resistance of copper is positive, the losses increase as temperature rises.

Figure 32 - Loss against load for a typical standard motor



Magnetic steel

Magnetic steel is the most expensive component of the motor, so any increase in the total amount used is undesirable on cost grounds. The iron losses are of two types - hysteresis loss and eddy-current loss. Hysteresis loss is due to the non-linearity of the flux density/magnetising force curve and is a property of the steel itself and to minimise it two properties are required - a low energy loss and good high field permeability, i.e. the steel must be easy to magnetise and must not saturate at high flux densities of up to 1.8 Tesla. This is the subject of on-going research that is making promising progress. Eddy-current losses are due to induced current in the stator laminations and are reduced by reducing the thickness of the laminations and by ensuring good insulation between adjacent laminations. Thinner laminations are, naturally much more expensive to produce and more difficult to handle, so the chosen thickness is always a compromise. Magnetic losses are particularly important when the supply is distorted by harmonics because eddy current losses increase with the square of the frequency while hysteresis losses are proportional to frequency. The benefit of using improved magnetic steel is a reduction in loss across the whole of the working range, but, because it is not load dependent, it is particularly apparent at low loadings.

Thermal design

New modelling techniques have allowed the production of motors with optimised cooling flow, reduced clearances (increasing the efficiency of the magnetic circuit) and lower copper losses. Lower losses and good thermal design result in lower operating temperatures and hence a longer service life.

Aerodynamics

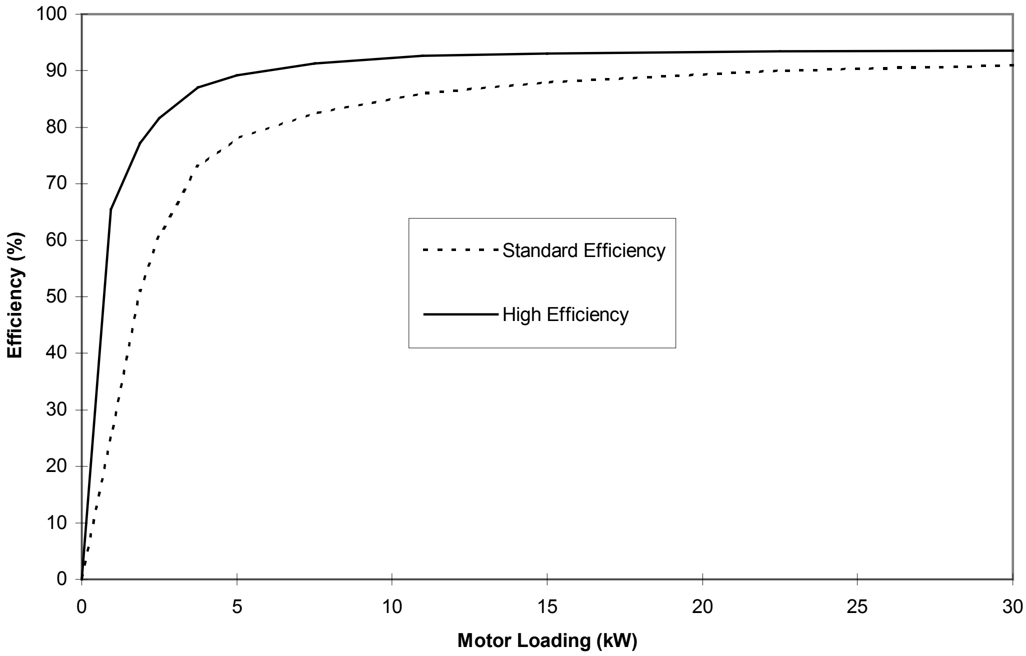
Most electric motors are cooled by drawing air through the windings by an integral fan and exhausting it over the externally ribbed casing. The airflow is complex and computer modelling has been used to optimise the design of the fan and cowling to produce more efficient cooling with a lower noise level. Windage losses can be reduced by careful design of the rotor.

Manufacture and quality control

The introduction of stresses in the magnetic steel during motor assembly can increase iron loss by up to 50%. By considering assembly techniques at the design stage and by paying attention to handling techniques, this increase in iron loss during manufacture has been reduced to negligible proportions. Eccentricity between the stator and rotor generates harmonic fluxes with consequently higher losses.

The overall result of these improvements is an increase in efficiency of 3% (corresponding to a reduction in loss of about 30%) at full load and a halving of losses at low loads. Figure 33 shows the comparison between the efficiency of 75 kW standard and high-efficiency motors against actual load.

Figure 33 - Comparison of efficiencies of standard and high-efficiency motors



Because many motors spend considerable time running at low loading or idling, designers of high-efficiency units have paid great attention to reduction of the constant losses. The result is a halving of losses at loadings less than 25% load and an efficiency improvement of 3 to 5% at full load, a reduction in losses of about 28%. This represents an impressive achievement.

7.2.1.2. Application of high efficiency motors

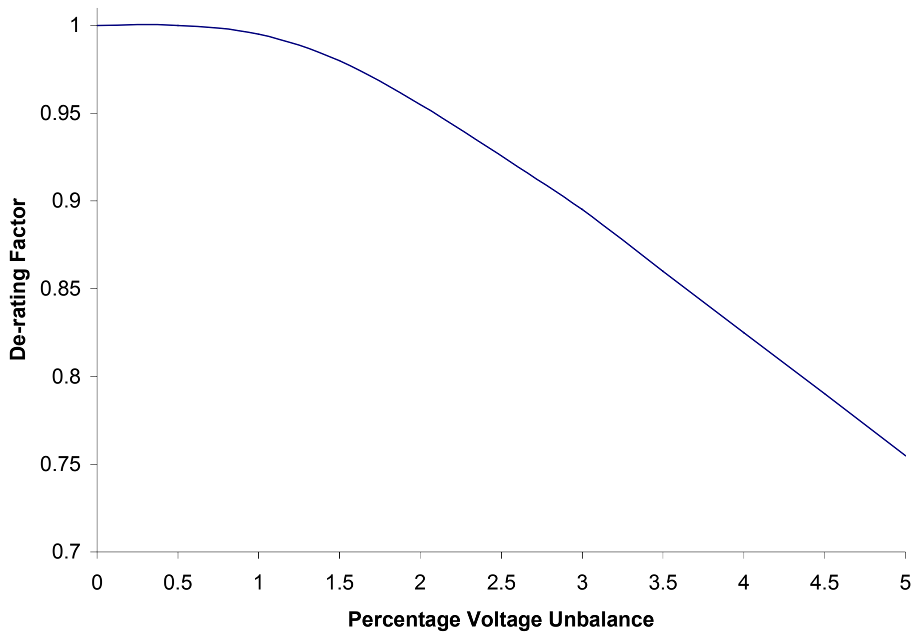
The benefits of HE motors will only be realised if good installation techniques are used. Energy is lost in cabling and this is discussed in section 7.3. Voltage balance in three phase machines causes unbalanced currents in the stator winding. The effect is super-proportional; i.e. the percentage unbalanced current is much higher than the percentage unbalanced voltage, causing significantly increased temperatures. The effect is equivalent to the introduction of a negative sequence voltage, i.e. one that has a rotation opposite to that of the fundamental, leading to higher current, reduced torque and reduced full-load speed. Preferably, the voltages should be balanced as closely as can be read on a voltmeter, and where this is not possible, the motor should be de-rated according to Figure 34. Operation above 5% unbalance is not recommended.

