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CONTENTS

A New Dual Reserve Power System for Small Telephone Exchanges

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This article describes a new small DC power system, which employs an aluminium-air battery as an emergency stand-by reserve, in a 'dual reserve' configuration. The background to the development is described, along with a simplified description of the system operation.

INTRODUCTION

All telecommunications centres, such as switching exchanges, transmission stations and, latterly, computer centres, are equipped with some form of emergency power back-up, which can be provided in a variety of ways. Most telecommunications operators use rechargeable batteries of various types, occasionally backed up by an engine alternator set.

In British Telecom, the term *single reserve* is used to describe power systems with rechargeable batteries as the sole source of stand-by power. The term *dual reserve* is used to describe systems with two sources of stand-by power: a rechargeable battery (the DC reserve) backed up by an engine alternator set (the AC reserve).

BACKGROUND

Since the beginning of the 1970s, BT policy has been to install dual reserve stand-by power systems at telephone exchanges and transmission stations. The DC reserve, typically capable of supplying power for one hour, is backed up by an automatic engine alternator capable of running for up to 20 days.

Digital telephone exchanges and optical-fibre transmission will result in new telephone network configurations. Larger traffic carrying capacity at ever-reducing cost and size is also a feature of modern equipment. This is leading to a proliferation of small operational sites, and consequently a re-evaluation of the economics of power provision at these sites has been undertaken. The engineering or technical validity of BT's approach is accepted; it is the cost and the physical size of the power equipment that are at issue. BT is reluctant to abandon a succesful philosophy, and has therefore explored other ways of providing a more economic stand-by reserve.

The introduction of valve-sealed recombining lead-acid batteries has eased the economic constraints. A single reserve system is a viable option where loads are small, but this still leaves an area of power demand where an engine-alternator-backed power system, although cheaper than a single battery reserve, is deemed too large and expensive. In addition, small automatic AC alternator sets are not as reliable as the larger three-phase units (most reported problems are caused by vibration). Small remote sites, the places most likely to need longer-term stand-by, therefore carry an economic burden of capital and maintenance costs on power systems which are disproportionate to their revenue earning capacity.

The main item of cost is the engine alternator set, with its fuel tank, acoustic canopy, and associated control equipment. It appears, therefore, that the greatest savings would be achieved by replacing the alternator set with some cheaper alternative. A variety of options, some rather speculative, have been explored, and it seemed that a cheap primary reserve would be the most feasible alternative.

STAND-BY REQUIRED

An analysis of interruptions to the main electricity supply shows that mains is restored typically within three to five hours, depending on the type of site location. Prolonged breakdown of the mains supply at individual sites is comparatively rare, and such events are virtually never repetitive. Periods of low mains supply voltage are very unusual in the UK. In other words, we do not suffer from so-called *brownouts*. In a previous paper by Banfield[1], it was shown that a 24 hour battery would be adequate for security in service. Experience has shown that a longer stand-by time is necessary when the communication

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network is experiencing problems over a wide geographical area; for example during storms, severe winter weather, or industrial action. However, even under these conditions, the longer reserve would only be employed once during the emergency, and it could easily be replenished later. In other words, a primary battery reserve can be used in place of an engine set, provided it is cheap enough, and small enough.

The capacity of the primary reserve will need to be tailored to the site conditions. An analysis of typical mains downtimes indicates that a reserve period of 48 hours would be adequate for the majority of situations, with a maximum of five days at more remote locations, estimated to be less than 10% of the total number of sites. It is therefore possible to tailor the power system more economically to the site requirements.

PREVIOUS SOLUTIONS

BT has experimented with primary reserve systems, and has built and tested large primary batteries, of 1·5 kWh, using lithium couples. These were not pursued because of cost and especially safety considerations. However, these tests did show the way, and a small lithium battery reserve system is in use in some applications where the power demand is of the order of a few milliwatts. The savings in battery charging equipment made this particular application very cost effective.

PRESENT APPROACH

After discussions with AlcanInt, BT considered the use of a mechanically rechargeable primary battery, using the aluminium-air couple. This battery offered an economic safe way of providing large amounts of DC reserve. During tests on a prototype, an energy density of over 350 Wh/l was achieved, supplied at 600 W for over 60 hours. The battery as described is economical, having few expensive components, and it can be mechanically recharged.

POWER SYSTEM OPERATION

Under normal operating conditions, the DC supply is derived from the AC/DC converter (see Figure 1). This converter is a standard switch-mode design used in BT. The unit used in the prototype system complies with all the relevant specifications for electrical noise, electromagnetic compatibility (EMC), etc.

When the AC supply fails, the load is taken by the operational battery; the fuel cell battery is not affected. After the operational battery has been discharging for over two hours, or its voltage has fallen to a predetermined level or on receipt of a remote command, the control circuit starts the electrolyte pump, and the battery begins to generate power. The electrolyte pump will take energy from the operational battery for a few seconds during start up. After this, the battery is self powered.

Control of the fuel cell battery is effected via the electrolyte pump. Switching the pump on starts the battery. Switching it off stops the battery generating power.

The aluminium-air battery has sufficient capacity to recharge the operational battery during the early stages of discharge. This feature means that the operational battery will have 90% of its capacity available should the emergency reserve fail during its 48 hour run. In most cases, this would be sufficient to allow corrective action to be taken.

The fuel cell battery cannot supply full load until the electrolyte reaches a temperature of about 30°C. This typically takes 30 minutes, depending on load and ambient temperature. The time delay is caused by the conductivity of the electrolyte, which is proportional to temperature. During this time, the load is shared between the operational battery and the aluminium-air battery.

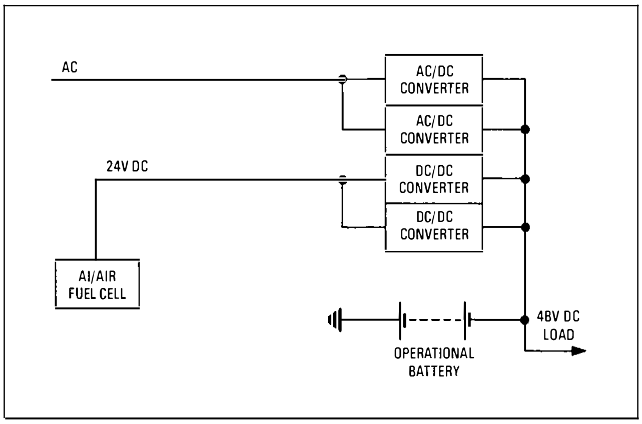

Figure 1—Power system layout

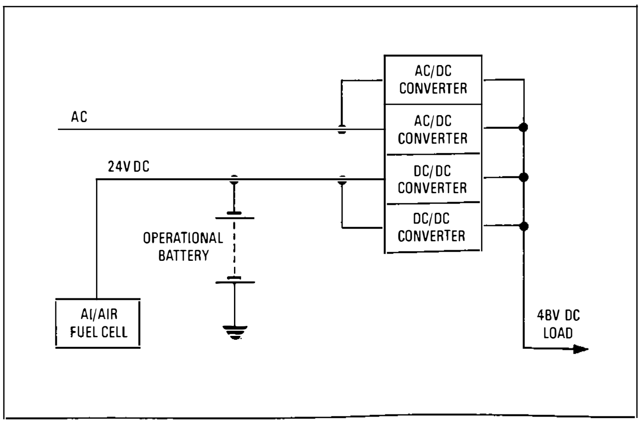

Figure 2—Alternative power system layout

ELECTRICAL LAYOUT

There are two ways of interfacing the operational battery with the load. Where the operating window of the battery is compatible with direct connection to the load, the electrical layout in Figure 1 is used. Where the battery type chosen does not have a compatible voltage range, the electrical layout in Figure 2 is used. These options allow for the use of a variety of battery types. In some cases, the use of a solid-state lithium polymer battery is envisaged.

DESCRIPTION OF ALUMINIUM-AIR BATTERY

A diagram of the fuel cell battery is shown in Figure 3. The relevant features are:

- the common electrolyte design;
- the air supply for fuel and cooling purposes; and
- the gap between the anode and cathode in the cells.

A more detailed description of the system is given in Reference 2. Description of the battery in this article is confined to features relevant to the power supply system design and layout.

The output voltage of the aluminium-air battery has three well-defined regions, as shown in Figure 4.

1. In this region, the voltage rises with temperature, and then stabilises for 1 – 2 hours, with an essentially constant voltage.
2. The second region shows a falling voltage profile with a fairly sharp recovery. The output voltage is affected by the internal resistance of the battery, which is largely determined by the electrolyte conductivity. At constant temperature, the conductivity falls as the concentration of reaction product (aluminium hydroxide) dissolved in it rises, and, as the concentration approaches saturation, the voltage falls to a minimum. As the hydroxide starts to crystallise out after saturation, its concentration falls and the output voltage rises as the conductivity of the electrolyte rises.
3. The third region of the curve is essentially flat, with a slowly falling voltage profile. This is caused by the increasing distance between the electrodes, as the anode is consumed.

