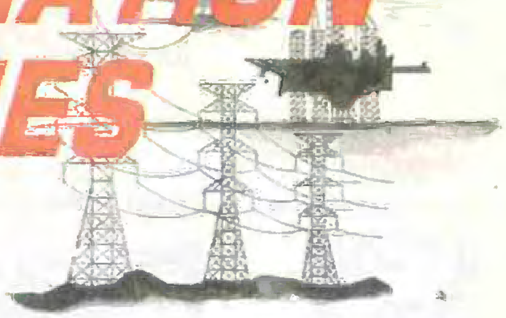
Special Feature

POWER GENERATION FROM PIPELINES TO PYLONS



ALAN WINSTANLEY

Part Two

Supported by the expertise of the international power generation company National Power plc, Alan describes some of the high technology involved in generating power – from a gas pipeline to the turbines and generators and then to the electricity pylon and beyond!

WE CONCLUDE our in-depth look at power generation by examining some of the techniques related to the provision of a 230V a.c. supply to our housing and industry.

Power to the People

Let us return to the process of electrical power generation and examine it in greater detail. Previously it was mentioned that each of the three gas turbines in our adopted power station drives an a.c. generator; a steam turbine drives a fourth.

A power generator consists of an electromagnet (*rotor*) which is rotated directly by the turbine shaft. Each revolution of the turbine turns over the generator once. The rotor is surrounded by stator coils in which the moving rotor induces a voltage that will ultimately be delivered to the consumer.

Power Spin

If a simple two-pole rotor is used, this could be likened to a simple electromagnet having a North and a South Pole. The spinning electromagnet induces a voltage in the stator coils each time it passes by, and the stator voltage will therefore reverse polarity with every half-revolution of the rotor. The voltage level generated in the stator coil depends on how far the rotor has travelled during one revolution (its rotational angle).

How a sinewave is generated with this setup is depicted in Fig.9. Because it delivers alternating voltage, this generator is more correctly called an ***alternator***. (A *dynamo* produces a d.c. voltage instead.)

To get the most out of each revolution of the rotor, several stator coils are deployed so that multiple sine wave voltages are generated per revolution. In fact, three coils are spaced at 120 degrees apart (see Fig. 10) and the coils are designated by a colour code which will be familiar to every electrician: they are Red, Yellow and Blue. The generator windings produce 15·75kV between the phases.[1]

The overall result can be plotted as a three-phase voltage, see Fig. 11. It can be seen that the voltage in the red phase is 120 degrees behind the yellow phase, which lags 120 degrees behind the blue phase.

By increasing the rotor's speed, the frequency can be increased, although the three phases will always be 120 degrees apart. This simplified approach assumes that there is only one pair of magnetic poles on the spinning rotor as shown, and this is normally the case in practice.

If the rotor spins once per second, then the a.c. voltage generated in each phase will have a frequency of one Hertz (Hz).

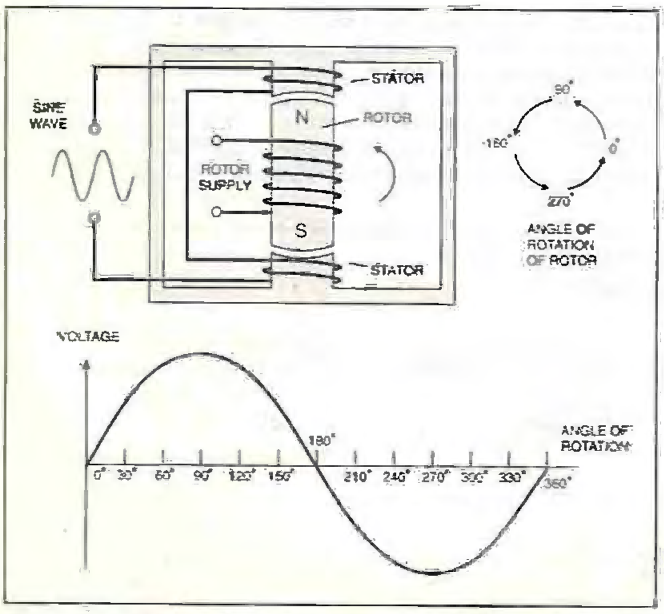
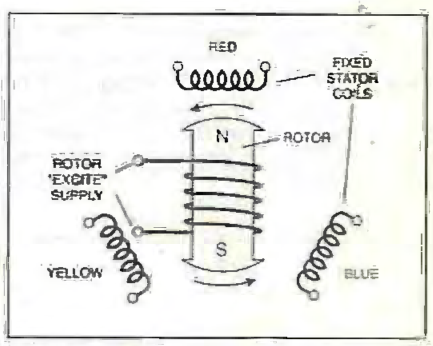


Fig.9. A sinewave is produced in the stator coil by the spinning rotor. The voltage level depends on the rotor's angle of rotation, and it reverses polarity every 180 degrees.