Voltage balance can be improved by segregating motor supply circuits, using oversized conductors to reduce voltage drop and ensuring that single-phase loads are not fed from a three phase motor circuit.

7.2.1.3. Economic justification for selecting high-efficiency motors

Justifying a capital purchase is probably one the most difficult tasks faced by managers; in part this is because there are so many methods of calculation, and even more opinions about which is right! There is enormous pressure to minimise the cost of projects, and this means that decision makers tend to be looking for lowest first cost. However, this initial cost is only part of the story - as mentioned above, a motor may consume up to 200 times its capital cost in electricity, so a proper examination must include running costs.

Figure 34 - Motor de-rating factor due to unbalanced voltage



Starting from the premise that the need for, and cost justification of, the purchase of a new motor has been made, how can the selection of a premium quality motor be justified? As with any project, the capital outlay required, in this case the *difference* in cost between the high-efficiency motor and a standard unit, must be judged against the future cash, in this case the *savings* due to reduced energy consumption, generated in future years. The criteria by which the results are assessed will depend on the culture of the organisation, and may often involve comparison with other potential uses for the capital available. CDA publication 116, 'Electrical Energy Efficiency' defines some of the popular methods of calculation, together with several case histories, which demonstrate that, under a wide range of circumstances, the payback periods are typically around two years. This payback period is short enough to be considered a good investment by most organisations. To assist managers to explore the savings available in their own circumstances, CDA has made available a software package which enables users to enter motor utilisation characteristics, day and night electricity tariffs and demand charges and calculate the relevant costs. The program is easy to use, interactive, and produces prints of the results for distribution and easy future reference.

The economics of the installation of high-efficiency motors are best when new plant is being built. However, in certain circumstances, the cost of replacing an existing motor before the end of its serviceable life can be justified, but the economic considerations are more complex. It may be justified by comparing the additional cost of early replacement (the lost value of the residual life of the existing unit, the higher cost of immediate, rather than future, capital) with the future savings, or by taking account of future energy savings to avoid or delay the expense of increasing the capacity of local supply transformers and circuits.

Another good time to consider the selection of high-efficiency motors is when an existing unit is being considered for rewinding. Approximately 300,000 motors are rewound in the UK every year, with an average rating of about 12 kW, so the efficiency of rewound motors is extremely important. The loss in efficiency on rewinding depends on the techniques, processes and skill used to perform the rewind, and is usually between 1 and 2%. If the choice is between rewinding a standard efficiency motor or purchasing a new HE motor, the difference in efficiency will be 4 to 5% at full load in favour of the HE motor, which will also have a much longer service life. It will be found more cost effective in most cases to prefer the new high-efficiency unit. The rewinding of HE motors has been studied with the objective of defining rewinding techniques which will limit the reduction in efficiency to 0.5%, so that the advantage of the HE motor can be preserved after rewinding[20].

Whenever a motor is to be newly installed or replaced, it should be standard practice to examine the cost benefits of selecting a high-efficiency type. The cost of running the plant can be estimated for both types of motors. If the equipment is going to be running for a significant proportion of each day, then it is very likely that it is worth selecting a high quality high-efficiency design. There is a need for a management policy commitment towards potential cost savings at the design and specification stages.

7.2.2. Transformers

Although all power transformers have a very high-efficiency - the largest are probably the most efficient machines devised by man - their throughput and the number of them installed means that the energy which they waste is indeed enormous. As with electric motors, there is scope for improvement in the efficiency of power transformers and real economic benefits to be gained.

The largest transformers operating in the UK have an efficiency of around 99.75% at full-load, but since full-load can be as high as 800 MVA, the lost 0.25% can amount to 2 megawatts. Large transformers have the highest efficiencies, of course, since in a transformer costing around two and a half million pounds it is economic to build in the degree of sophistication necessary to reduce the losses to the minimum attainable level. At the opposite end of the scale small distribution transformers are less efficient, somewhere around 99.5%, but there are so many more of them that it is equally, if not more, important in these to aim for the highest efficiency that can be practicably achieved. A recent survey commissioned by the Copper Development Association revealed that distribution transformer losses represent 23% of the network losses from the UK system. Under peak load conditions these amount to 1,300 MW, equivalent to the output of one large power station.

By the time it is received at most consumers' premises, at 400 V, three-phase, or 230 V single phase, most electrical energy has been through at least five transformations in voltage level; initially being stepped up to 400 kV by the generator transformer, then down to 132 kV via an interbus transformer, to 33 kV at an REC bulk-supply point, to 11 kV in a primary substation and finally to 400 V at a local distribution substation. All of these transformers are energised 24 hours per day, for almost twelve months of the year and are therefore consuming losses almost all of the time. It has been estimated that some five percent of all electricity generated is dissipated in iron losses in electrical equipment[21]. In the UK alone in the year 1987/88 the cost of these no-load losses in transformers was put at £110 million[22]. At that time around 10^9 units of electricity were estimated to be wasted in core-losses in distribution transformers each year, equivalent to seven million barrels of oil to produce it and releasing 35,000 tonnes of sulphur dioxide and four million tonnes of carbon dioxide into the atmosphere[23].

7.2.2.1. The nature of transformer losses

Transformer losses fall into three categories: -

- i) No-load loss, or iron loss.
- ii) Load-loss, or copper loss.
- iii) Stray-loss, which is largely load related.

For some larger transformers there are also losses absorbed by fans and pumps providing forced cooling.

No-load Loss

Iron loss arises within the laminated steel core of the transformer and is due to the energy consumed in hysteresis and eddy-currents within the material as it is taken through its alternating cycles of magnetisation - in the UK fifty times per second. Iron loss has been regarded by electrical engineers as the major area for improvement in transformer efficiency since the earliest examples were built and tremendous strides have been made in reducing iron losses over the last century, mainly due to improvements in the core steel.

Efficient operation of a power transformer requires the greatest possible flux linkage between primary and secondary windings and, for the best use of the core material this requires that the core be operated at as high a flux density as possible whilst avoiding approaching too closely to magnetic saturation. Flux density is measured in Tesla, T. Losses in the iron increase as flux density is increased, nevertheless modern core steels operating at 1.7 T can have losses only a little more than 10% of those associated with the steels of the 1920s at 1.5 T. In addition 1.7 T represents a normal working flux density for a modern steel, whereas those of the 1920s could really only operate at about 1.35 T because of the lower levels at which saturation occurred.