The crucial features of the curve are:

- The rate at which the output voltage rises at the start of the discharge. The voltage must rise quickly enough for the battery to take load well within the remaining time in the operational battery. It is considered desirable to conserve the capacity of the operational battery.
- The minimum voltage during the initiation of the crystallisation process. The minimum voltage reached prior to the start of crystallisation is important as this could also cause 'assisted discharge' to occur, which is not considered desirable, although it could be tolerated.

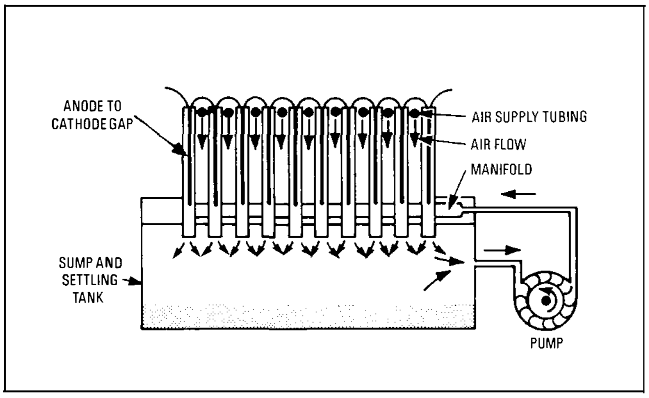

Figure 3—Fuel cell battery

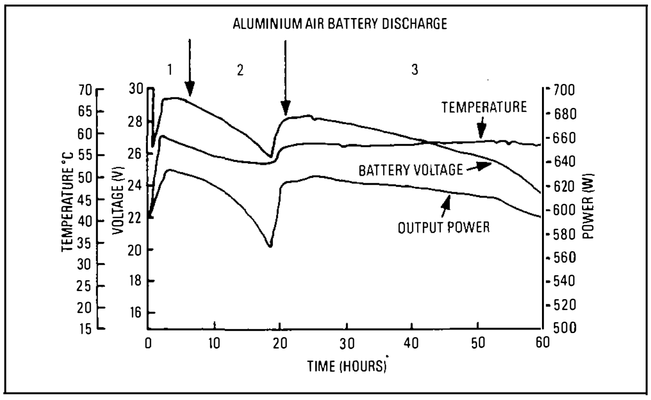

Figure 4—Typical discharge curve showing regions

INFLUENCE OF ALUMINIUM-AIR BATTERY ON CONVERTER

The output characteristic of the fuel cell battery affects the DC/DC converter design. The voltage variations and the overload characteristic while the battery is warming up must be taken into account. The problem is that the battery must supply some load to expedite the heating effect, caused by the thermodynamics of the reaction and the resistive heating of the load current, and to keep the output voltage low enough to suppress hydrogen emission. Too much load would drive the battery voltage down, and as the output characteristic is not constant power but constant current, the voltage can be driven too low, causing the battery to fail. The converter must therefore adjust its input power to suit the battery output capability.

With the layout as in Figure 2, the converter can be arranged to have constant input power regulated by the operational battery voltage.

EFFICIENCY

The use of a common electrolyte for the fuel cell battery has a bearing on efficiency. The design offers the most economical option, but it does limit the number of cells to the equivalent of 24 V. This necessitates a DC/DC converter between the battery and the load, and introduces efficiency loss due to internal shunt currents. The auxiliary load for the pump and fans has also to be taken into account: Shunt currents and the auxiliary load can be controlled by careful layout. A flyback design of converter was chosen for its high efficiency (90%).

The gross output of the aluminium-air battery is approximately equivalent to 420 Wh/l, which reduces to 350 Wh/l delivered to the load when all losses are taken into account. It is the author's view that these figures will be considerably improved as the system design improves, and, of course, should 24 V be adopted as a standard supply voltage.

SYSTEM RELIABILITY

At this stage of the evaluation, it would be premature to quote estimates of reliability for the sealed lead-acid/aluminium-air dual reserve system. However, the electrical layout adopted should ensure a highly reliable source of stand-by power for the following reasons:

(*a*) The first units into service will employ the layout in Figure 1, in which the operational battery, a valve-sealed recombination lead-acid type, is directly connected to the load. In this respect, the system resembles BT's existing distributed power systems and will therefore be expected to have a similar reliability in service.

(*b*) Starting reliability of the fuel cell battery essentially depends on the reliability of the electrolyte pump. Put simply, if the pump starts and runs, and the fans operate, the battery will generate power. Pump reliability is not expected to be a serious problem, once sufficient experience is gained of the application.

(*c*) The cooling system is also powered from the same pump and fans, and therefore does not have a serious influence on reliability, unless the piping connections become blocked, which is unlikely. The battery has a fairly large surface area and thermal mass, and failure of the cooling system would therefore reduce the stand-by time available, rather than cause a failure to start.

(*d*) The fans are a standard type, of which there is considerable operating experience, and no problems are expected in this area. The pump and fans are monitored by measuring the DC current feeding them. A failed fan or pump will either draw too little or too much current.

LITHIUM POLYMER BATTERIES

In some applications in the near future, the operational battery will be of the lithium polymer type. This battery is a logical step forward from the valve-sealed recombination lead-acid battery. It has obvious attractions in communications applications, especially in portable equipment. For stand-by power applications, the technology offers a completely sealed battery which is smaller by a factor of three, lighter by a factor of eight, has better storage characteristics, and, from tests so far carried out, appears to be inherently safe. This last point is very important. The demand for small high-energy batteries is driving battery chemistry towards more reactive materials, particularly lithium couples. This will bring with it problems of safety which need to be addressed during early development. The 'thick film' concept used in polymer batteries offers an elegant approach to the realisation of safe high-energy batteries. The prototype battery operates over a voltage range of 32–20 V.

The design has considerable potential for development. Higher energy densities and much improved characteristics can be expected over the next decade as the system matures.

FUTURE DEVELOPMENTS

Primary power sources, and the new polymer batteries, will open up a new era in power system design and provision. A variety of options will be open to the system designer. This will enable the development of a family of small power systems tailored to a variety of requirements in the most economic way, for the telecommunications networks of the future.

ACKNOWLEDGEMENTS

Thanks are due to colleagues in BT and AlcanInt who have contributed to this article and for their many helpful comments.

References

1 BANFIELD, K. E. Telecommunications Power System Reliability in the UK. INTELEC 82.
2 O'CALLAGHAN, W. B., FITZPATRICK, N. P., and PETERS, K. The Aluminium-Air Reserve Battery—A Power Supply for Prolonged Emergencies. INTELEC 89.

Secure Power Supplies for British Telecom's Major Computer Centres

R. H. HOWARD†

Any major multi-office computerisation project requires careful attention to its power supplies. This article describes how British Telecom provides no-break AC power to its biggest such project—Customer Services Systems—in almost 30 District Offices. With call-off contracts for the main power supply equipment, BT is able to ensure a quality power supply for its in-house clients and for the ultimate benefit of its customers.

INTRODUCTION

The operation and administration of the British Telecom network is becoming increasingly reliant on the use of real-time on-line computer systems. In 1985, BT began to implement Customer Services Systems (CSS)—one of the biggest computerisation projects in Europe and offering over 50 front- and back-office functions.

Each of BT's Districts has CSS running to help serve 26 million customers. It was recognised in the Power and Building Services Division that the power supplies for CSS would need to be no-break, conditioned against transients, and highly reliable. It was also realised that a high degree of standardisation was both possible and desirable. Consequently, specifications were written and call-off contracts established for the major plant items.

This article sets out to describe the types of equipment specified to achieve these aims, and to report on several years of experience. It also discusses some common problem areas which were anticipated, and some others which were not.

CUSTOMER SERVICES SYSTEMS

CSS is a purpose-designed interactive information system conceived to play a crucial part in BT's drive to become 'Top Telco' by 1990, by achieving the following objectives:

- improvement in quality of service by using comprehensive systems to support staff dealing with customers,
- better systems to improve staff efficiency,
- exploiting state-of-the-art technology, and
- demonstrating BT's competence as a producer and operator of sophisticated information technology (IT) systems.

The scale of the project may be appreciated by considering the customer and local network related database, with each District needing to input tens of millions of records organised into hundreds of different record types.

Powerful mainframe computers were clearly required and most Districts were obliged to build a new computer centre. Some were located in existing major telecommunications centres, having the benefit of existing stand-by AC power systems. Some were converted industrial premises and a few were greenfield sites. A typical CSS mainframe computer hall was originally conceived as approximately 300 m^2 consuming perhaps 200 kVA at 50 Hz and 50 kVA at 400 Hz. With successive upgrades and new generations of computer systems, these power figures have typically doubled or even trebled in four years.

