HANDBOOK OF ELECTRICAL INSTALLATION PRACTICE

Volume 1
Systems, Standards and Safety

Editor
E. A. Reeves, DFH(Hons), CEng, MIEE

Technical Adviser
A. G. Howell, CEng, FIEE

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Chapter 1

Power Supplies in the UK

D. C. Murch, CEng, FIEE
formerly Chief Technical Officer
London Electricity Board

In Great Britain the electricity supply industry was fully nationalised on the 1 April 1948. Changes were made in 1957 to create the present structure which consists of the Central Electricity Generating Board (CEGB) responsible for major generation and transmission throughout England and Wales; twelve area boards responsible for distribution within their areas in England and Wales; two Scottish boards responsible for both generation and distribution within their areas; and the Electricity Council which has the co-ordinating role and performs special functions in relation to research, industrial relations and finance.

The area boards are autonomous bodies and thus variations of policy and practice are found between them. This can be a source of irritation for those who have to deal with more than one of them. It should, however, be remembered that their prime responsibility is to provide the most economic supply to their consumers. Their autonomy enables different practices to be employed for particular areas and clearly the problems in London are different to those, say, in Devon and Cornwall. It also allows some measure of experiment which, if successful, will be generally accepted by consensus.

The area boards are themselves divided into smaller units for better consumer contact and system operation. Each board has developed its own pattern and nomenclature to suit its own terrain, some are three-tier and others two. London, for example, is two-tier with five divisions whose areas coincide where possible with those of the local boroughs.

The organisation of an area board is usually set out in detail in the local telephone directory. For those who need the full organisation this is set out in the *Electricity Supply Handbook* published annually by the *Electrical Times*.

From an engineering standpoint the supply industry is co-ordinated by the Chief Engineers' Conference which is held quarterly. Under its structure individual chief engineers are allocated responsibility for promoting and co-ordinating the industry in a specific sphere. For this function he is assisted by one or more specialists from other area boards and a technical assistant from the Electricity Council, who is responsible for detail co-ordination and secretarial assistance.

The work of the Conference is mainly reflected in the publication of ACE Reports, Engineering Recommendations and Electricity Supply Industry (ESI) Standards, the latter being produced in conjunction with the electrical manufacturing industry. The majority of these documents are not confidential and may be purchased from the Electricity Council. A catalogue is also available.

VOLTAGE AND FREQUENCY

The supply system in Great Britain is standardised at 240 V single-phase and 415 V three-phase with a frequency of 50 Hz. Major generation is connected to the supergrid system which operates at 400 kV although some sections are at 275 kV. In England and Wales this network is owned and operated by the CEGB. The original 132 kV grid system which was started in 1926 has now been transferred from the CEGB to the area boards and, as the older power stations disappear from the system, it is being re-developed to be the higher strata of their distribution systems.

The major primary distribution voltage is 11 kV although a small proportion still operates at 6.6 kV. For most of the system there is an intermediate stage of 33 kV, but direct transformation between 132 kV and 11 kV is becoming common policy in city areas, where over 100 MW can be economically distributed at 11 kV from one site. The frequency is maintained by the CEGB which regulates the input power to the generators to match the instantaneous load on the system and thus maintain their speed and thereby the frequency. This is manually controlled to very close limits, thus enabling synchronous clocks, time-switches and other motors to be used.

The voltage supplied to the consumers is mainly regulated by on-load tap-change gear on the transformers which supply the 11 kV system. Fixed tappings are used on the 11 kV to the 415/240 V transformers as it would not be economic to put on-load tap-changing on these. The statutory limit of voltage variations is ± 6% and for economic reasons the distribution system is normally designed to make use of this allowance. The greater part of the energy is sold at 240 V and thus is of direct use to most apparatus. For large machines or equipment supply is at a higher voltage, usually 11 kV or transformed to 3.3 kV.

Apart from the size of the largest item, the need to bring an h.v. supply on to a consumer's premises is determined by the relative strength of the local network in relation to the total load. In order to determine what supply can be made available at any particular location, the local office of the appropriate area board should be consulted at an early stage. While generators produce a near perfect waveform and the on-load tap-change gear maintains the voltage at the 11 kV source within fine limits, all load on the system creates some distortion. The extent to which the various types of load can be connected to the system depends upon the distortion they are likely to create and the nuisance this disturbance causes to other consumers. This subject is dealt with more fully in a later section.