In addition to the above development of these so-called conventional core steels, there has, over the last few years, been a totally new electrical steel produced which has specific losses of only around one tenth of those of the best conventional steels. This is amorphous steel. There are, as yet, limitations in its manufacture and use; it is exceedingly thin, around 0.05 mm, can only be produced in sheets up to 200 mm wide and its saturation flux density at about 1.56 T is lower than that of modern conventional steels. It is additionally very brittle, making it difficult to handle and build into complete cores and the thickness tends to vary across the width of the sheet. Nevertheless, these limitations can be overcome for smaller transformer cores so that amorphous steel can be of very real benefit in reducing the losses of distribution transformer cores.

Load Loss

The magnitude of the load loss, or copper loss, varies in accordance with the square of the load and has tended to receive less attention than iron loss in the pursuit of energy-efficient transformers. Most transformers operate at less than half rated load for much of the time so that the actual value of the load loss might be less than one quarter of the nominal value at full rated load. Only in the case of generator transformers is it usual practice to cost load losses at the same value as no-load losses, since normally when a generator transformer is energised at all, it will be operating at or near to full load.

The placing of a lower value on load loss than that on no-load loss has tended to create the view that load loss is not important, but, of course, this is far from the case. Load losses are maximum at the time of maximum demand on the system and so place an extra drain on this at the very time when it is least able to meet it. At such times it is the most expensive generating plant which is called into operation and any savings in network losses that can be achieved will result in savings at an exceedingly high system marginal rate. As an indication of the effect that the placing of high demands on the system can have on the cost of electrical energy, it is of interest to note that in early December 1995, the price for energy in the UK Electricity Pool rose to in excess of £1 per kilowatt hour. (The *annual average* industrial price was £0.043 per kilowatt-hour.)

Copper loss arises mainly as a result of the resistance of the transformer windings, that is it is the I^2R loss produced by the flow of the load current within the windings. There is however a significant additional component which is the eddy-current loss. Winding eddy-currents are produced as a result of the alternating leakage flux cutting the windings and these flow within the conductors at right angles to the load current path. For a particular winding, the eddy-current losses are a fixed proportion of the load-losses. They do however vary as the square of the frequency so that the presence of any harmonics in the load current leads to significant additional eddy-current loss.

For many years eddy-current losses presented an obstacle to reduction of I^2R losses within transformer windings, since increasing the conductor cross-section with the object of reducing winding resistance had the effect of worsening the eddy-current component, so that little overall benefit was obtained. Since the mid 1960s continuously transposed conductor (CTC), which consists of a large number of individually enamel-insulated strands to increase the resistance of the eddy-current paths, has been available which has largely eliminated this problem. Its use, coupled with the use of flux shunts to control the distribution of leakage flux, means that eddy-current losses can now normally be contained within 10-15% of the I^2R loss so that reduction of load loss depends simply on the amount of materials, copper and iron, that it is considered economic to put into the transformer.

Stray loss

So-called stray losses are those which occur in leads and tanks and other structural metalwork. Until the recent development of computer calculation techniques using finite element analysis, the magnitude of stray losses was usually determined empirically, with tolerances on guarantees taking care of instances where designs did not quite conform to previous experience. Modern computer programmes have not only removed the uncertainty from this aspect of design but have made possible improvements in the designs themselves by enabling designers to calculate and compare losses for differing arrangements as well as enabling the placing of suitable flux shields in critical areas. Stray loss, which is load dependent, has thus been reduced from perhaps 10% of the load losses to around half this value.

Figure 35 - Relative losses for different transformer types

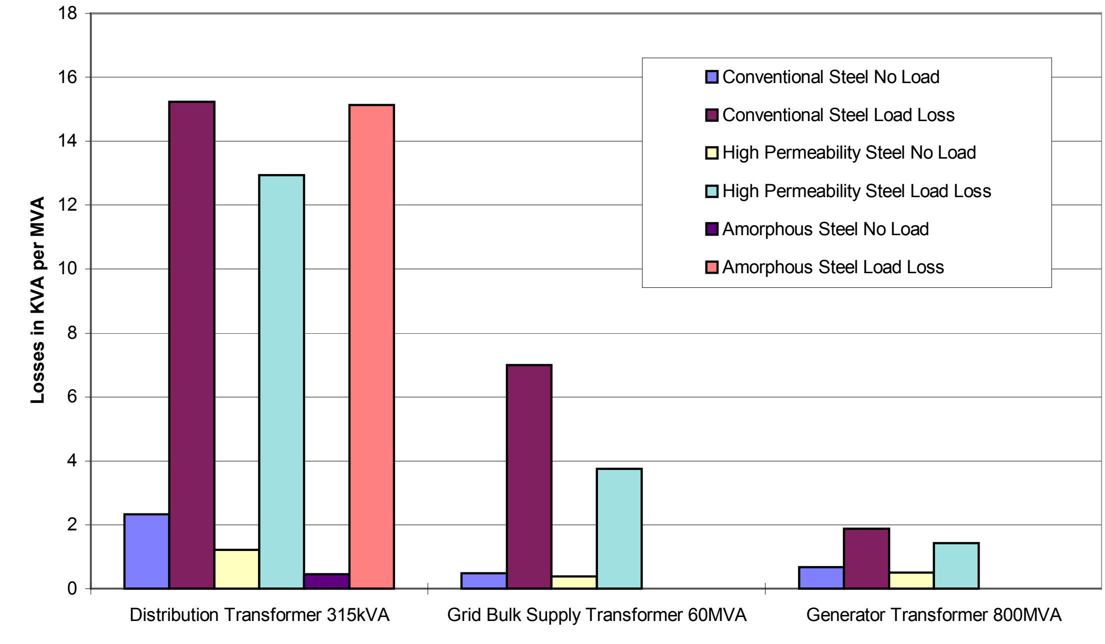


Figure 35 shows the very poor efficiencies of the smaller distribution transformers - even when supposedly of the low-loss types - compared to the larger sizes of transformers. As distribution transformers make up 23% of the total transformer population, considerable savings can be made by increasing their efficiency. Note that amorphous steel is not available for transformers larger than about 630 kVA. All loss values are typical only. The subject of transformer losses is discussed in greater length in CDA publication 116, 'Electrical Energy Efficiency'.

7.2.2.2. Loss evaluation

In the power transformer business, standard designs are not common. Each design is tailored to the customer's technical requirements and to a level of losses that reflect the importance that the user places on energy efficiency. This is the case even for distribution transformers that might be manufactured in quite large quantities.