Fig.10 (right). A three-phase generator has three fixed stator windings, placed 120 degrees apart around a spinning rotor, which itself is an electromagnet, having a North and South pole.



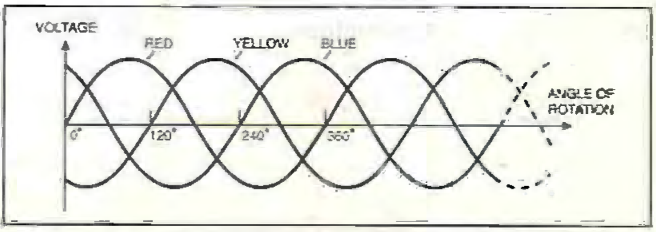


Fig.11. Three-phase electricity generated by the alternator of Fig.10. The three phases are 120 degrees apart.

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[1] For reasons which will be clarified later, it is usual in the power industry to talk of "line voltages" as phase-to-phase voltages, rather than the voltage which is generated in a single-phase circuit with respect to a "common" or "earth" reference. In a three-phase generator, the voltage which is generated in an individual phase is 9·1kV, which is $15{\cdot}75\text{kV}/\sqrt{3}$. This produces 15·75kV between phases. *ARW.*

changing polarity every half second. The frequency of the generated voltage is calculated by:

$$\text{frequency} = \frac{\text{no. of pairs of poles} \times \text{revs. per minute}}{60}$$

From the above formula, a generator with one pair of poles as illustrated must rotate at 3,000r.p.m. to produce electricity at 50 Hertz, which is the *declared system frequency*. The statutory limits defined in the Electricity Supply Regulations of 1937 are 50Hz. ± 1% (i.e. 49·5 – 50·5Hz) although the National Grid (NGC) strives for a variation of no more than 0·1% as best practice. The turbines operate at this speed, 24 hours a day for months on end.

In the mid 1920's before electrical power generation was standardised, several frequencies could be used – anything from what was probably a migraine-inducing 25Hz and must have been murder to read by, all the way up to 80Hz. The Electricity Supply Act of 1926 resulted in a standardisation of supply frequency across Great Britain, at 50Hz, although in the USA and some other countries the supply has been set at 60Hz.

In fact most generators tend to have two poles although certain types e.g. hydro-electric generators may have four or more poles. This allows for a slower rotor speed of 1,500 r.p.m for a four-pole machine which is more appropriate for the medium involved, whilst still generating a 50Hz sinewave.

Frequency Control

The actual method of controlling the supply frequency ultimately boils down to speeding up or slowing down all the generators on the system, by increasing or decreasing their load.

Great effort is made to maintain this value and to eliminate cumulative errors in the consumer's supply, which might otherwise affect electric clocks, time switches, audio equipment etc. Any minor change in frequency is compensated for later on, in order to enable frequency-sensitive equipment to catch up (or slow down).

All power plants interconnected by the National Grid can be considered as part of an enormous "pool" of electricity hooked together on an "infinite busbar", which runs at a set frequency.

A circuit breaker unit connected to the gas turbine. Notice the colour coding "spots".

Every power station thus connected operates at this frequency. If at this time a small isolated power station was *not* connected to the busbar, but was then hooked in later, the frequency of the existing "pool" would easily dominate the generator of the newly-connected power plant. The net result is that *all parts of an interconnected system operate at the same frequency.*

The operating frequency of the rest of the grid is thus physically applied to an individual generator, in what is effectively a contest of wills. Since a generator's stator is synchronised to its rotor (and turbine shaft), it is necessary to ensure that a gas turbine runs at a speed which enables the generator's frequency to be matched to the rest of the grid. Hence, the challenge is to supply just enough fuel to the turbines so that the generator runs at the prevailing system frequency adopted by the rest of the grid.