SYSTEM IMPEDANCE AND SHORT-CIRCUIT LEVELS

From the consumer's point of view another important parameter of the supply system is its impedance as viewed from his terminals. On the one hand, the lower the impedance the greater will be the stress on his switchgear and protective devices, but on the other hand, the higher the impedance the greater will be the risk of annoyance due to distortion caused by either the consumer's own load or by that of a nearby consumer.

The 15th edition of the IEE Regulations requires installation designers to have a knowledge of the limits of system impedance to which the supply will be kept in order that he may install the necessary protective devices to an appropriate rating and to operate within the required time. All supply systems are dynamic and many area boards' staff are continually employed laying cables and moving and installing plant in order to ensure that the system configuration meets the demands of the consumers. For this reason it is not possible to give an exact impedance figure for any one location, but the appropriate local area office should be able to give installation designers the maximum and minimum likely to be encountered for a particular location.

For many years it has been common practice to express the energy available on short-circuit in terms of 'Short-circuit MVA'. This is simply $\sqrt{3}$ VA $\times 10^{-6}$ where V was the normal system voltage between phases and A the symmetrical component of the short-circuit current.

In 1971 the International Electrical Commission (IEC) introduced a standard for switchgear ratings (IEC 56) which specified that the working voltage rating should be expressed in terms of the system maximum, for example 12 kV for an 11 kV system, and that short-circuit ratings should be expressed in terms of the maximum symmetrical fault current. A range of ratings was specified, for example 12.5; 16; 25 kA for 12 kV gear.

For any three-phase system voltage the short-circuit level and the system impedance are inverse functions of each other, kA = kV/$\sqrt{3}$ Z.

On l.v. systems the cables will generally be the major contributors to the system impedance since the h.v./l.v. transformers are of low impedance. The governing factor is thus the distance of the consumer from the nearest substation.

On area board h.v. systems the short-circuit ratings of the switchgear have a considerable economic significance and, therefore, system designers aim at keeping these to as low a figure as practicable. A common method of achieving this is to employ high impedance 33/11 kV or 132/11 kV transformers. The high impedance is achieved by judicious spacing of the windings and does not increase the transformer losses or costs to any appreciable extent. The high impedance does not affect the voltage output as the tap-changer regulates accordingly. At 11 kV the impedance of the cables is generally much less significant.

Until the publication of IEC 56 many 11 kV systems were designed for a maximum level of 250 MVA which is equal to 13.1 kA. The new rating method therefore poses a problem where new or additional switchgear is required on an existing system, since the 16 kA switchgear is more expensive. In general, however, British manufacturers can supply switchgear tested to 13.1 kA at similar to 12.5 kA prices. With the low growth of demand, these 250 MVA systems will remain for many years.

LOADING EFFECTS ON THE SYSTEM

Any normal load causes a voltage drop throughout the system. This is allowed for in the design and the costs associated with the losses incurred are recovered in the related unit sales.

Unbalanced loads

Unequal loading between the phases of the network causes an unequal displacement of the voltages. Extreme inequality causes motors and other polyphase equipment to take unequal current and perhaps become overloaded on one phase. For this reason area boards impose limits on the extent to which they accept unbalanced loads at any particular location in order to ensure that other consumers are not adversely affected. Installation designers need to ensure that the same problem does not arise due to an unbalanced voltage drop within the consumer's installation itself.

While most voltage unbalance is caused by single-phase loading, the effect on a three-phase motor can best be assessed in terms of the negative phase sequence component of the voltage thereby created. Providing this is less than 2% the inequality of current between phases should not be more than the motor has been designed to withstand.

Power factor

Many types of apparatus like motors and fluorescent lighting also require reactive power and thereby take a higher current than is necessary to supply the true power alone. This extra current is not recorded by the kWh meter but nevertheless has to be carried by the distribution system and uses up its capacity thereby. It also increases the losses on the system. A power factor of 0.7 means that the current is 1/0.7 = 1.43 times as great as absolutely necessary and thus doubles the losses (I^2R). If all the loads in the United Kingdom were permitted to have as low a power factor as this the additional cost of the losses (if the system could stand the burden) would be in the order of £200 million per annum.