The different requirements and evaluation processes of the Regional Electricity Companies (RECs) and industrial users mean that the two groups are best served by different transformer types. Most utilities and a few industrial users quantify the value of energy efficiency when transformers are being procured by evaluating losses on the basis of marginal cost of producing or buying one extra kilowatt, amortised over a period of between 25 and 40 years, taking into account probable inflation and interest charges. In recent years utilities have become accustomed to weight this assessment in favour of minimising initial outlay by requiring that the energy savings show a return of up to 10% on the additional capital employed. This they have done by applying a "test discount rate" (TDR) of up to 10% to the capitalised values of the losses at the time of carrying out their loss evaluation. However, this practice applies a very short term bias to the pursuit of energy efficiency and tends to steer utilities away from making savings in losses for which the payback period would be relatively short if the "true" cost of losses were put into the equation.

Regional Electricity Companies (RECs) typically apply capitalisation values of, say, £3,000 per kilowatt to no-load losses and £625 per kilowatt to load losses. These values will probably be derived using a test discount rate of between 8 and 10%. The lower value placed on load losses is because of the fact that most transformers operate at substantially less than full-load for most of the time, as explained above. If the test discount rate were reduced to just 5% this could increase the values placed on losses to about £3,750 per kilowatt for iron loss and around £780 per kilowatt for load loss. If the true cost of the units lost per year was totalled up this might give values of around £4,000 for iron loss and £800 for load loss.

Table 10 shows typical distribution transformer variation of first cost with variation of losses enabling the effects of differing capitalisation rates to be seen.

Table 10 - Typical first cost and loss data for transformer types

Unit	Iron loss (Watts)	Copper loss (Watts)	Price £
315 kVA standard	735	4,800	5,000
315 kVA low loss	380	4,080	6,690
315 kVA amorphous	145	4,770	7,315

In the table the description 'standard' describes the loss values and price which might typically be offered by a manufacturer in response to an enquiry from an REC specifying typical loss capitalisation values as quoted above, i.e. £3,000 per kilowatt for no-load loss and £625 per kilowatt for load loss.

Table 11 shows the results of an evaluation exercise for each of the above alternative designs using three sets of loss values.

Table 11 - Evaluation of typical transformers

	Typical REC (10% TDR)	Typical Industry User	Typical REC (5% TDR)
Loss capitalisation values per kilowatt	£3,000/£625	£3,988/£814	£3,750/£780
Standard loss alternative			
No-load loss 0.735 kW	£2,205.00	£2,931.18	£2,756.25
Load loss 4.8 kW	£3,000.00	£3,907.20	£3,744.00
Price	£5,000.00	£5,000.00	£5,000.00
Totals	**£10,205.50**	£11,838.38	£11,500.25
Low loss alternative			
No-load loss 0.38 kW	£1,140.00	£1,515.44	£1,425.00
Load loss 4.08 kW	£2,550.00	£3,321.12	£3,182.40
Price	£6,690.00	£6,690.00	£6,690.00
Totals	£10,380.00	**£11,526.56**	**£11,297.40**
Amorphous steel alternative			
No-load loss 0.145 kW	£435.00	£578.26	£543.75
Load loss 4.77 kW	£2,981.25	£3,882.78	£3,720.60
Price	£7,315.00	£7,315.00	£7,315.00
Totals	£10,731.25	£11,776.04	£11,579.35

It is clear from this exercise why manufacturers are driven to supply to RECs the low-first-cost option identified as the 'standard loss' alternative. The low loss alternative is however the most attractive option for the industrial user and this would also be the most attractive option for the 'typical REC' if they were to use a slightly lower test discount rate than that currently employed. The other interesting fact to emerge is that the amorphous steel core option is not attractive to any user who operates a 'net present value' type of assessment procedure. Only if a 'true cost' system which costs a lifetime's no-load loss at £10,550 per kilowatt and load loss at £2,152 per kilowatt, is used does the amorphous steel option appear to be the most attractive, as can be seen by reference to Table 12.

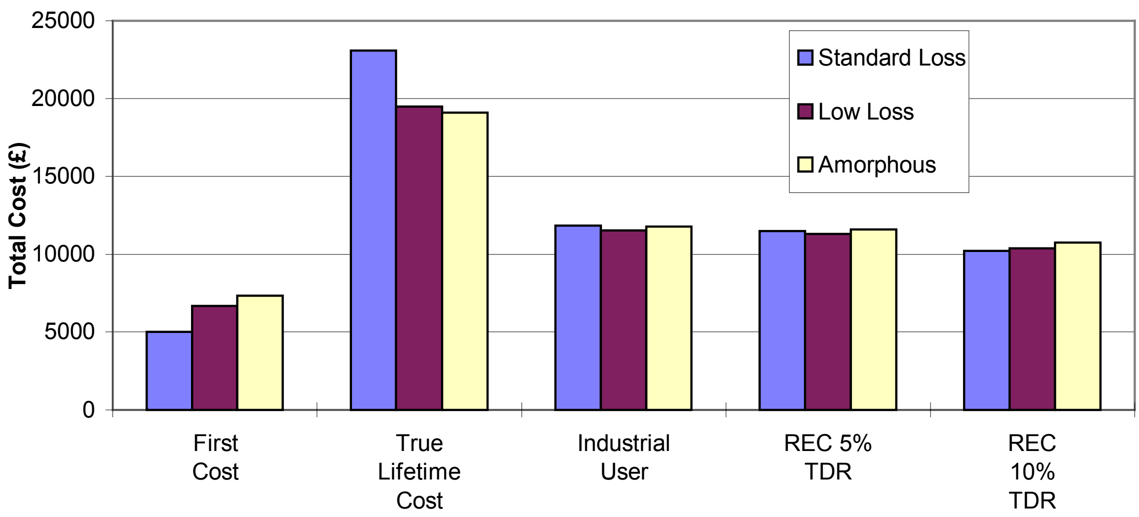
Table 12 - Assessment using true lifetime cost of losses

	Standard loss		Low loss		Amorphous steel	
	loss	cost of loss (£)	loss	cost of loss (£)	loss	cost of loss (£)
No-load loss kW	0.735	7,754.25	0.38	4,009.00	0.145	1,529.75
Load loss kW	4.8	10,329.60	4.08	8,780.16	4.77	10,265.04
Price £		5,000.00		6,690.00		7,315.00
Totals £		23,083.85		19,479.16		**19,109.79**

7.2.2.3. Industrial users

Many industrial users do not evaluate losses at all when procuring transformers. They either consider transformers to be so efficient that the losses can be neglected or they take it that the manufacturer's design process will automatically provide them with the most appropriate value of losses. An industrial user's priorities are not necessarily the same as those of an REC so there is no reason why a design that a manufacturer has recently optimised for an REC should be the best for them. If an industrial user should decide to compute the cost of energy consumed by transformer losses the result can often lead to a decision to opt for lower losses than might otherwise have been the case.