Any increase in the fuel supply will *not* necessarily cause the turbine to run any faster, because the generator is already synchronised or locked to the frequency of the grid: instead the turbine will simply be "loaded", which is undesirable. The system frequency can be best controlled by ensuring that the generator's MW output constantly matches the consumer MW (megawatts) demand.

Test Run

The best analogy of this is to consider a car which is being driven at a fixed speed. If the car encounters a hill it will slow down, making it necessary to open the throttle to maintain engine speed. If the hill levels out, the throttle can be closed again. If it goes downhill, the engine can be used as a brake to slow the car.

The other key parameter is, of course, *voltage*. For consumers, the statutory limits on their 230V supply is ± 6%. Unlike the system frequency, the voltage levels can vary in different parts of the transmission system. The voltage output of a generator is directly related to the rotor voltage – the excitation voltage, which is controlled by a complex automatic voltage regulation (AVR) system. Every aspect of the generator and the turbine's performance is constantly monitored by the power plant's fully computerised control room.

Down-the-Line

The next part of the electricity generation process relates to the way in which the power generated in the stator coils is transmitted to the user. Typically, the generator outputs 15-75kV and is rated for more than two hundred megawatts (MW).

The three phases – red, yellow and blue – are carried outdoors from the generator by cables using large ducts which resemble pipelines. These pipes are pressurised in order to prevent corrosion or water ingress. The ducts are also colour coded to identify the phases, and this same theme is used all the way through to the end-user's premises.

One major problem is, how to actually switch such high magnitudes of voltage?

Leaps and Volts

All of the high voltage areas at National Power's Killingholme "A" station – just like every other high voltage installation – are surrounded by a perimeter fence or wall. Such areas are padlocked and it is ***strictly forbidden*** to enter the area – even to pick a weed – without the relevant safety permit.

Although much of the equipment is safely earthed, many high tension wires and terminals are of necessity uninsulated. *High voltages can flash over and strike a human being with deadly effect if they stray too close to high voltage power lines, transformers or other electrical equipment.*

For high voltage operations, the industry-standard minimum safe working distances are:

400kV	3·1 metres	66kV	1·0 metres
275kV	2·4 metres	33kV	0·8 metres
132kV	1·4 metres		

Remember that the human body is a walking 3 kilohm resistor and is effectively grounded at one end. If a person unwittingly encroaches within the safe working distance then there is a very serious risk of arcing and flashing over. That person may suffer devastating electrical burns as well as risking death. There may also be an explosion and fire.

It would be impossible for anyone to rescue a person from such a dire predicament because of the same risks *they* would face from arcing by the same high voltages, so any attempt to mount a rescue near to high voltages would be **highly dangerous.**

If you should see a person next to high voltage power lines or equipment whom you suspect may have suffered electrocution or burns, there is nothing you can do except stay a safe distance away and call for help. All rescue attempts must be left to the experts who will insist on making the area safe before entering it. (The separate box-out *"Heartfelt Shock"* is a timely reminder of emergency first aid procedure which can be undertaken for persons who may have received a shock from the domestic 230V supply.)

Every year many people lose their lives by electrocution purely through carelessness and ignorance. Children must never be permitted to play anywhere near an electricity substation, and must never attempt to retrieve, say, a lost ball from within a fenced-off substation compound.

Playing near overhead power lines (including electric train overhead wires) should also be strongly discouraged, so the flying of kites and model aircraft in these areas is exceedingly dangerous. ***The dangers of death caused by flashing over are very real and are ignored literally at one's peril.***

Since these extremely high potential voltages can arc across considerable distances (see the box out entitled "*Leaps and Volts*"), one can image the nightmarish problems which exist in the power plant when trying to switch thousands of volts.

The switchgear concerned must be able to withstand not only their full loads but six-fold overloads which occur when motors are starting. They must also be capable of carrying or interrupting fault currents and must also cope with 17,500 volts peak across the contact terminals. Evidently, we are not talking 6mm (¼in.) toggle switches here!