PLANT CONFIGURATION

The decisions about what plant to purchase and how to configure it depend on a number of factors, one of the most important being the risk of power supply failure. Linked to this is the assessment of the consequences of such a failure. The power engineer can seldom get much objective help with these decisions from either the client or the equipment supplier, both of whom have somewhat limited knowledge of, or interest in, the whole problem.

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In the case of CSS, if the computer system 'crashed' because of a failure in the power supply equipment, BT would not lose revenue immediately; nor were there any safety or regulatory implications. It was therefore decided that the power system need not be engineered to quite the same high standards as a major telecommunications switching centre[1]. On the other hand, a failure could result in major disruption to a District's operations. In the front office, for example, customers might well be frustrated if their queries or transactions were abruptly curtailed 'because the computer is down'. And in the back office, functions such as billing and service provision could be seriously delayed leading to customer dissatisfaction and a poor public image.

These considerations led to the conclusion that the CSS mainframe should be protected against mains supply outage by stand-by diesel generators. To bridge the diesel starting gap, to condition the supply against transients, and to provide time for an orderly shut-down if necessary, an uninterruptible power supply (UPS) with at least 10 minutes battery autonomy time was specified. A separate analysis showed that a further worthwhile increase in availability would result from providing active redundancy in the 50/400 Hz converters for the central processor units (CPUs). The basic schematic diagram for a typical centre is shown in Figure 1. This arrangement could be repeated according to the number of computer halls.

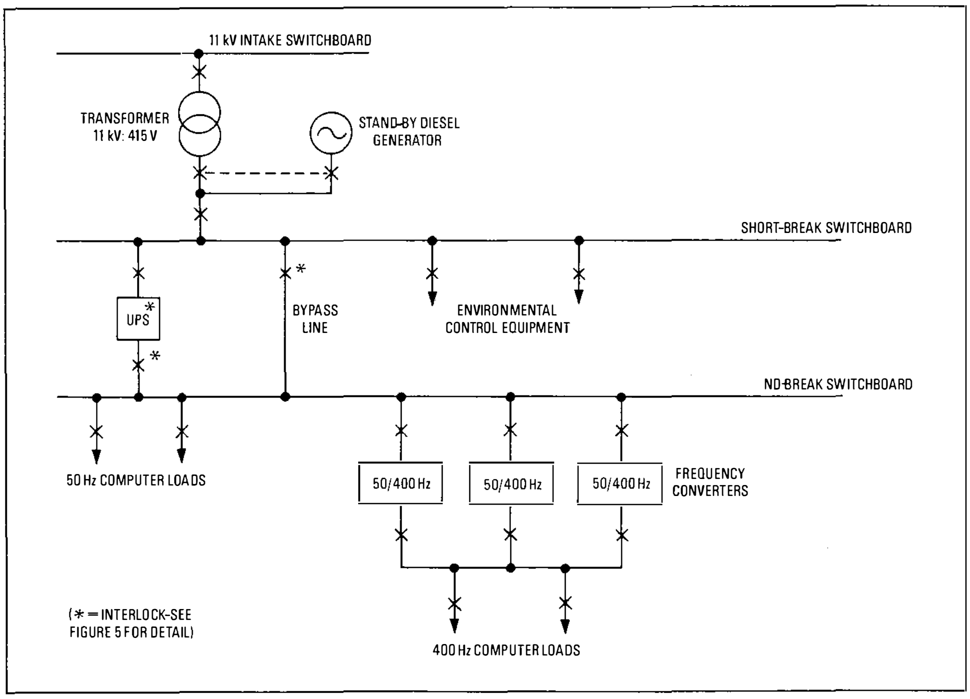


Figure 1
Typical AC distribution scheme

PLANT PURCHASING POLICY

There is adequate capacity in the UK and the rest of Europe for a range of stand-by generating sets (gensets), UPSs, and frequency converter equipment. Thus there was no point in using valuable resources trying to develop new equipment or systems. In any case, the required timescales precluded any such ideas. The approach was to specify the required performance and to establish call-off contracts for the main equipment.

In selecting suitable suppliers and evaluating tenders, many factors had to be balanced, including

- cost—initial and operating,
- accommodation requirements,
- track record for similar installations,
- quality of manufacture,
- quality of installation and commissioning, and
- back-up resources, including response time.

By this means, it has been possible to limit and define the number of equipment interfaces, to achieve economies of scale, to help manufacturers to schedule their work and to ensure timely deliveries.

Without this organisation, it is possible that several Districts would have bid against each other for the same equipment in the same market, with severe penalties. The scheduling of delivery is very important because computer equipment can be purchased and installed in much shorter timescales than its major power supply equipment. With the call-off contract, it is often possible to take advantage of flexibility in the production programme, perhaps by taking some other customer's unit early or late.

Another significant advantage of the call-off contract is that procedures for site planning and equipment ordering, installation and commissioning can be standardised. As an example, all UPS/battery installations should be subjected to full autonomy time testing before acceptance. This procedure is potentially time consuming and expensive, involving the use of load banks, temporary cabling, skilled personnel and instrumentation. Unfortunately, it is the only way that a customer can be satisfied that the full specified performance is available and that the integrity of the vital battery circuit, with its hundreds of high-power connections, is sound. By working with the same contractor's personnel on the first few installations, it has been possible to establish a formal procedure to ensure that nothing is overlooked and that everyone involved knows what is expected of them.

PLANT SELECTION CRITERIA

Diesel Genset

The UK has quite a number of genset manufacturers able to offer the required range of output (300 – 1500 kVA). To minimise the cost and physical size, high-speed (1500 rev/min) sets were specified, capable of installation outdoors where necessary in weatherproof canopies with integral sound-attenuated ventilation and roof-mounted exhaust silencers.

After tender adjudication and vendor assessment, the contract was awarded to a UK genset builder who has since supplied over 50 sets for CSS and similar BT applications. (See Figure 2.) BT's suppliers have their own installation and commissioning team for most of the work; underground fuel tanks and any associated electrical installation work is carried out by approved sub-contractors.

Uninterrruptible Power Supply

The UPS contract was awarded to the UK's largest manufacturer after adjudication of tenders from manufacturers of both rotary and static types. The main selection criteria in favour of the static UPS were cost and accommodation, but manufacturing and service back-up capacity and track record were also important. This has since been borne out by experience. Some features of the selected equipment (see Figure 3) are:

- static rectifier/inverter system;
- static bypass facility;
- 'blip to bypass', for large overloads;
- input current 'walk-in';
- harmonic filter option;
- isolating transformer option;
- redundancy in cooling fans; and
- input, output and battery current limit.