Figure 36 - Evaluation of typical transformers



From Figure 36, it is clear that the most economical option depends on the loss capitalisation values chosen. If 'true cost' system values are used, amorphous steel appears to be the most attractive option. However, the low loss transformer appears to be the best option for both the industrial user and RECs using 5% TDR. Only in the case of a REC using 10% TDR - the typical case for RECs - does the standard transformer appear most attractive. Most manufacturers will use loss capitalisation values appropriate to a 10% TDR when quoting for supply, so it is important that customers specify their requirements carefully when requesting and comparing quotations.

7.2.2.4. Dry-type transformers

To many industrial and commercial organisations, dry-type transformers are seen to be advantageous compared with oil-filled units. They avoid the perceived fire risk of oil-filled transformers and can thus be accommodated inside a building or even on the roof of an office block. Savings can be made on LV connections by installing the transformer integral with 400V switchgear. There is no need to house the transformers in bunded enclosures or make any other provision for spillage as would be the case if a transformer filled with any type of liquid dielectric were installed.

All of these advantages as well as the apparent benefits of low maintenance and high reliability are energetically marketed by manufacturers and cast-resin insulated dry-types, in particular, are being installed in increasingly large quantities.

Most users of dry-type transformers are aware of the extra initial costs and accept these as the price to be paid for greater convenience. What users often do not realise, however, is that dry-type transformers are less energy-efficient and can involve significant increases in running costs. Architects, in particular, may be very conscious of the benefits arising from the installation of dry-type transformers without having to live with the running costs and the potential user would do well to recognise this and examine available options with great care.

KVA for kVA a dry-type transformer will always be larger than its oil-filled counterpart. This is because larger electrical clearances are required when air is part of the insulation system. In addition, air is less efficient than oil as a cooling medium, so that, although a higher temperature rise is usually permitted, larger cooling ducts will be required. Increased size means greater no-load loss and, because the transformer runs hotter, winding resistance will be increased, thus increasing I^2R losses too. All of this is regardless of the class of dry-type transformer used. In addition, cast resin transformers often use aluminium as a winding material because its coefficient of thermal expansion is closer to that of resin and this provides a better quality of encapsulation. This in turn leads to bulkier windings that have still higher losses.

Finally, of course, the additional burden placed on ventilation plant by the imposition of transformer losses must not be overlooked.

7.3. Energy losses in cables

The cost of energy dissipated in cables is frequently ignored but can, in fact, be very significant. Although it was once common practice to install cables that were two sizes larger than the minimum size recommended by standards, many cables are now installed with a conductor size that is the minimum permissible to avoid overheating. This results in very significant energy losses. Lowest overall lifetime cost will be achieved by taking into account not only the material and installation cost of the cable but also the cost of the energy wasted in the cable over the whole life of the circuit. There are additional benefits from a reduction in I^2R losses; reliability and service life of cables is improved because the running temperature is lower, the cost of removing waste heat is reduced and there is improved capacity for future load growth and less chance that extra cabling will have to installed at a later date.

7.3.1. The standards issue: BS7671 v IEC 1059

Electrical Installation standards in the UK are determined by the IEE Wiring Regulations[24], 'Requirements for Electrical Installations' 16th Edition, now also a British Standard, BS 7671:1992. This standard closely follows the European Harmonisation Document HD 384, which is derived from International Electrotechnical Committee Standard IEC 364. The latter two standards are being developed and published as individual chapters in a process which has now been in hand for 20 years. All these standards are concerned primarily with the safety of personnel and property. Consequently, cable-sizing recommendations are based simply on the need to maintain a sufficiently low working temperature so that the insulation does not degrade and there is no risk of fire in surrounding materials. For the majority of installations, this means conductor running temperatures of up to 90°C are to be expected. There is, of course, no doubt that this practice is perfectly safe – given that suitable materials are selected – but there is also no doubt that this is a very expensive waste of energy. Note that the standards also recommend a maximum voltage drop in cabling of 4% between the point of common connection (PCC) and the load. If advantage is taken of this margin then 4% of the supplied energy will be wasted.

As an example, a cable of 16 mm^2 section can be rated at 109 amps and run at 90^o C but over a 50 metre run would drop over 15 volts and waste nearly 1.6 kW. This would cost over £600 per year if electricity were bought at £0.043 per unit. The use of 35 mm^2 section more than halves this wastage, saving £300 per year, *every year*.

Calculations show that overall savings can be made after as little as 8000 hours or less than one year of full time running.

The need to minimise the overall lifetime cost of the circuit is recognised in British Standard 7450:1991[25], identical with IEC 1059:1991, 'Economic Optimisation of Power Cable Size' which states:

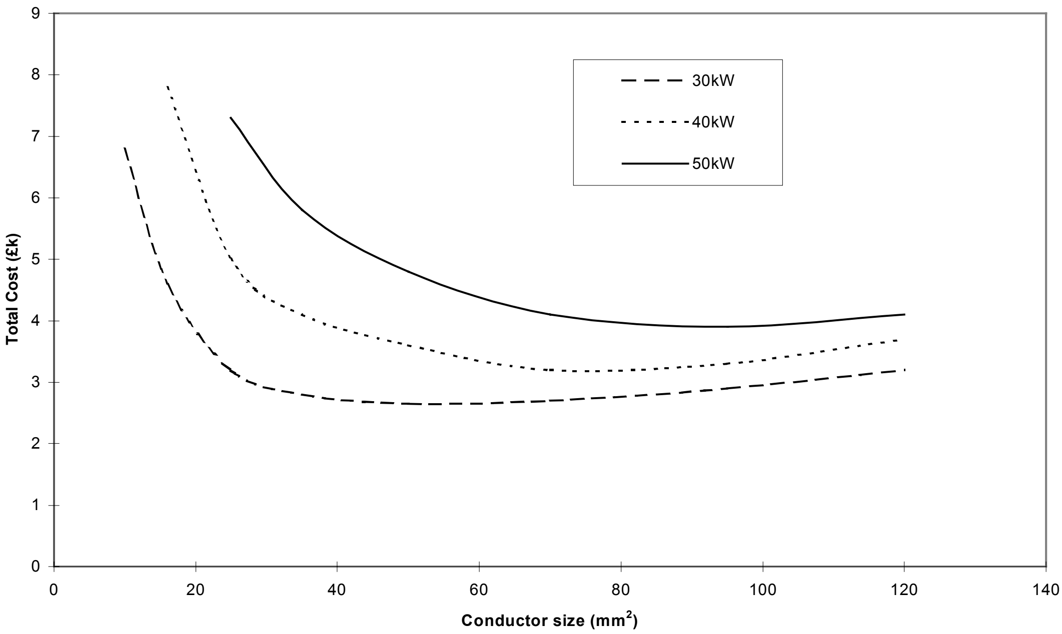
> **'Rather than minimising the initial cost only, the sum of the initial cost and the cost of losses over the economic life of the cable should be minimised.** For this latter condition a larger size of conductor than would be chosen based on minimum initial cost will lead to a lower power loss for the same current and will, when considered over its economic life, be much less expensive.'