It will readily be seen, therefore, why area boards are keen to ensure their consumers' power factors are near to unity. Where practical, some penalty for poor power factor is built into the tariff or supply agreement.

Power factor correction is therefore an important aspect in the design of installations, although too often forgotten at the outset, see chapter 20. The most simple and satisfactory method is to have each equipment individually corrected as this saves special switching and reduces the loading on such circuits. Bulk correction of an installation is, however, quite commonly used, particularly where it is installed as an afterthought. There are then problems of switching appropriate blocks of capacitance to match the load, since overcorrection again increases losses and, in addition, creates voltage control problems at light load.

Switching transients

One of the primary uses of electricity is for general lighting and the area board must ensure that its supply is suitable for this purpose. Repeated sudden changes in voltage of a few per cent are noticeable and are liable to cause annoyance. The authority must ensure that these sudden variations are kept within acceptable levels and this means placing limits on consumers' apparatus which demand surges of current large enough to cause lighting to flicker.

In order to evaluate flicker in measurable terms, two levels have been selected, firstly, the threshold of visibility and secondly, the threshold of annoyance. Both are functions of frequency of occurrence as well as voltage change. Since both these thresholds are subjective it has been necessary to carry out experiments with various forms of lighting and panels of observers to ascertain consensus relationships between frequency of occurrence and percentage voltage change for the two thresholds. The authorities use this information to determine their regulations governing motor starting currents, etc.

The network impedance from the source to the point of common coupling between the lighting and the offending load is of paramount importance and thus the local office of the supply authority should be consulted in cases where the possibility of creating an annoyance arises.

Intermittently loaded or frequently started motors, such as those on lifts, car crushers, etc., together with instantaneous waterheaters, arc welders and furnaces, are all potential sources of trouble. Large electric furnaces present a particular problem and it is frequently necessary to connect them to a higher voltage system than is necessary to meet their load in order to achieve a lower source impedance.

Fluctuations occurring about ten times a second exhibit the maximum annoyance to most people, but even those as intermittent as one or two an hour will annoy if the step change is of sufficient magnitude.

Harmonics

Harmonics on the supply system are becoming a greater problem due to the increasing use of fluorescent lighting and semiconductor equipment. Cases have been known where large balanced loads of fluorescent lighting have resulted in almost as much current in the neutral as in the phases. This current is almost entirely third harmonic. The use of controlled rectifiers and inverters for variable speed drives, as used on many continuous process lines, can also be a problem and supply authorities have frequently to insist that 6- or 12-phase rectification be used. It is another case for local consultation to determine what the system will stand. Even a multiplicity of small equipment can summate to create a big problem, for example television set rectification, and for this reason international standards have been agreed.

SUPERIMPOSED SIGNALS

For many years load control systems have been in use which superimposed signals on the normal supply system. The earlier ones were usually at a higher frequency and were referred to as ripple control, though one system used a d.c. bias. Tuned relays respond to the appropriate signal and switch public lighting; change various tariffs according to time of day or system load; switch water or space heating according to tariff availability or weather conditions, and perform various other functions, even to calling emergency staff.

Although these did and still do perform satisfactorily, they did not come into universal use, probably because the full expenditure on signal generators was necessary to cover the system even though initially there were only a few receivers and this caused cash flow problems.

A decade or so ago equipment came on the market which could communicate from one premises to another over the supply system. The supply authorites were not very happy about this as any widespread use could cause problems, but fortunately this has not happened.

With the advent of the thyristor and the transistor, supply authorities started experimenting with them on their network as a communication media, using pulse techniques both for one-way and two-way communication. Practical installations have been developed and a number of one-way systems installed to perform similar functions to those carried out by the earlier ripple control method.

One such system developed by the London Electricity Board was a range of codes transmitted by short pulses injected at the zero point of the 50 Hz wave, fig. 1.1. Injection at this point requires less power and thus enables smaller transmitters to be used. This method has been taken up by a major UK manufacturer and several installations have been commissioned. The two-way communication objective is to read meters remotely and a workable system has been in use for several years, but only as a pilot scheme since it was not economically viable using discrete components.