The solution lies in the use of special gas-filled circuit breakers. These are spring-loaded and motor driven and are designed to quench the high tension arc which develops between opening contacts. The compound sulphur hexafluoride (SF_6) is used and this is six times less conductive than air. Earlier types used oil-filled contacts or compressed air to snuff out the arc.

The 15·75kV (phase-to-phase) generator voltages are stepped up to 400kV by an external transformer – one per generator – for onwards transmission to the National Grid.

Stay Cool

Many readers will be aware that large transformers are oil-cooled in order to aid heat dissipation. With the largest types, the oil will be circulated by pumps and heat will be exchanged with a water-filled coolant circuit.

In the event of a transformer internal failure (e.g. winding shorts, or contacts starting to burn out), hydrogen is one of the first gases to be produced, so by testing for this gas any trends can be spotted early. A device known as a Bucholz relay is used as an automatic switch that responds to increasing levels of gas build-up in the oil.

More accurate tests of oil samples are also undertaken by National Power and other gases such as acetylene can be measured over, say, a month and a good estimate made of the nature of an internal fault. Ultimately the oil can be drained and then the fault can be repaired.

Also worthy of mention is a small digital counter near to the transformer's perimeter steel fence. It displayed "20": when this was queried, the author was cheerfully told that this meant the transformer had been hit by lightning twenty times . . . Er, quite.

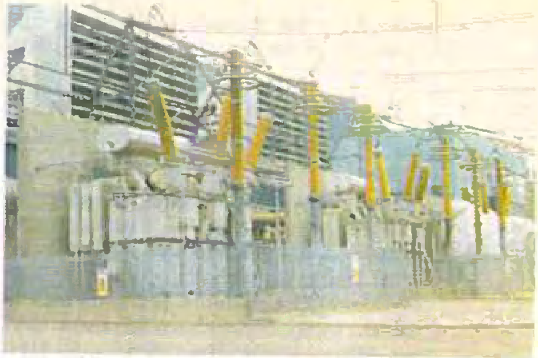
Quite a Buzz

A compound area called the "banking compound" adjacent to the main power transformers contains an array of insulators and busbar isolating switches. Usually, when Killingholme "A" is in full swing, the crackle of high tension voltages fills the air around this bus-bar area. The same compound contains current transformers which monitors the station's output.

From there, the 400kV supply is fed underground to a nearby sub-station, before finding its way on to a transmission tower, the very first in a series of many hundreds which will be used to distribute the power around the countryside.

Super Grid!

The enormous 400kV supply – known as the Super Grid (275kV in certain



Four 400kV transformers connected to the outputs of the four generators.

A gas-filled circuit breaker, rated at 17·5kV 10,000A, connected to the gas turbine generator.

A Bucholz, safety switch, relay is fitted on oil-cooled transformers and detects any build-up of gases in the oil.

Pylon on the Power

The electricity pylon – more correctly called a *suspension* or transmission tower – carries overhead three-phase electricity between substations in all weathers. *Terminal* towers are located at each end of the route, whilst *deviation* towers enable the wire route to be realigned.

These "lattice" towers are significantly more economical to construct and repair than attempting to bury high voltage insulated cables underground, and the ambient air also acts as a natural cooling system to help with heat dissipation on the wires. Larger towers provide a greater span, needing fewer towers to suspend cables over a distance, but variations in design are used depending on local conditions (e.g. aircraft or natural landscape considerations).

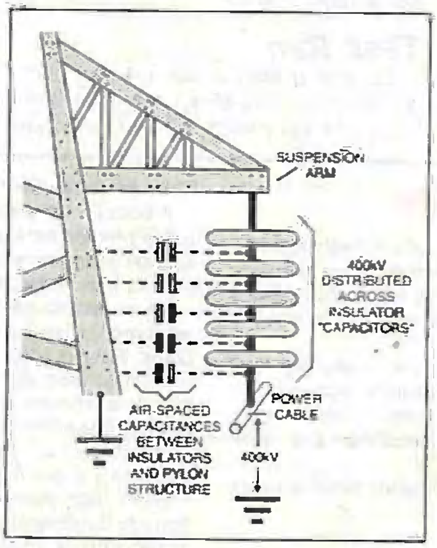
The largest Super Grid towers support wires operating at 400,000V. Fibre optical cables are wrapped around many cables to carry Internet traffic: the light signals are unaffected by the high voltages. The smaller towers seen in the countryside or near towns and villages are usually owned by the Regional Electricity Companies (RECs) rather than the National Grid.