This standard was developed for distribution circuits, but the principles are fully applicable to installations in industry and commerce where high-demand equipment often runs for 24 hours per day all year round. Case studies show that substantial savings can be made over relatively short time scales.

Parr[26,27] has published two papers as a result of work done at ERA Technology (contributing to the publication of BS 7450) in which he developed a list of sizes of cables that could be considered most economic within given current ranges. Parr has now expanded and updated these papers, and the resultant material is published in CDA publication 116, ‘Electrical Energy Efficiency’ as *‘Economic Selection of Cables for Industry’*. Formulae are given for carrying out calculations of the most economic sizes of conductors which involves taking account of variables such as the discount rate, load increase per year, energy cost increase per year, electricity costs and lifetime expectancy.

The results of some of the basic calculations are shown in Figure 4-1. They show the total costs over the expected lifetime of a nominal 100 metre length of three-phase cable insulated with PVC and armoured with steel wire, installed with typical ventilation. The smallest size shown for each cable is that determined according to BS 7671 as a thermal limit; it is clear that much larger sizes of conductors are the most cost-effective. For the values of the financial and electrical parameters used here, the saving in the combined cost of purchase and operation is of the order of 50%.

Figure 37 - Typical total cost/size curves showing total costs in £k per 100m of three phase, insulated PVC/SWA



It may be difficult to give an accurate forecast of some of the time-dependent variables given above. However, the methods chosen have the result that the impact of errors in financial data, particularly those that determine future costs, is small. While it is advantageous to use data having the best possible accuracy, reasonable estimates will still give useful results. Note that the slopes of the curves around the minima are quite shallow, indicating that the result is not critically dependent on the data used – the important point is to use a size which is near the minimum and well away from the steep slope.

It is important to remember that laying costs for cables do not increase proportionately to cable size since most of the operations are common. For conductor sizes up to 100 mm^2, the laying cost for buried cables is higher than the cable cost.

In modern office and industrial buildings with a heavy demand for power, air conditioning plant has to be used to export surplus heat for much of the year. The cost of waste heat removal can more than double the cost of I^2R losses in cable ducts.

High temperature insulated cables should not be selected merely to allow a smaller conductor size to be used. They should be reserved for use where space limitations or high ambient temperatures are such that a high conductor temperature cannot be avoided at any reasonable cost. It is false economy to save a little money by reducing conductor size and then waste expensive energy throughout the lifetime of the circuit.

7.3.1.1. Conductor material

The preferred material for electrical conductors is copper. The conductivity of copper is 65% higher than that of aluminium, which means that the conductor size of similarly rated cables is proportionately smaller. Correspondingly less expense is then incurred in providing for insulation, shielding and armouring the cables themselves. Transport of the less-bulky cables is easier and so is installation. In limited spaces in cable ducts, the smaller volume and better ductility of copper cables can have an even larger benefit.

Copper cables are easily jointed; the oxide film that forms on the surface is thin, strongly adherent and electrically conductive, causing few problems. Cleaning and protection of copper is easy and if joints are made as recommended they will not deteriorate to any great extent with age, which saves on maintenance costs. Aluminium rapidly forms a tough non-conductive oxide layer that is very difficult to remove and, consequently, aluminium cables are notoriously difficult to joint reliably. There is a significantly increased risk of fire due to deterioration in joints in aluminium cable.

For the same nominal current rating, a cable with an aluminium conductor is significantly larger in diameter, carries a proportionally greater weight and volume of insulation, and is less flexible and more difficult to install.

7.3.2. Busbars

Considerations for economic sizing of busbars are similar to those for cables. Busbars normally carry very large and varying currents and are subject to large forces due to the magnetic effect of adjacent bars and to expansion and contraction as their temperature varies with load. They are often uninsulated and are therefore subject to corona discharge if operated at high voltage.

Busbar tracking systems are becoming popular for under-floor distribution systems. They are discussed in more detail in Section 8.2.

Design criteria for busbars are dealt with in detail in another CDA publication[28] that gives formulae for calculating the appropriate current rating for various busbar arrangements, taking account of resistance, inductance, skin effect and heat loss mechanisms. Performance under short circuit fault conditions is also discussed. Mechanical properties, including the ability to withstand thermally and electromagnetically induced stress, are fully considered.

7.4. Cable installation software packages

In recent years a number of computer aided design (CAD) software packages have become available which enable designers to calculate distribution board loadings, short circuit currents and cable sizes quickly and easily. There are additional benefits, such as the preparation of accurate documentation and design checking, so many designers rely on CAD tools and would be reluctant to relinquish them

Unfortunately, all the available packages calculate conductor sizes according to the thermal ratings given in BS 7671 and therefore give the minimum thermally safe size. Therefore, the design will not provide the lowest overall lifetime cost. The most economic cable size is easy to calculate using the formulae given in CDA Publication 116, or, for a single conductor, using the program on CDA Datadisk No 6[13], but so far none of the software vendors has added this capability.

A 'work around' is possible. Some of the programs allow the designer to override the calculated size, so one possible solution is to calculate the most economical size separately and force the result into the design. Alternatively, the designer could simply reduce the default maximum voltage drop used by the program to force a more efficient design, although separate calculation would be necessary to determine the degree of optimisation.

8. Future Trends in Electrical Design Practice

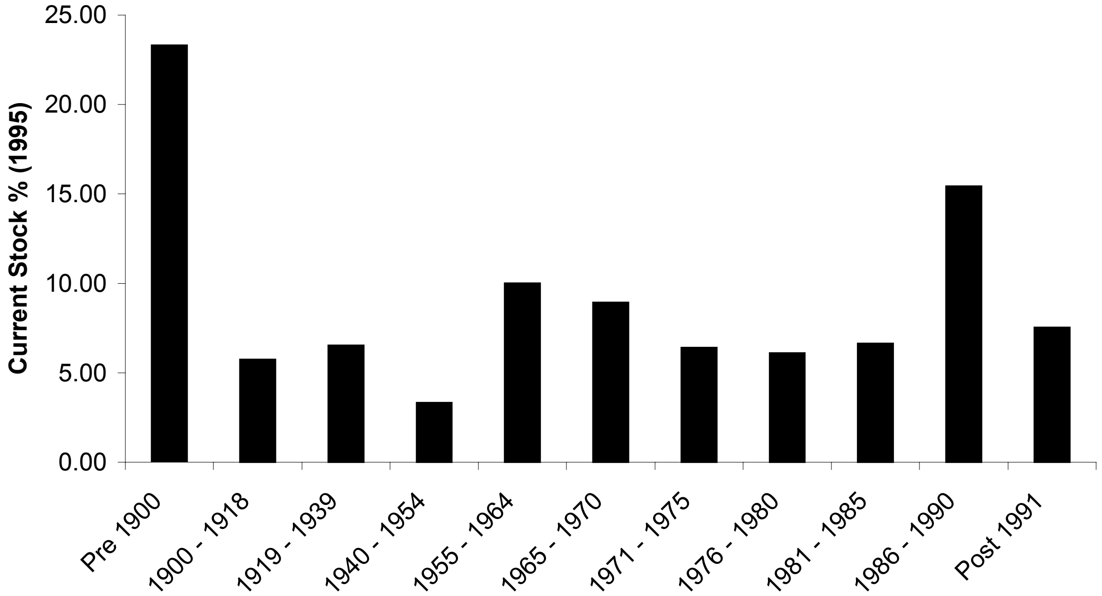
There are a number of factors that will influence electrical design practice in the near future, including: -

- Age of building stock
- Load growth
- Flexibility
- Cost

8.1. Age of building stock

Figure 38 shows the age profile of office buildings in the UK. Note that the time periods are not uniform. From this chart it can be seen that about one quarter of office space is less than 10 years old, but half is over 30 years old and about a quarter of it was built before 1900. This may be partly explained by the fact that modern buildings are designed for a limited lifetime, after which they are demolished, while older buildings tend to be refurbished.