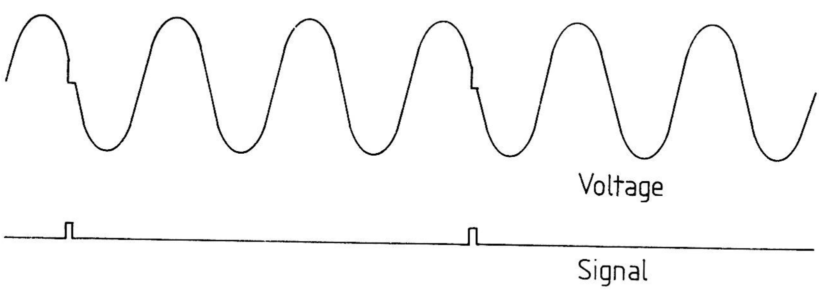

Figure 1.1 Cyclocontrol signals

The advent of the microprocessor and its relatively low cost in quantity production has widened the development field and made many schemes attractive. Solid state metering with sophisticated control and tariff regulating functions will definitely be in use in the near future. Deciding what these 'black boxes' should be made to do is the big problem facing the area boards, remembering that there are some 20 million energy meters in the UK alone and the task of changing these is a mammoth one. If the change were carried out as part of the normal re-certification programme it would take 15-20 years to complete. Consumers who had to wait this long for an attractive tariff or control function to be available to them would be far from happy!

There is another side to the picture. Sophisticated control systems which are already available for use within a consumer's premises enable a master programme controller to send signals over the main conductors to slave controllers on appropriate apparatus. The master controller being flexibly programmed via a keyboard and display is even capable of responding to signals sent via the telephone.

Interference, both accidental and wilful is a problem which needs careful consideration and rejection circuits may be needed where such systems are in use on both sides of the supply terminals.

While the use of the network itself, as a control medium, is attractive to an area board it has its drawbacks and other methods using superimposed signals over the radio or telephone are being studied. The radio is attractive for one-way communication as the transmitter cost is minimal and full coverage is available. The telephone is attractive for two-way communication since the addressability exists within the telephone system.

From the electrical contractor's point of view this expanding field of superimposed control is likely to extend the range of his work and so add to the complexity of some installations.

SYSTEM AND INSTALLATION EARTHING

In the UK the Electricity Supply Regulations govern the way systems are connected to earth.

Low voltage systems

For many years the Regulations required that each l.v. system should be solidly connected to earth at only one point, that being the neutral of the source transformer. Special permission was necessary to earth at more than one point. The Regulations also required that cables buried in the highway must have a metallic sheath. Systems earthed at only one point require the neutral conductor to be electrically separate and are now known as SNE (separate neutral and earth).

It was and still is the responsibility of each consumer to provide the earth connection for his own installation. This was commonly achieved by connection to a metallic pipe water main. The growing use of PVC water mains makes this impossible for new installations and causes problems with existing ones when water mains are replaced. Gradually, supply authorities developed a practice of providing consumers with an earth terminal connected to the sheath of their service cable. This is, of course, a very satisfactory arrangement but it is not universally practical as many cables laid in the 1920s or earlier are still in use and many of these are not bonded across at joints. The arrangement is not practical on most overhead systems.

In Germany and elsewhere in Europe an earthing system known as 'nulling' grew up. This employed the principle of earthing the neutral at as many points as possible. It simplified the problem of earthing in high resistance areas and by combining the sheath with the neutral conductor permitted a cheaper cable construction. These benefits were attractive and during the 1960s the official attitude in the UK gradually changed to permit and then encourage a similar system known as PME (protective multiple earthing). Blanket approvals for the use of this system and setting out the required conditions to be met were finally given to all area boards in 1974. In the 15th edition of the IEE Regulations this system is classified as TN-C-S.

Providing the consumer with an earth terminal which is connected to the neutral conductor ensures that there is a low impedance path for the return of fault currents, but without additional safeguards there are possibilities of dangerous situations arising under certain circumstances.

If the neutral conductor becomes disconnected from the source of supply then the earthed metalwork in the consumer's premises would be connected via any load to the live conductor and thus present a shock hazard from any metalwork not bonded to it, but which has some connection with earth. In order to eliminate this rare potential hazard the Secretary of State, in his official approval order, requires that all accessible metalwork should be bonded together as specified in the IEE Regulations and so render the consumer's premises a 'Faraday cage'. This is the reason for the more stringent bonding regulations associated with PME, fig. 1.2.