Power cables are uninsulated and usually made of aluminium alloy, which is lighter than comparable conductors so that slimmer, smaller towers can be used. The towers are inherently earthed, and an individual earth conductor wire can often be seen connecting the tops of towers together.

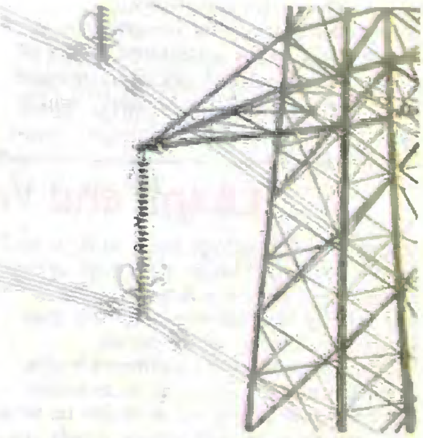
To ensure that the high voltage cable and the earthed tower are separated from each other, chains of porcelain or toughened glass insulators are used. A 132kV wire might use just nine insulators, whilst a 400kV Super Grid power line may demand twin chains of 24 insulators. Atmospheric pollution is another factor which determines how many insulators are needed, because fall-out from industry and salts in the atmosphere can degrade the insulating effect.

Each insulator is actually a *capacitor* having metal end caps separated by the dielectric material of the insulator. This produces a series of air-spaced capacitors between the metal caps and the tower, resulting in an uneven distribution of voltages across the insulators. Hence the power line voltage will be unevenly dropped across the capacitances, but the one nearest the power cable could operate near its maximum voltage breakdown limit.

The addition of a *guard ring* helps relieve the stress on the insulator dielectrics nearest the power cable by shunting their capacitance, and it also ensures that any possible flashover is diverted away from the insulator surfaces to prevent damage, see diagram. Insulators have a undulating cross section to increase their surface area, useful in wet weather.



Porcelain or toughened glass insulators are used in chains to prevent contact with the earthed transmission tower. The voltage on the power line is distributed across all insulators as shown; which have metal caps and therefore form capacitors.



Typical pylon insulator set-up carrying 400kV supplies. Note the guard ring nearest the cable.