Figure 38 - Age of office building stock in the UK



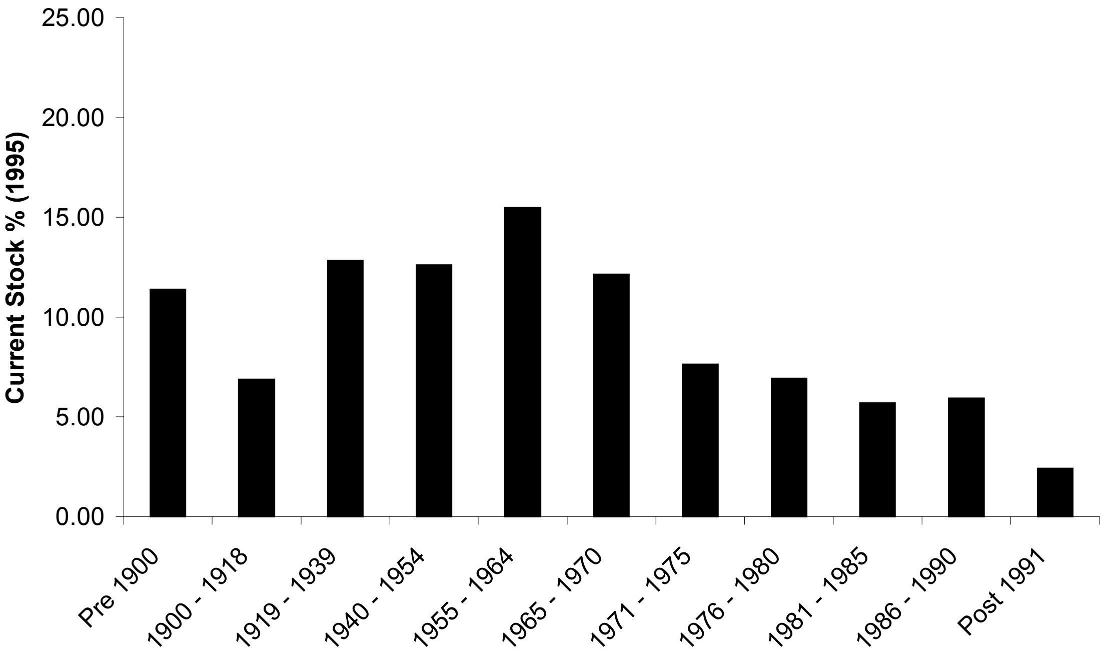
More than 15% of the office space was built in just 5 years between 1985 and 1990. Most of these buildings were the product of property speculation and were built and fitted out to a cost budget rather than to meet the needs of their future occupants. It is probable that the electrical systems in the majority of these buildings are inadequate in terms of reliability and resilience and will be subject to power quality problems. In many cases, these potential power problems will not have been recognised, perhaps because the present activity is undemanding, but will become apparent as soon as a more critical operation is introduced. Buildings in multiple occupation are especially critical: a new occupant may install equipment that will disrupt long-standing operations of other occupants or for which the electrical system is inadequate, making power problems suddenly apparent.

A recent unpublished survey showed that, on average, the electrical infrastructure of buildings is refurbished every 9 years with about 37% of the installation being replaced, so many of the older buildings will have been re-furbished, some perhaps many times. Unless the refurbishment has been especially targeted at power quality, they are unlikely to have been brought up to a good modern standard.

Figure 39 shows the age profile of factory buildings in the UK. About 75% of factory space was built more than 30 years ago. This probably reflects the practice of redeveloping larger factory buildings into smaller units as large heavy industry is replaced by smaller lighter industry. Often, this is undertaken on a speculative basis so that the needs of the ultimate occupier are not necessarily properly addressed in the design phase. More modern factory buildings tend to be deliberately designed and constructed for low cost and short life, so many of those built in the last 30 years will already have been demolished; this, and the overall reduction in manufacturing activity in the UK, explains the relatively low population of modern factory buildings.

These considerations underline the importance that must be attached to the planning and design of electrical system refurbishment. Most refurbished buildings will be used for purposes never envisaged by their original designers and, in all cases, the needs of the ultimate occupier must be taken into account. Occupiers whose business activities depend on data processing, such as a networked order processing centre, will have higher requirements than, say, a small manufacturing unit.

Figure 39 - Age of factory building stock in the UK



8.2. Load Growth

The average life of an electrical installation is long compared with the length of a typical business plan, so it is essential that load growth and flexibility are fully considered during design.

There is little doubt that the use of electronic equipment in commerce and industry will continue to increase rapidly in the short-term future. This growth will be due to: -

- further increase in the use of IT
- enhanced voice communications systems, often integrated with PCs
- increased use of e-mail and Internet services
- wider adoption of video conferencing and video phones.

This increase may be partially offset by a reduction in the power consumption of individual items of electronic equipment due to improvements in design, especially development of lower power semiconductor devices. Additionally, the design of switched mode power supplies (SMPS) can be improved to reduce the harmonic currents and earth leakage currents produced (such improvements may be required by future standards) so reducing the impact of each item. Both these improvements result in increased manufacturing cost.

Industrial and Commercial consumption for 1984 to 1994 are listed in Table 13.

Table 13 - Industrial and commercial consumption, 1984 to 1994

		1984	1994
Industrial	No of consumers	209,000	258,000
	Consumption (TWh)	83.2	86.0
	Average (MWh/consumer)	398	333
Commercial	No of consumers	1,788,000	1,585,000
	Consumption (TWh)	50.8	54.7
	Average (MWh/consumer)	28.4	34.5
	Increase for 1984 to 1994		**+ 21.4%**

Industrial consumption has risen by only 3.4% while the customer base has increased by 23%, so that average consumption per customer has fallen by 16%. This is probably due to the massive shift in the heavy industrial base in the UK in the late 1980s, and masks the likely increase due to the use of IT equipment. However, it is probably safe to assume that IT use in industry has risen in a similar way as it has in the commercial sector.