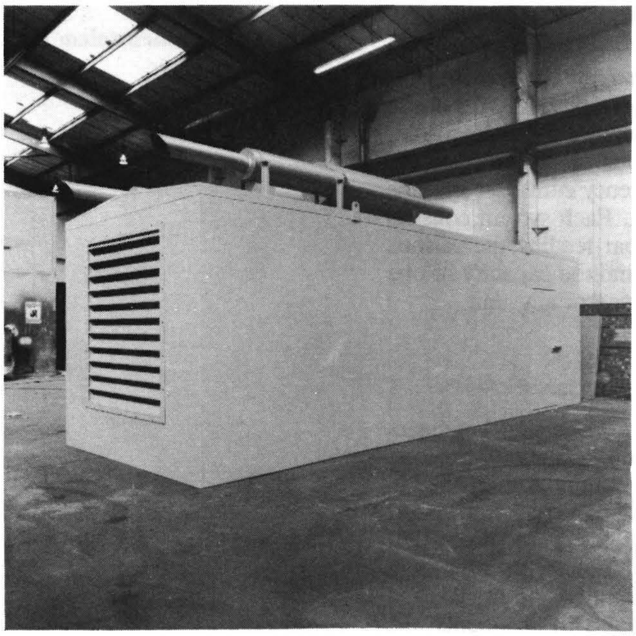


Figure 2—Typical genset installation for CSS

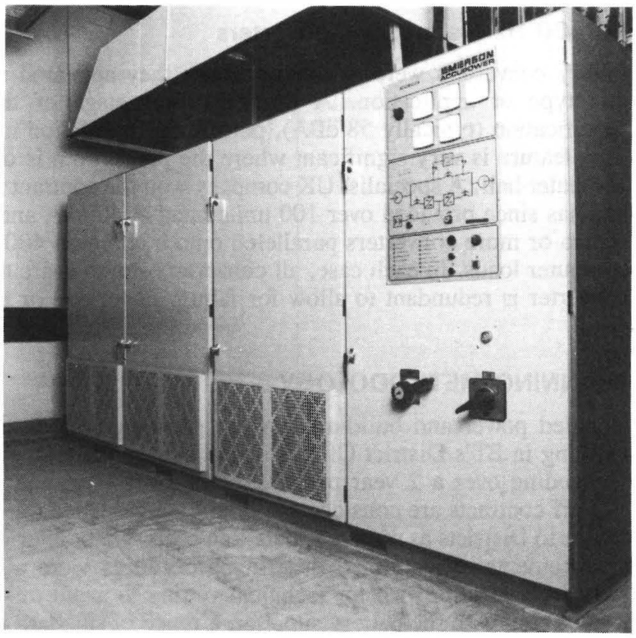


Figure 3—Typical UPS installation

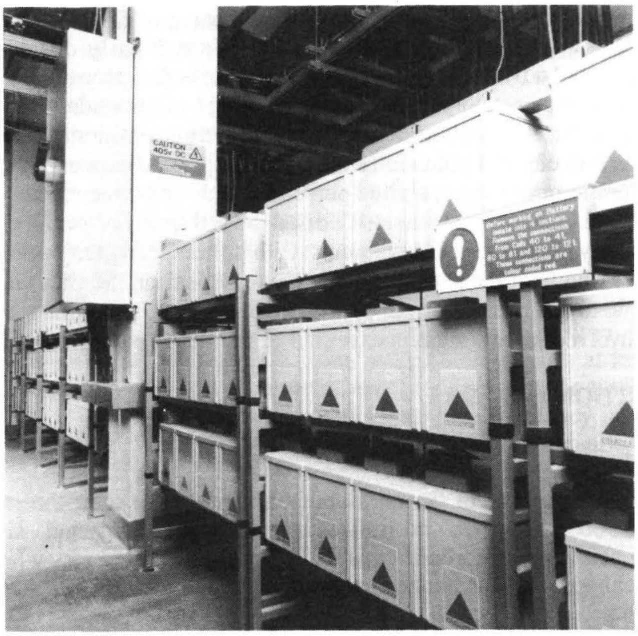


Figure 4—Typical UPS battery

Batteries

By 1985, the valve-regulated sealed lead-acid (SLA) cell had already become established as the standard for 48 V power plant serving the BT network. The advantage of high power density, very low maintenance requirement and relatively safe construction made SLA the obvious choice for the CSS UPS applications. (See Figure 4.)

After considering the options, it was decided to have the UPS batteries supplied by sub-contract via the UPS manufacturer. By this means, BT gained the advantage of a single interface for all commercial dealings and hence obviated any difficulties concerning 'who does what'; for example, battery cable dimensioning, protection, installation and commissioning. Some features of a specified installation are:

- multi-tier (up to six) battery stand,
- all live parts insulated,
- prominent precaution notices,
- means of battery isolation,
- means of sectioning, and
- means of measuring cell voltages.

50/400 Hz Frequency Converters

Rotary converters were selected because they appeared to be the industry standard for this type of application. A particular advantage of the rotary type is its acoustic specification (typically 58 dBA), permitting installation in the computer hall if required. This feature is very significant where the plant room is overcrowded or distant from the computer hall. A specialist UK company won the contract for frequency converter systems and has since provided over 100 units rated at 40 kVA and 75 kVA. Each system consists of two or more converters paralleled onto a common 400 Hz busbar feeding the various computer loads. In each case, all converters run to share the load and the capacity of one converter is redundant to allow for failure in service or maintenance of any unit.

PLANNING METHODOLOGY

Detailed power and building services planning was carried out by specialist engineers working in BT's District Offices or by their consultants. With approximately 30 projects proceeding over a 2 year period, the benefits of standard power supply equipment via call-off contracts are considerable. Planning guidance was issued and updated from Head Office to Districts as required, detailing costs, sizes, interface requirements and protection arrangements. Streamlined ordering procedures were also introduced, with all orders routed via Head Office for technical vetting to avoid misunderstandings and mistakes.

Working with the battery supplier, a range of standard battery stand arrangements was determined to suit most applications. Where necessary, these had to be modified to suit particular site requirements such as odd-shaped rooms, mezzanine floors etc.

It has also been possible to establish certain 'rules of thumb' to assist District Offices in their planning. For example, it is well known that large rectifiers, such as the front end of UPSs, can cause interactive problems when powered from relatively high-impedance stand-by generators. By obtaining from the UPS manufacturer an analysis of harmonic input current and power factor at various loads, and presenting this analysis to the generator manufacturer, these problems can be obviated or at least minimised. The rule of thumb now used in BT is that for a single-UPS single-generator installation, the ratio of genset kVA to UPS kVA should be not less than 1·4:1 (nominal ratings). The remaining genset capacity is, of course, used for linear loads.

MAINTENANCE REGIME

Diesel Stand-by Generators

It is BT's practice to exercise gensets once per month on the station load. This can be by 'black start'—simulating a mains supply failure, or by synchronising and soft load transfer, depending on the degree of local confidence in the system. In any event, a black start prolonged run (preferably 6 hours) should be performed once per year, with the generator fully loaded.

Uninterruptible Power Supply

It is useful to be able to cut over from the UPS output to the mains supply without disturbing the load. In conjunction with the UPS supplier, this facility has been provided at minimal cost by the arrangements shown in Figure 5.

The facility works by first operating a control switch on the UPS, forcing it to synchronise its output with the mains supply. The static switch then closes, followed rapidly by its internal bypass circuit breaker. This operates a solenoid switch on the UPS control panel, releasing a trapped key which can then be safely transferred by the operator to close the external bypass circuit breaker.

Finally, if it is required to exercise the UPS, say into a test load, the key trapped in the UPS output circuit breaker can be transferred to the UPS interlock to gain full control of its circuit breakers.

Routine maintenance on the static UPS system is limited to visual examination, test point and connection checks as prescribed by the manufacturer, plus the battery circuit integrity checks.

Battery Monthly Checks

Each month the integrity of the battery circuit should be tested by the mains supply failure simulation associated with the stand-by genset. This forces the battery to take load via the inverter and gives confidence that the system is available.

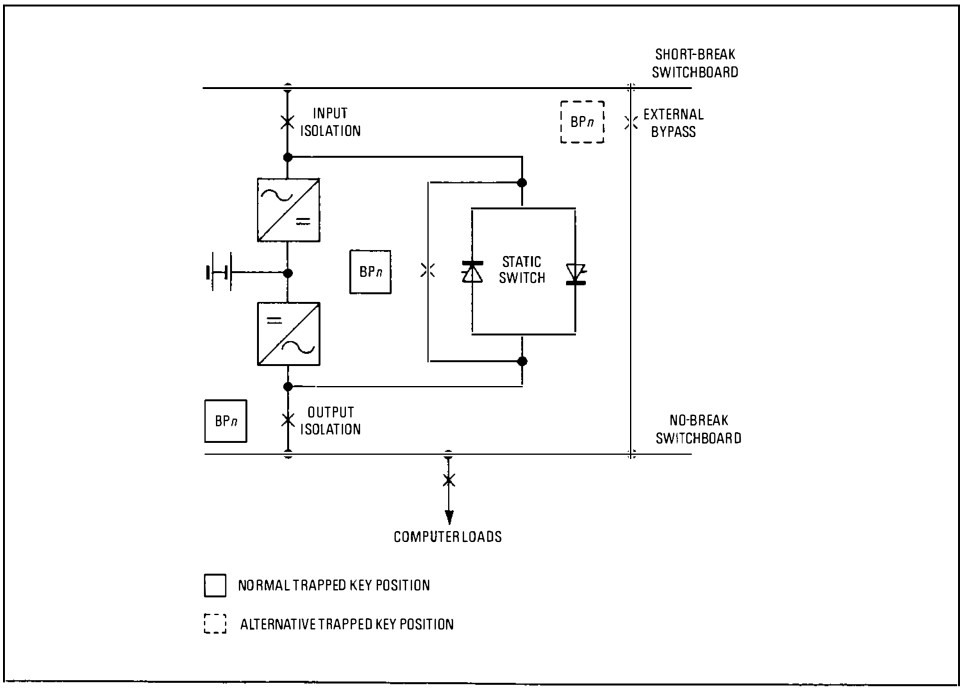


Figure 5
UPS maintenance bypass facility

Battery Annual Check

For the annual check, the load is set constant by arrangement with the computer operations manager. By reference to a look-up table, the maintenance personnel know how long the battery should last at a given temperature into a given load, down to a given voltage. Thus by measuring DC volts and amps, a reasonably accurate assessment can be made of the battery's capacity, and an investigation can be initiated if necessary. (See Table 1.)