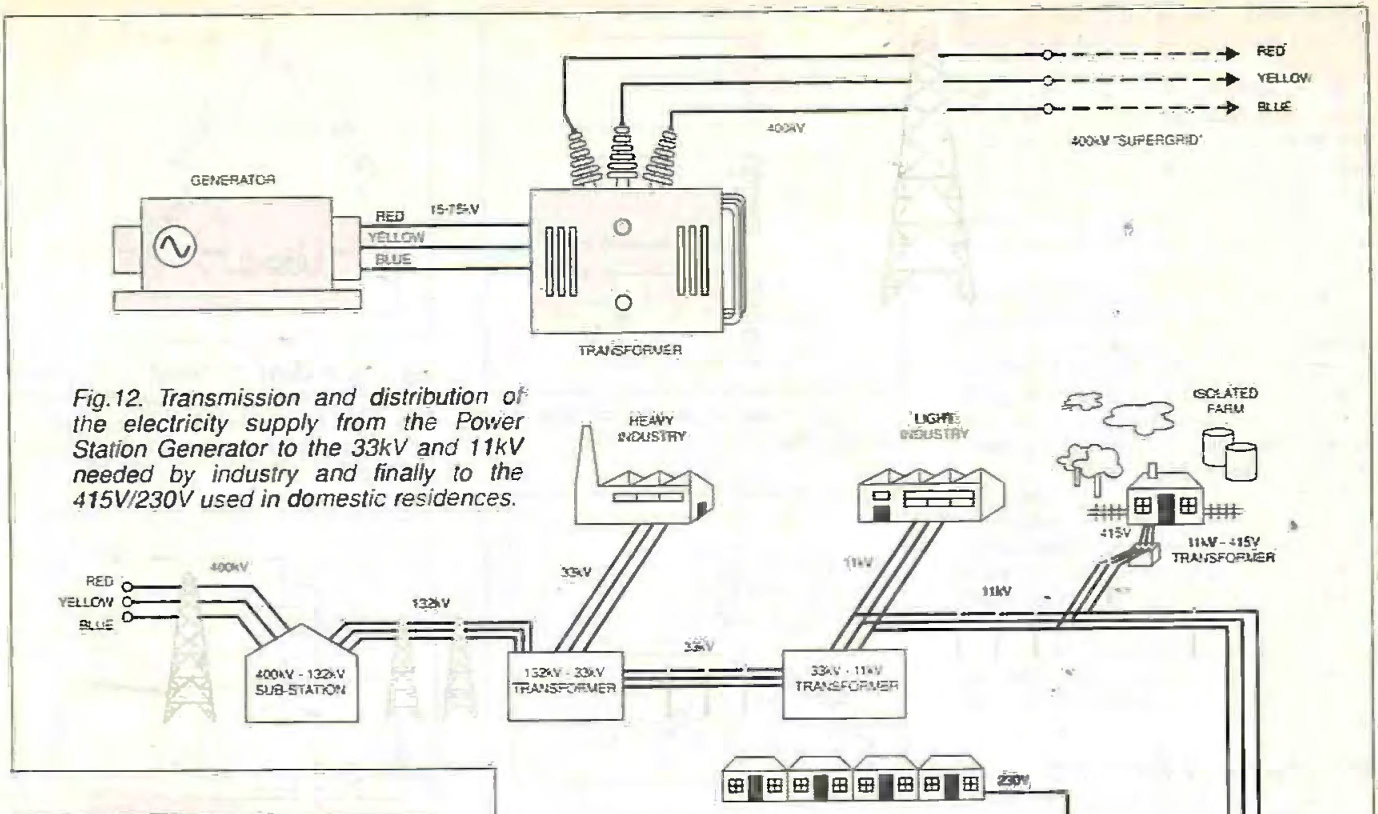
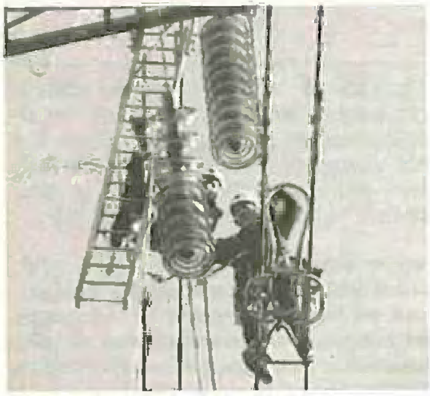


Fig.12. Transmission and distribution of the electricity supply from the Power Station Generator to the 33kV and 11kV needed by industry and finally to the 415V/230V used in domestic residences.



National Grid engineers installing glass insulators on an overhead cable.

regions) will be found hanging off the largest of pylons (as a general rule, the larger the pylon, and the bigger the insulators, then the higher the voltage being carried). The same pylons also carry Super Grid voltages generated by neighbouring power stations.

If ever one wondered why there are three arms to each side of a pylon, the answer is suddenly blindingly obvious: there is one wire per phase, with each tower usually carrying two circuits. Sometimes, wires may be paralleled, which will be witnessed by two wires running next to each other to share the load. (See the separate box out, "*Pylon on the Power*".)

These extremely high voltages are transmitted over considerable distances to regional sub-stations, where they are progressively stepped down by transformers (auto transformers are usually used on the Super Grid). Outline structure of the electricity distribution system is shown in Fig.12.

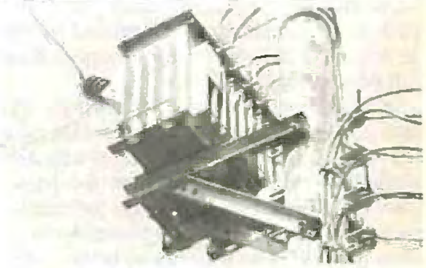
The Super Grid is first reduced to a 132kV grid system and then to 33kV for use by industrial estates and heavy industries. Light industries may require an 11kV supply which is provided by a sub-station. The final reduction occurs in residential areas, where the 11kV is stepped down to three-phase 415V from which single phase 230V a.c. is produced, as we shall see later.

(Officially, UK domestic supplies have been "harmonised" at 230V a.c. for reasons best understood by the European Union. In reality, UK supplies are 240V a.c. just as they always have been, evidenced by taking a quick measurement of 243V!).