While the commercial sector customer base has fallen by 12%, total consumption has risen by 7.6% so that average consumption has risen by 21.4%. The fall in the number of customers is probably the result of the take-overs and mergers and the increase in homeworkers (who are not classified as commercial customers) which followed the economic recession of the early 1990s.

Much of the growth in average consumption is the result of the increase in the use of IT and other office equipment, a process that was just beginning during the period in question. It is likely that this trend will at least continue, and, more likely, accelerate over the next decade. It is also likely that the majority of the increase will be in the form of problem loads.

Designers should allow for load growth of about 2% per annum, or 20% over the average refurbishment period of 9 years.

8.3. Flexibility

The rapid change in business practice and the tendency to re-organise frequently has imposed new flexibility requirements on electrical installations.

The initial response to a need for additional and moveable outlets is to provide multi-point extension leads. Often, extension leads are cascaded. This solution is cheap, but is unsatisfactory on many counts:

- Safety is compromised, protective conductor integrity is poor

  Earth leakage currents combine in the earth wire of the extension lead. Since each item of equipment can have a leakage current of 3.5 mA, the total leakage can reach dangerous levels very easily. A break in the earth wire can result in lethal voltages on the metal work of all the associated equipment.

- Reliability is very poor

  Trailing leads are dangerous and are subject to excessive wear and tear. Disconnection affects all the connected equipment, causing serious disruption. Intermittent disconnection is particularly disrupting, since fault location can be difficult.

- Circuit impedance is increased

  The impedance of the supply and the protective conductor are increased, so that harmonic currents cause voltage distortion that can affect other loads and leakage currents result in earth noise voltages that can affect sensitive equipment.

This practice should be prevented by the implementation of a strict maintenance policy that bans the introduction of extension leads into the workplace.

The proper solution is to provide an adequate number of fixed socket outlets, fed by an adequate number of distribution circuits. Proper attention should be given to the integrity of the protective conductor, bearing in mind that almost all circuits will be subject to high earth-leakage currents.

The desire for flexibility has led to increased interest in pre-fabricated under-floor busbar distribution systems, such as that manufactured by Electrak International Limited and others. The busbars are supplied in pre-fabricated sections in a variety of lengths that are simply pushed together and secured to the floor in total lengths of up to a little under 30 metres. Tap-off points are provided at intervals of 300mm into which special plug connectors can be inserted to make connection to standard dual BS 1361 outlets. At the recommended spacings, the system provides 0.6 tap-off points per square metre of floor area or 7.2 sockets per occupant at typical office densities. Flexible corner assemblies and cross connectors are also available. Each track is a radial final circuit and should be separately protected and independently connected to the distribution board.

The advantages of these systems are low cost of installation and improved flexibility in that the wiring system can be modified very easily to suit changes in the business needs of the office space, often without the need for the services of a qualified electrician. As long as measures are in place to ensure that the circuits are not overloaded, this is satisfactory. When designing this type of installation it is important to fully consider the loading at the feed end of the track, especially when subsidiary cross tracks are connected to it.

Distribution tracks are available in standard and low-noise earth versions. In the former, the earth busbar is connected to the external casing of each section and in the latter, the busbar and casing are insulted from each other throughout. The latter type can be used to satisfy the requirements of Section 607 of BS 7671.

All the good practice points, such as circuit separation and conductor rating, given for traditionally wired circuits apply equally to distribution tracks.

8.4. Cost

Cost is the essential factor in almost all decision processes, and is over-ridden by safety considerations only in the most hazardous environments, such as the petrochemical and nuclear industries.

This is perfectly understandable, but is only justified when the cost data used is complete and accurate. This means that the total lifetime costs of the installation must be determined, including all ancillary costs such those for maintenance, breakdowns, lost staff time and excess air conditioning. Usually, the lowest first cost design will be found to incur greater ancillary costs and therefore a higher lifetime cost.

The guidance given in earlier sections of this publication will be helpful in making an initial judgement about the likely problem areas for a particular situation. For example, IT intensive installations will require particularly close attention to circuit separation, earthing and resilience, while for a heavy industrial plant the emphasis may be on energy efficiency. This initial evaluation will provide the basis for a risk and cost analysis.

9. Good Practice Check List

Treat all circuits in industrial and commercial installations as high earth-leakage circuits. Install a high integrity copper earth wire, with each end separately terminated at the distribution board.

Install a generous number of well-rated final circuits.

Use separate circuits for harmonic generating loads and for loads that are sensitive to harmonics.

Consider potential load growth.

Install a generous number of socket outlets.

Use double sized neutrals for all three-phase circuits supplying harmonic loads.

Separate circuits supplying large motors to isolate voltage sags from other equipment.

Do not 'hang' single-phase loads on three phase supplies to motors – the resulting voltage imbalance will reduce motor efficiency.

Check all three-phase neutral currents for harmonics whenever a change is made to the installation or installed equipment.

Do not permit the use of extension leads and boards.

Specify power factor correction capacitors carefully to cope with harmonics.

Install copper earth grids below the floors of IT intensive areas.

Use socket outlets with dual earth terminals for all rings that supply electronic equipment.

Use copper earth conductors in preference to cable armouring wherever high frequency noise may be present.

Standards

BS 4778:1991	Quality vocabulary (Parts 1 to 3).
BS 5760:Part 2:1994	Reliability of systems, equipment and components. Guide to the assessment of reliability
BS 5760:Part 9:1992.	Reliability of systems, equipment and components. Guide to the Block Diagram Technique.
BS 7450:1991	Economic Optimisation of Power Cable Size.
BS 7671:1992	Requirements for Electrical Installations.
EN 50081-1	Generic emission standard, residential, commercial and light industrial environments.
EN 50081-2	General emission standard, industrial environments.
EN 50082–1	Generic immunity standard, residential, commercial and light industrial environments.
EN 50082-2	General immunity standard, industrial environments.
EN 55011	Industrial, scientific and medical equipment (ISM) radio frequency equipment.
EN 55014	Household and similar electrical appliances.
EN 55015	Fluorescent lamps and luminaires.
EN 55022	Information technology equipment (emissions).
EN 60555-2	Mains harmonics in household appliances (will be superseded by EN 61000–3–2)
EN 60555-3	Flicker in household appliances (will be superseded by EN 61000-3-3)
EN 61000-3-2	Mains harmonics (applies to all equipment).
EN 61000-3-3	Mains flicker (applies to all equipment).
EN 61547	Equipment for general lighting purposes (immunity).
EN 61800-3	Adjustable speed electrical power drive systems.
US MIL-STD-721	Definitions of effectiveness terms for reliability, maintainability, human factors and safety. National Technical Information Service, Springfield, Virginia, USA.

BS and EN Standards can be obtained from British Standards Institution, 398 Chiswick High Road, London, W4 4AL.

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