TABLE 1
Look-Up Table for 180 × 400 Ah Cells

Temperature	End Voltage (V)	Loading (kW)				
		110	140	179	190	211
		Time in Minutes				
25°C	330	37·2	24·2	15·4	11·0	7·5
	320	41·4	28·1	19·6	15·4	12·0
	310	43·6	31·4	22·4	17·7	14·0
	300	44·2	32·0	23·2	18·6	15·0
20°C	330	35·6	23·0	14·2	10·0	6·4
	320	39·6	27·0	18·3	14·2	11·2
	310	41·9	30·0	20·8	16·4	13·0
	300	42·5	30·6	22·0	17·4	14·1
15°C	330	33·4	20·5	12·4	8·4	5·0
	320	36·8	24·6	16·4	12·8	9·4
	310	39·4	27·7	18·8	14·6	11·3
	300	40·2	28·4	19·8	15·8	12·5
10°C	330	30·2	18·6	10·4	6·6	3·4
	320	34·4	22·7	14·8	10·8	7·4
	310	37·0	27·7	16·8	12·8	9·4
	300	38·0	26·4	18·0	14·1	11·0

BATTERY SAFETY

Background

BT is one of the major users of sealed lead-acid batteries in the UK, has established a good safety record and has considerable knowledge of their characteristics. The safety standards applied to large UPS systems have to be a reasonable balance between ultimate caution and cost-effective engineering judgement. With voltages present up to 450 V, it is clearly necessary to assess the risks to personnel and to build adequate precautions into the engineering and procedural design.

Risks to Personnel

The main potential risks to personnel are considered to be

(*a*) inadvertent casual contact with a live part; for example, when passing by the plant or working near it; and

(*b*) accidental contact with live parts while maintaining the battery.

The risks have to be addressed separately. The inadvertent contact with passers-by is dealt with in three ways. For UPS ratings from 100 kVA to 400 kVA, the BT specification calls for a double-wound isolating transformer in place of the regular autotransformer. Hence the battery is effectively floating, that is, not referenced to earth, so that anyone making a single contact with a live part should not receive an electric shock. For UPS ratings above 400 kVA, the isolating transformer becomes impracticable because of the physical size and cost implications. For these installations, the most practical solution is a wire cage around the battery, or a separate battery room. For all installations, the battery is designed with all live parts insulated, the intercell connectors having clip-on plastic covers.

The accidental contact by maintenance personnel is difficult to guard against physically. It is desirable to have the facility of checking cell voltages with the rectifier switched on, so the problem is best dealt with by careful procedures.

Safety Procedures

The BT specification calls for prominent safety notices listing the precautions to be taken before working on the battery. These precautions are as follows:

- do not work alone on the battery system,
- isolate the battery before working on it,
- use only insulated tools, and
- split the battery into sections of 120 V or less by using the special links.

POTENTIAL SYSTEM PROBLEMS

The following notes represent BT's approach to, and experience of, certain common problems which can arise on site unless anticipated at the design stage.

Rectifier Harmonics and Power Factor

Rectifiers specified to comply with national standards[2] should not cause any problems when working on the mains supply. Stand-by generators, however, have much higher source impedances, and a poorly specified combination can give rise to excessive harmonic voltage distortion, overheating and inadequate voltage regulation.

Many UPSs, especially those fitted with an harmonic filter, will exhibit a leading power factor at light load. For some designs, the input power factor is leading for all loads less than 50% of the nominal rating. Without careful design, this can lead to generator instability due to the armature reaction effect. It is therefore important to determine, from the UPS manufacturer, the full information on harmonic input currents and power factor over the load range. With this information, the genset manufacturer can then select a design accordingly. The general rules for success are, for the generator:

- no-load phase—neutral voltage distortion less than 1·5%,
- fully linked damper winding,
- sub-transient reactance less than 12%,
- separate exciter,
- full thyristor divert automatic voltage regulator (AVR), and
- pitch winding design to minimise relevant harmonics.

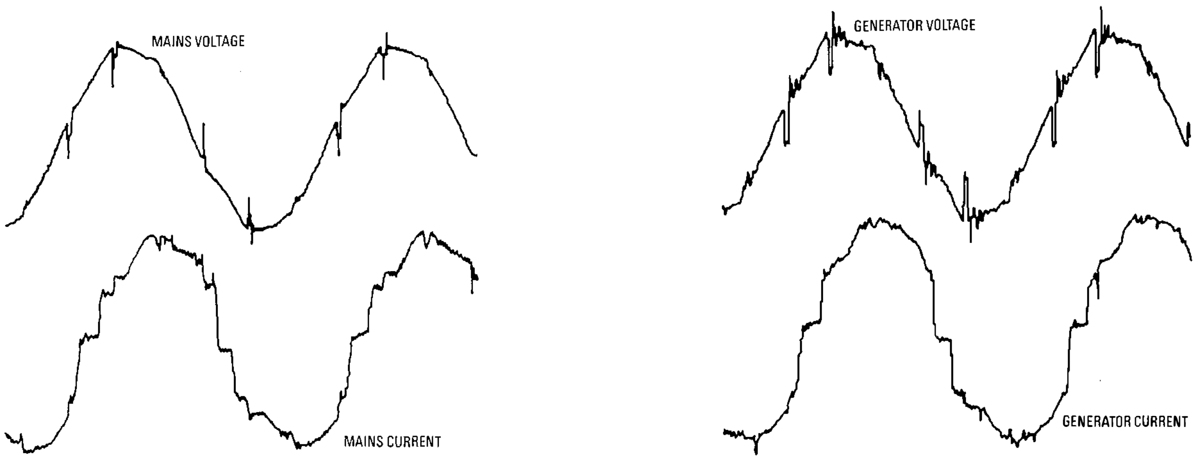
In addition to these 'technical rules', it is also prudent to limit the non-linear load on such a generator to a maximum of 75% of its nominal rating. Even then, voltage distortion of the order of 15% must be expected. It follows that any loads which are sensitive to such distortion should be connected to the UPS output. Figure 6 shows the difference between mains supply and generator waveforms when feeding a 700 kVA 6-pulse UPS fitted with an harmonic filter. The voltage distortion is estimated to be 5% on the mains supply and 12% on the stand-by generator supply.

Crest Factor

This topic is the subject of much debate and is dealt with in some detail in Reference 3. It can be defined as the ratio of peak current to RMS current. High crest factor can be caused by switched-mode power supplies having large capacitors fed by single phase rectifiers. If many such units are connected to a UPS supply, problems such as waveform distortion, poor voltage regulation and excessive neutral currents can be caused.

The CSS mainframe computers and their peripherals have been found to form a good mixed load which is kept well balanced, by design, across the three phases. Measurements

Figure 6—UPS input waveforms



(*a*) Mains supply (*b*) Stand-by generator on site have revealed very little voltage distortion and negligible neutral currents under normal operation. It is acknowledged, however, that precautions are necessary, especially on outstation sites with many terminals but no mainframe.

PROBLEMS ENCOUNTERED

Uninterruptible Power Supply

Only one serious technical problem has arisen, and this on only one of the UPS ratings. As was mentioned earlier, input harmonic filters were specified to alleviate possible voltage distortion problems. On one particular design, it was found that under certain load conditions an interaction occurred between the input filter and the rectifier DC smoothing filter, resulting in overheating. The problem was cured by redesigning the DC choke and retrospective site work was necessary.

Batteries

Two problems have emerged causing considerable inconvenience to BT and an expensive retrospective programme for the battery manufacturer. The first problem was caused by manufacturing technique and the use of alloyed lead in the group bar casting. This had the unexpected effect of causing rapid corrosion in the negative plate/group bar welds, leading to open-circuit failures. Once the situation was realised, the manufacturer responded by replacing all defective batteries. In the meantime, however, two computer system 'crashes' were caused under mains supply failure conditions as the UPS batteries failed before the stand-by generators came on line.

The second problem—leaking pillar seals—was more of an inconvenience than a threat to service. Again, the manufacturer has replaced or repaired all leaking cells.

The response by both manufacturers to problems arising in the field reinforces the value to BT of the ongoing contracts. Good customer/supplier relationships and plant/site records make it relatively easy to plan and co-ordinate retrospective modifications when necessary.

Other System Problems

In spite of all the efforts made to design and implement a reliable system, human error can often cause more problems than the equipment itself. Automatic circuit breakers and their associated protection devices are particularly prone to misoperation or maladjustment. At least four 'system crashes' are known to have been caused by protection settings which were too low.

One or two 'crashes' have also been caused by misoperation of the UPS plant controls, including one incidence of inappropriate use of the emergency stop button!

This type of incident can never be completely eliminated, but properly organised operator training and thorough documentation can help. A high degree of standardisation makes both these tasks easier.

CONCLUSIONS

(*a*) The roll-out of 30 CSS installations has been matched by secure AC power supplies consisting of stand-by diesel generators, static UPS and '$n + 1$' redundant frequency converters.

(*b*) The power systems procurement and installation standards have been managed by the part-time efforts of a small unit in Head Office; there are many benefits of managing such a project in this way.