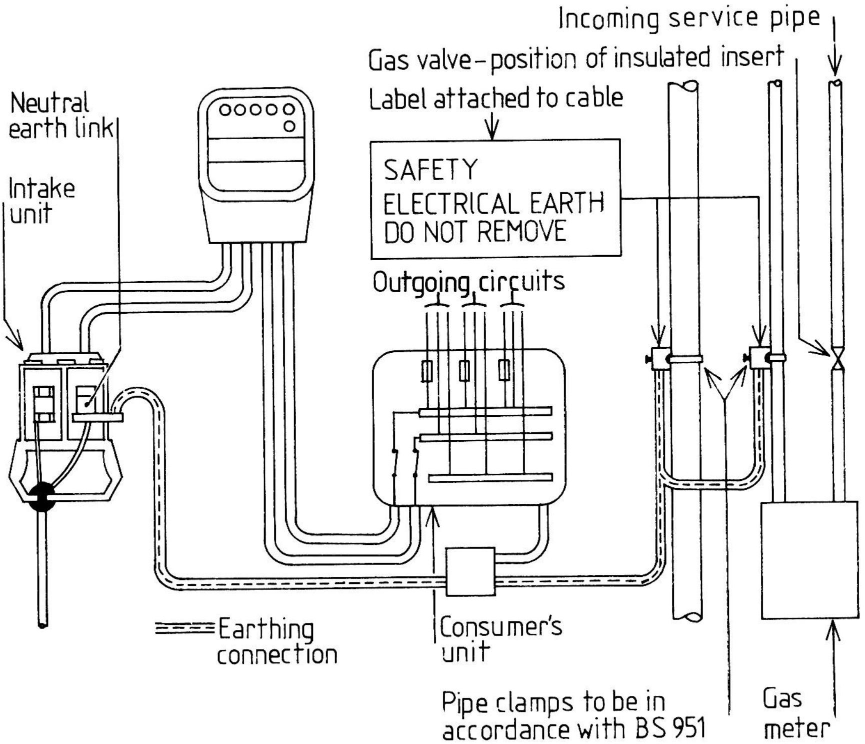

Figure 1.2 PME bonding arrangements

Under the circumstances of a completely broken neutral there is still a danger of shock on the perimeter of the 'cage', for example, someone using an earthed metal appliance in a garden, which of course would not accord with the IEE Regulations. For the same reason, area boards do not like metal external meter cabinets.

In order to eliminate as far as possible the chance of a completely separated neutral, a number of precautions are taken. Firstly, all cables must be of an approved type with a concentric neutral, either solid or stranded, of sufficient current carrying capacity. Secondly, all spur ends on the system must be connected to an earth electrode to provide an alternative path and, where possible, cable neutrals are joined together. A faulty or broken neutral will give an indication of its presence by causing a low and flickering supply which, of course, should be reported to the supply authority as soon as possible. All these measures contribute to a system which is as safe as practicable.

It is the declared intention of the UK supply industry to provide earth terminals wherever required and practicable within the foreseeable future. The local area board should be contacted regarding their requirements for the use of PME earth terminals for TN-C-S systems.

High voltage system earthing

The Electricity Supply Regulations specify that every h.v. system shall be connected with earth and that on every circuit the potential earth fault current must be at least twice that required to operate the protection.

There are various methods used to earth an h.v. system and practices between the area boards in the UK vary considerably. Most of the 11 kV systems are derived from 33/11 kV delta star transformers and thus there is a neutral point available. In quite a number of cases these are solidly earthed and the resultant potential earth fault current can be slightly higher than on a phase-to-phase fault. It is also quite common to restrict the current by the insertion of a resistance in the neutral to earth connection to limit the fault current to about the full load of the supply transformer.

Where the h.v. supply is designed directly for 132 or 66 kV, it is usual to have a star wound primary to minimise the transformer cost. In order to get the correct phase relationship, it is necessary to use a delta secondary winding in some cases and a star winding in others. When delta secondaries are used it is then necessary to employ a separate earthing transformer to create a star point and this transformer limits the earth fault current, though frequently a resistor is also used. Where the secondary winding is star connected, this is either directly connected to earth or through a resistor. Usually the resistors for this purpose are water-filled but in some cases a reactor is employed.

Where an h.v. supply is afforded the installation designer needs to know the range of the protective earth fault current in order to provide the correct protection.