In many cases, the customer (say, a farm in a remote locality) will have his own 11kV-to-415V step-down transformer and these are a common site in the English countryside, perched on top of a wooden pole. It is the job of the Regional Electricity Boards to distribute power to commercial and residential properties, and sub-stations with suitable step-down transformers will be used as appropriate. From Fig.12 it can be seen how the Super Grid voltage is systematically stepped-down as the end users' locality is approached.

More on Three-Phase

The red, yellow and blue colour code of the 3-phase system applies from the generator outputs of Killingholme "A" all the way through to the 415V transformer found by residential properties. One could be forgiven for thinking that the use of three very large stator coils to generate three-phase power would demand *six* wires to conduct the current, as shown in Fig. 13a, noting the direction of each winding (or the start/end of the coil) is denoted with a spot symbol.



A typical 3-phase transformer, mounted on a wooden pole. It has an 11kV primary and a 415V secondary, from which 230V a.c. is produced.

After all, a single-phase load requires two supply wires to power it: normally known as Live (or "hot) and Neutral, though the live is more correctly called the *Line* voltage.

However, a three-phase system is able to transmit three times the power of a single phase design without the need for six wires, simply by arranging the windings as shown in Fig. 13b. The start of one winding is connected to the end of another, and the three connections are brought out as shown. Because of its shape, this "triangular" configuration is known as a delta (or mesh) connection. Three wires can be used to transmit a three-phase supply in this way.

The alternative arrangement of windings shown in Fig. 14a is called a **star connection** (or Y connection), and the central connection is called the *"star point"* (or the *neutral* point). This is used universally by National Power on the output of all of its generators.

By commoning the "starts" of each phase together as shown, a four wire-system (three "line" voltages or phases, and a neutral conductor) can be created. The net current flowing into or out of the star point is *zero* because each phase uses the other two for its return path. The net voltage is also zero at the star point.

The principles of delta and star circuits are relevant throughout the power transmission network, all the way down to the 230V a.c. supply delivered to a home. In the case of a three-phase 415V supply, see Fig.14b, a step-down transformer is used (not shown) which has a 11kV delta primary and a star-wired 415V secondary.

Therefore, 415V is supplied between any two lines as shown. A voltage of 415V/√3 = 240V will be developed across a "load" placed between the star point and a single phase. This is precisely how a domestic 230V is derived – connected to the star/neutral point and any of the (nominally) 415V phases. (Note that our "230V" supply is in reality 240V – see previous page.)

On Neutral Ground

Having outlined the overall process of power generation, let's explore in more depth further aspects of power distribution which will be familiar to us all: the need for a neutral wire, and also the requirement for *earthing*.

In order to provide a 230V domestic supply from a 415V three-phase supply, the "live" 230V wire is taken from one of the transformer's 415V phases and the neutral is taken from the star point. The star or neutral point is also *physically* connected to the earth at the transformer, as depicted by the earth symbol in Fig. 14b, for reasons which will become apparent later.

In a typical residential installation, the three 230V supplies which are provided by a 415V three-phase transformer are evenly distributed to balance the load on the transformer. This is achieved by, say, connecting every third house to the same phase. A whole street of small 2 to 3 bedroom houses may have one phase whilst a small development of much larger houses – which will demand more power – might use a different phase to try to balance the loading, and so on.

A significant side effect of this arrangement is that neighbouring premises, whilst each enjoying a 230V supply, may endure a potential of 415V between their respective live supplies: it can be seen in Fig. 14b how 415V exists between any two phases or lines. For this reason, the 230V "live" of one residence should never be used in neighbouring installations because they might not share the same phase.

Each house drawn in Fig. 15 is connected to one of the 3-phase "lines", and the diagram shows how all three houses have their neutral wires commoned together to the star/neutral point of the 415V supply transformer. That same star point is also connected to the earth.

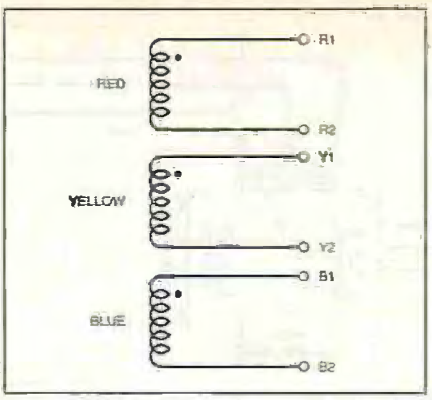


Fig.13a. Three separate phases require a total of six connections.