(*c*) Call-off contracts were established for all the major power supply equipment, leading to economies of scale and a high degree of standardisation.

(*d*) Several potential problems have been avoided by design and attention to the effects of one machine on another.

(*e*) Sealed lead-acid batteries with voltages around 450 V can be installed safely in plant rooms provided certain precautions are observed.

(*f*) In spite of all the care taken, several computer system 'crashes' have been recorded, due mainly to human error, and battery system failures.

(*g*) More attention is now being paid to the on-site quality—training, commissioning and maintenance.

References

1 HENDERSON, J. P. AC Power Systems in British Telecom for the 1990s. INTELEC 1988.

2 Electricity Council. Limits for harmonics in the United Kingdom Electricity Supply System. Engineering Recommendation G5/3. Electricity Council, London, 1976.

3 MCLENNAN, A. A. High Crest Factor Loads on UPS Systems. INTELEC 1989.

The Development of High Reliability Modular Cooling Systems in British Telecom

P. A. ALLEN†

In the early-1980s, with the introduction of fully digital switching systems, cooling became essential to the uninterrupted operation of an exchange. This led to a requirement for high-reliability cooling systems and a standardised approach to system design and installation. This article describes how the problem was approached in BT and operating experience to date.

A study of theoretical system reliability led to the conclusion that only by using modular cooling systems, feeding a common air delivery system, could the required levels of reliability be achieved. In practice, while such systems are reasonably easy to achieve, cost-effective reliability depends also on maintenance procedures, alarms handling and remote diagnostic facilities, and the time taken to respond to plant failures.

BT cooling systems are now based on highly standardised modular cooling units which use fresh air as the principle cooling medium and incorporate direct expansion (DX) refrigeration plant. A ventilated ceiling is normally used to deliver air to the room, but a downflow unit for use with raised modular floors is also available. More recently, a unit incorporating a dry cooler has been introduced. For small rural exchanges, total fresh air units are used. The units are sited in the exchange room, and each requires only a single hole through an outside wall. The control system is also standardised and has recently been redesigned to incorporate remote diagnostic features.

The approach adopted has been highly successful. Over 3000 units are now in use, and there have been no instances of service failure due to loss of environmental control.

INTRODUCTION

As switching systems in British Telecom and other world-wide telecommunications companies evolved from electromechanical to electronic, so the need for cooling increased. With the introduction of fully digital systems, cooling became essential to the operation of an exchange. So much so that reserve battery capacities are now often limited to one hour or less to prevent failure of the switch due to loss of the environment under total mains failure conditions.

Until the early-1980s, cooling systems in BT normally used central chilling plant which distributed chilled water to air handling units located in, or adjacent to, the exchange room. These systems were expensive to install, maintain and operate. Because switching systems were not entirely cooling dependent, central chilling systems rarely incorporated redundant plant and were consequently prone to complete failure.

In BT, it was realised that an entirely different approach would be required for digital switching systems if cooling systems were to meet the high levels of reliability demanded by the switch.

RELIABILITY

Appendix 1 shows two simple reliability calculations for a cooling system using a single cooling unit and a system using two cooling units in parallel (that is, using a common distribution system), each having half the capacity of the single unit. The calculations show clearly the dramatic improvements in reliability brought about by the use of modular systems. Using the modular system, the failure of one unit will cause the room temperature to rise, but the remaining unit will hold the environment within the operating limits of the switch. Thus the modular system does not need to incorporate redundant capacity.

Clearly, as the number of units increases, so the effects of the loss of one unit are reduced. The modular approach was therefore chosen for all new cooling systems.

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DESIGN PARAMETERS

The use of a modular system presents some problems in that each module must operate entirely independently. With the exception of the air distribution system (which is a passive component having virtually infinite reliability), no component of the system may be common to all the units.

In order to minimise the operating costs of the cooling system, it was decided at an early stage of the design to use filtered fresh air as the main cooling medium. Refrigerated cooling would be used only when the outside air temperature was too high to enable fresh air cooling. In the UK, humidity levels rarely reach extreme levels and it was decided in the interests of operating cost and efficiency not to provide humidity control. The basic design parameters therefore became:

(*a*) the unit would require a single hole through an external wall to reduce building costs and simplify installation,

(*b*) the main cooling medium would be fresh air,

(*c*) each unit would incorporate its own air filtration and DX refrigeration system,

(*d*) for ease of maintenance, all the main components would be mounted on a wheel-in/wheel-out sub-unit, and

(*e*) a standard control system would be used to operate all units regardless of capacity.

REALISATION

The first modular cooling unit to go into production in 1981 was rated at 15 kW sensible heat load with external ambient conditions between the limits −7 to +32°C. By 1986, some 1500 units had been installed and were working well. During that period, a number of minor design deficiencies were identified and in 1986 a modified version of the 15 kW unit was introduced. Figure 1 shows a cooling installation using the units. Figures 2 and 3 show the building details and the operating modes.

In the free-cooling mode, cold outside air is drawn in, passed through the filter and into the exchange room by the mains circulating fan at the top of the unit. The outside air temperature, and the inside air temperature and humidity, are measured by sensors. The control system achieves temperature control by regulating the quantity of incoming air with a damper. Positive pressure inside the room is maintained by a pressure relief ventilator.

When the outside air is no longer capable of cooling, either by reason of high temperature or humidity (70% RH), the unit switches to the refrigeration mode. The damper closes to allow only a small fresh air make up to pressurise the room, and the compressor starts up. The outside air is now used only to cool the condenser.

The unit is simple and fast to install. On completion of the necessary builder's work to form the single hole through the external wall, the external louvre and any internal silencer required is installed, followed by the outer part of the unit. The inner unit is then wheeled into the outer. The unit requires a 3-phase AC mains supply and single-phase 240 V AC supply which operates the compressor crank case heaters.

Figure 1—BT 15 kW standard cooling unit

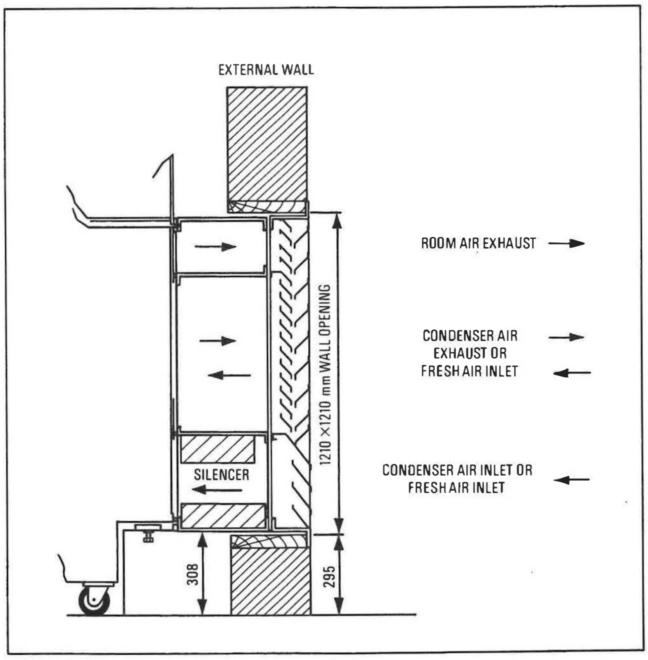
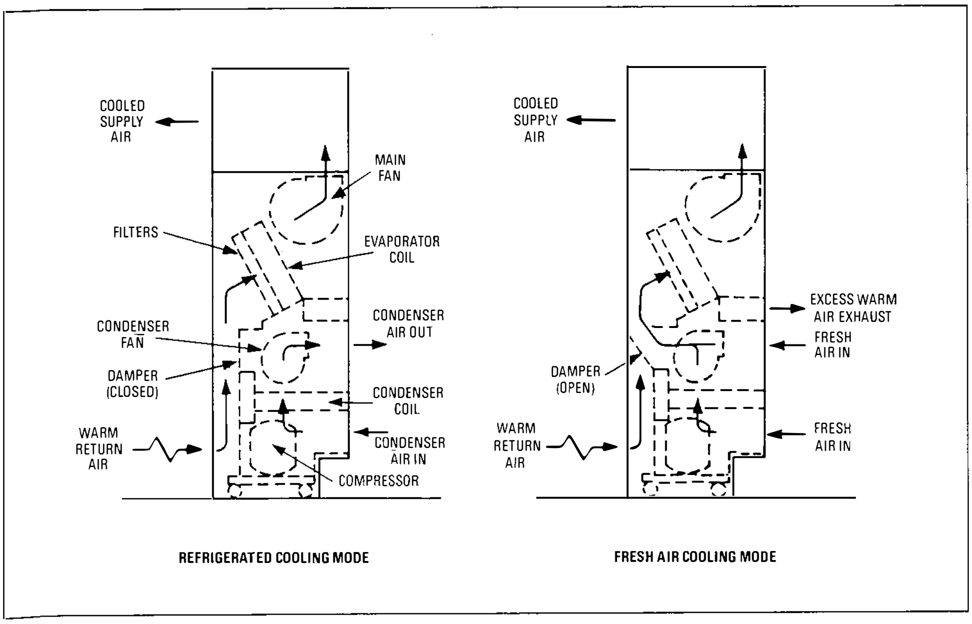


Figure 2—BT 15 kW standard cooling unit building details

Figure 3
Air flow schematics for BT 15 kW standard cooling unit



The introduction of the 15 kW unit was followed by 8 kW and 30 kW units operating on the same principles, and using the same standard control system. (The 30 kW unit does not have a wheel-in/wheel-out inner unit.)

FRESH AIR AS A COOLING MEDIUM

In practice, with the ambient temperatures experienced in the UK, fresh air has proved an excellent cooling medium. In general, the refrigeration circuit operates for less than 30% of the year, and the running costs of the unit are 50% less than those of the nearest available commercial unit using a standard DX system.

However, the use of large volumes of fresh air brings its own problems, notably the build up of small dust particles in the exchange room. Under normal circumstances, small sub-micron dust particles tend to agglomerate with larger dust particles and settle out. The panel filter used in the original design filtered particles down to 5 microns. As a result, smaller particles which entered the exchange room tended not to agglomerate but to remain in suspension. It was observed during operational tests that the sub-micron dust levels in certain exchanges were gradually increasing. While this has never caused a problem, it was felt that this problem should be addressed and the first step was to identify an improved panel filter medium.

Consideration was also given to reducing the amount of fresh air introduced into the exchange room. At the same time, it was felt that as digital switches advanced, their environmental requirements would become more rigorous and that the range of acceptable humidity would reduce. In order not to introduce expensive humidity control, and to retain the use of fresh air as the main cooling medium, the design of a dry cooler version of the 15 kW unit was commissioned.

DRY COOLER UNIT

Commercially available systems all used external dry coolers requiring extensive pipe runs and additional installation work. External noise levels would also have been a problem.

Accordingly, the unit was designed with the same physical specification as the original 15 kW cooling unit. The same size opening through the external wall is required and all the additional heat exchangers are contained within the original envelope. The main difference is that the dry cooler unit is not designed to supply fresh air direct to the exchange room. Figure 4 shows the general arrangement of the unit.

AIR DELIVERY

The cooling units, sited around the perimeter of the exchange room, supply cooled air to the switch either via ductwork, 'free blow' adaptors, or a ventilated ceiling.

The ventilated ceiling is the most commonly used delivery system, discharging air from the ceiling void through slots or ventilated strips. With a discharge velocity of 4·5 m/s, the ceiling is capable of handling cooling loads up to 400 W/m^2. However, with higher discharge velocities, the ceiling will handle loads up to 800 W/m^2.

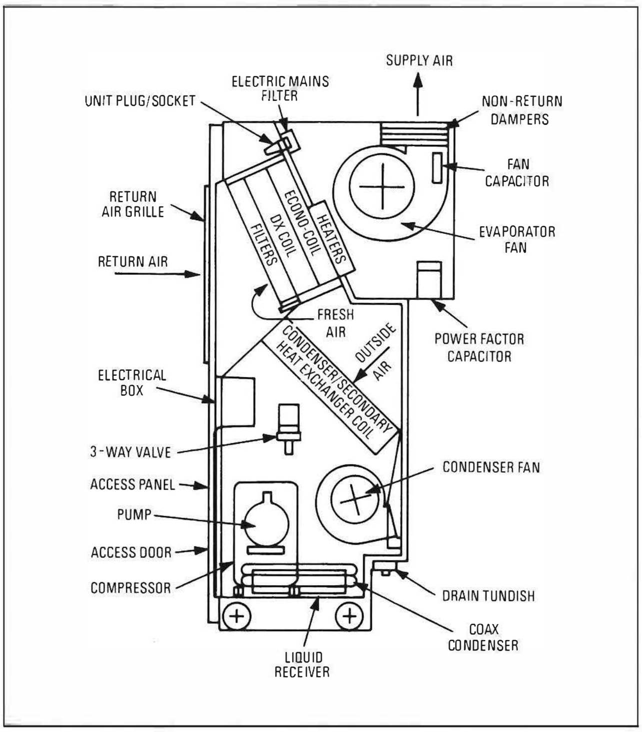


Figure 4—BT 15 kW dry cooler unit general arrangement

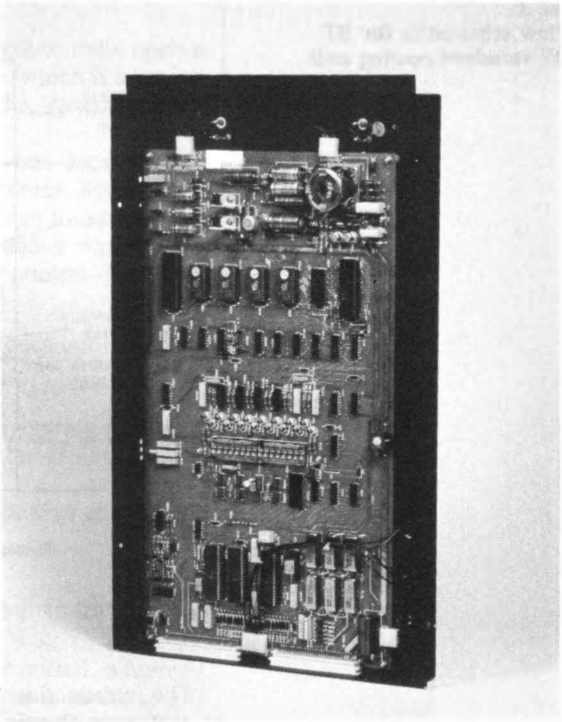


Figure 5—BT standard cooling control system Mk 1

Increasingly, there is a requirement to install switches on raised modular floors, to accommodate cabling. Accordingly, a new downflow 15 kW standard cooling unit has been developed which supplies air into the modular floor. In all other respects, the design of the unit follows the standard principles: fresh air as the main cooling medium; built in DX refrigeration system; standard control system.

STANDARD COOLING CONTROL SYSTEM (STACCS)

The development of a standard control system which would run all types of standard cooling unit was an important part of the unit development programme. The original system was realised as a single printed circuit card based on an 8085 microprocesssor and fulfilling three main functions:

(*a*) to provide all the necessary control signals to the cooling unit,
(*b*) to initiate alarm signals in the event of any malfunction, and
(*c*) to provide a readout of control system variables and set points.

The control card operated from a 50 V DC supply and is shown in Figure 5.

A serious disadvantage of the original system was that it had no communications interface enabling remote monitoring and control. In the mid-1980s, difficulties with obtaining obsolescent components were also experienced. As a result, in 1988, a completely new control card was introduced which incorporated a communications interface. Figure 6 shows the new control system. Figure 7 shows a typical screen display from the graphics software used to interrogate the card remotely, either following receipt

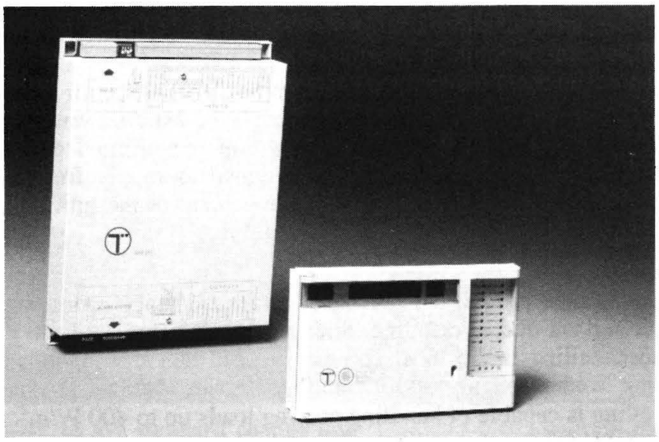
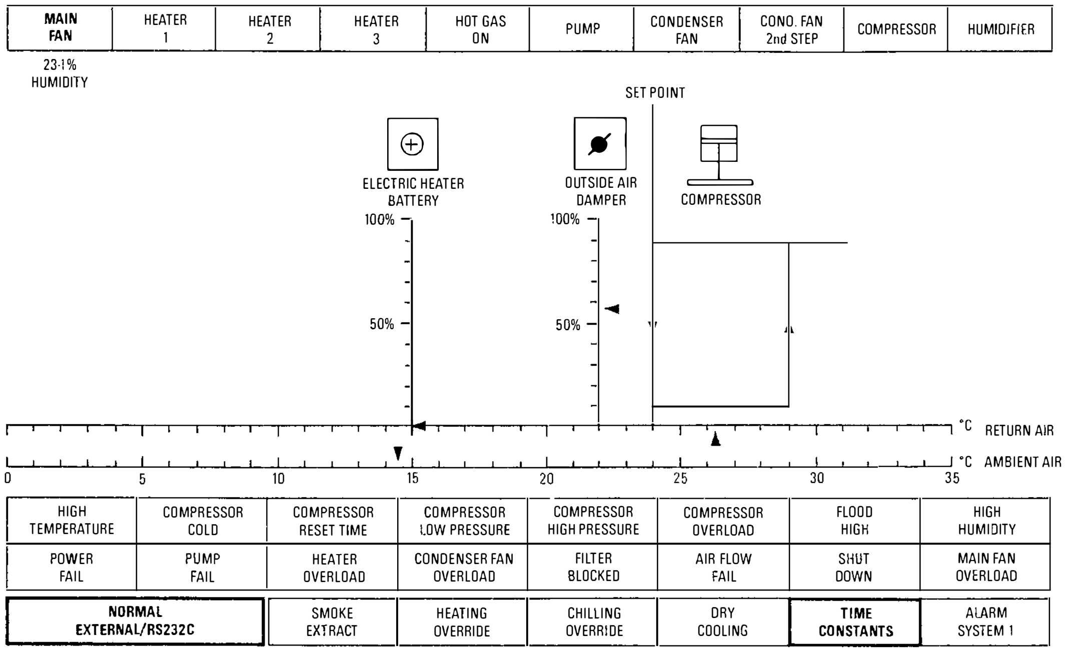


Figure 6—BT standard cooling control system Mk 2



MAIN FAN	HEATER 1	HEATER 2	HEATER 3	HOT GAS ON	PUMP	CONDENSER FAN	COND. FAN 2nd STEP	COMPRESSOR	HUMIDIFIER

HIGH TEMPERATURE	COMPRESSOR COLD	COMPRESSOR RESET TIME	COMPRESSOR LOW PRESSURE	COMPRESSOR HIGH PRESSURE	COMPRESSOR OVERLOAD	FLOOD HIGH	HIGH HUMIDITY
POWER FAIL	PUMP FAIL	HEATER OVERLOAD	CONDENSER FAN OVERLOAD	FILTER BLOCKED	AIR FLOW FAIL	SHUT DOWN	MAIN FAN OVERLOAD
NORMAL EXTERNAL/RS232C		SMOKE EXTRACT	HEATING OVERRIDE	CHILLING OVERRIDE	DRY COOLING	**TIME CONSTANTS**	ALARM SYSTEM 1

The display screen gives an illuminated indication of the plant and alarm status.
The diagram shows the system in the 'free cooling' mode with the outside air damper in the 56% open position.
The status of the screen is shown with the ON indicators highlighted.

Figure 7
BT standard cooling control system—typical remote interrogation display

of an alarm over an independent system, or when monitoring or fine tuning a cooling unit. The new control card can be fitted as a replacement for the original system.

MAINTENANCE AND OPERATION

BT's standard cooling units require virtually no maintenance apart from filter changing and simple routine maintenance of the fan and DX system. The low maintenance is due mainly to the fact that the refrigeration system is used less than 30% of the time, and system faults are consequently dramatically reduced. In practice, units rarely fail, and, because of the modular nature of the cooling systems, no switch has failed due to loss of the environment. (Some switch failures have occurred because the switch did not operate over its design temperature range.)

BT is presently rationalising its approach to network administration to enable 'hands-off' operation of all network elements as far as is possible. STACCS, coupled with a suitable alarms handling system, is fully compatible with this approach.

SMALL BUILDINGS

Many of BT's smaller exchange buildings have cooling requirements below 8·0 kW. For these buildings, two fresh-air-only cooling units are available, delivering 1·0 and 0·5 m^3/s respectively. The units comprise a high-grade filter, one or two fans, and a simple control system. The units do not control the temperature in the room within precise limits; rather, they hold the temperature rise in the exchange room to within the environmental operating limits of the switch. With a 4°C temperature differential between internal and external ambient temperatures, the larger unit gives 5 kW of cooling.

SPOT COOLER

Despite every attempt to design a cooling system which is reliable and flexible enough to accommodate a wide range of switching equipment, occasions arise when ambient temperatures peak above design levels, and hot spots develop in equipment racks having abnormal heat densities. In order to maintain the environment on these rare occasions, a transportable spot cooler was developed. Rated 1 kW, the unit provides a simple method of providing local cooling.

CONCLUSION

BT's approach to the design of high-reliability cooling systems, conceived in the early-1980s, has proved entirely successful. A range of standard cooling units is available to meet the cooling requirements of almost all situations. Design of cooling systems is standardised and greatly simplified, and the design of the units minimises installation timescales. Coupled with their low running costs, BT's cooling systems have proved to be not only highly reliable, but cost effective too.

APPENDIX 1

Simplified Mathematical Demonstration of the Reliability of Modular Cooling Systems

Consider a cooling unit in Figure A1 consisting of a main air fan, refrigeration circuit and control system:

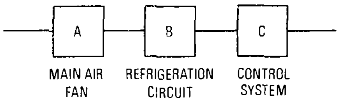


Figure A1

	A	B	C
Failure rate λ (failures/year)	0·2	0·125	0·25
Repair time r (hours)	3	24	20

Assumptions:

- Repairs are performed when necessary.
- No scheduled maintenance is carried out.

Consider a single cooling unit shown in Figure A2.

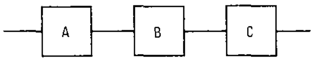


Figure A2

$$\begin{aligned}\text{Failure rate } \lambda_s &= \lambda_A + \lambda_B + \lambda_C,\\ &= 0{\cdot}2 + 0{\cdot}125 + 0{\cdot}25,\\ &= \underline{0{\cdot}575 \text{ failures/year.}}\end{aligned}$$

$$\begin{aligned}\text{Unavailability } U_s &= \lambda_A r_A + \lambda_B r_B + \lambda_C r_C,\\ &= 0{\cdot}2\times 3 + 0{\cdot}125\times 24 + 0{\cdot}25\times 20,\\ &= 0{\cdot}6 + 3{\cdot}0 + 5{\cdot}0,\\ &= \underline{8{\cdot}6 \text{ hours/year.}}\end{aligned}$$

$$\begin{aligned}\text{Average repair time } r_s &= U_s/\lambda_s = 8{\cdot}6/0{\cdot}575,\\ &= \underline{14{\cdot}95 \text{ hours/failure.}}\end{aligned}$$

$$\begin{aligned}\text{Mean Time Between Failures (MTBF)} &= 1/\lambda_s = 1/0{\cdot}575,\\ &= \underline{1{\cdot}74 \text{ years.}}\end{aligned}$$

Consider a system, as in Figure A3, comprising two identical cooling units, each having half the cooling capacity of the single unit in Figure A2.

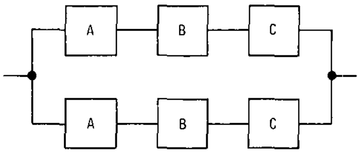


Figure A3

$$\begin{aligned}\text{Failure rate } \lambda_p &= \lambda_s^2 2r_s/8760,\\ &= 0{\cdot}575^2 \times 2 \times 14{\cdot}95/8760,\\ &= \underline{0{\cdot}00113 \text{ failures /year.}}\end{aligned}$$

$$\begin{aligned}\text{Average repair time } r_p &= r_s^2/2r_s = 14{\cdot}95^2/2 \times 14{\cdot}95,\\ &= \underline{7{\cdot}475 \text{ hours/failure.}}\end{aligned}$$

$$\begin{aligned}\text{Unavailability } U_p &= \lambda_p r_p = 0{\cdot}00113 \times 7{\cdot}475,\\ &= \underline{0{\cdot}0084 \text{ hours/year.}}\end{aligned}$$

$$\begin{aligned}\text{Mean Time Between Failures (MTBF)} &= 1/\lambda_p = 1/0{\cdot}00113,\\ &= \underline{885 \text{ years}}.\end{aligned}$$

Note:

1. In the single cooling unit case, the minimum repair time for any component is 3 hours. If the room environment would go out of condition within 3 hours of a cooling system failure, then the system is vulnerable to a single breakdown.
2. In the second case, where two separate cooling systems are installed, any one cooling unit is capable of maintaining the room environment within the upper working limit of the telecommunications equipment (normally 40°C). The system is only vulnerable when simultaneous breakdowns occur on both cooling units.
3. This system should not be confused with a stand-by or redundant cooling unit system. Both cooling units are worker units and both are required in order to maintain the room at its nominal 24°C operating temperature. It is only during the failure of one cooling unit that the room is allowed to drift to the upper working temperature of the telecommunications equipment (normally 40°C).
4. An MTBF of 1000 years means that, in a population of 1000 similar systems, one system failure could be expected every year.