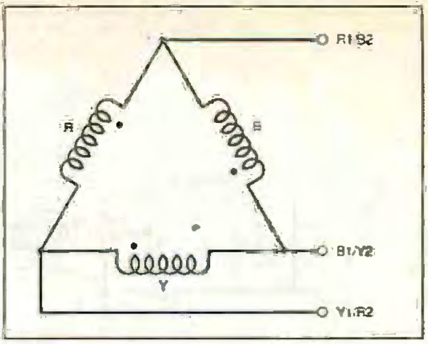


Fig.13b. A delta or "mesh" connection for a 3-phase supply dispenses with the need for six wires. The net sum of voltages around the delta configuration is zero.

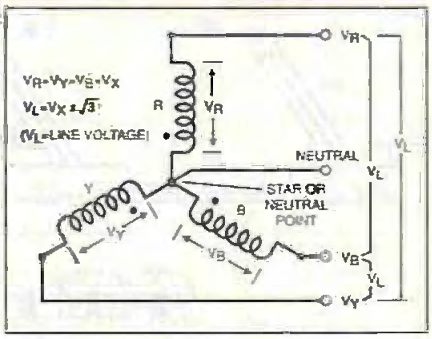


Fig.14a. A star (or "Y") connection with the star being the neutral point.

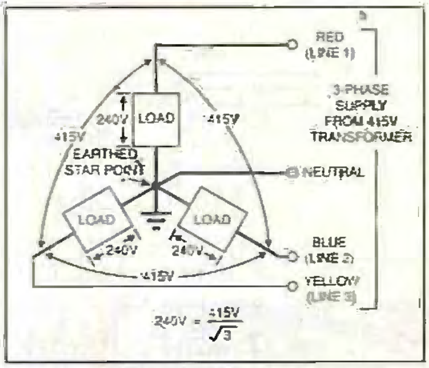
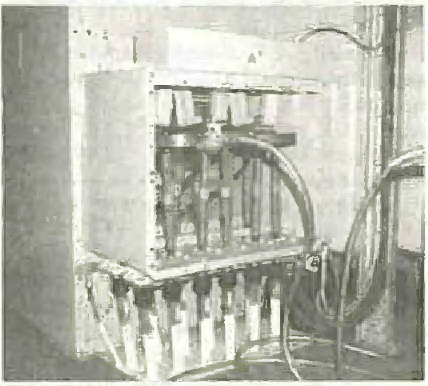


Fig.14b. A 415V 3-phase voltage produces 240V across each "load" connected to the star point. Since the net voltage is zero in the 3-phase system, the star point is neutral, or zero volts. It is connected to the ground.

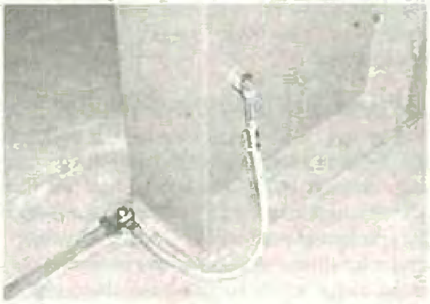
Quite how an individual house will be connected in practice depends on several factors, but assuming that an underground supply is taken to the property, then usually a 230V supply will be routed there using an armoured cable, see Fig. 16. The steel armour is wired as a "protective earth" and connects the house earth system to the earthed star/neutral point of the local 415V transformer.

This completes a good quality metal earthing connection between the domestic earth system and the star/neutral point of the 415V transformer. All exposed domestic copper water pipes and other metal work which could possibly become live through a fault, are hardwired together by "equipotential bonding", which ensures that no individual route to earth will be more resistant to a fault current than any other.

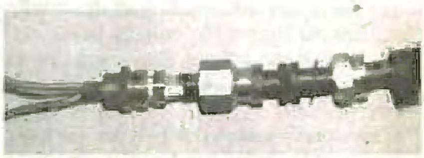
Incidentally, the consumer's neutral may also be directly connected to an earth stake at their incoming supply, but usually this only occurs if the existing earth connection path is found to be inadequate, or if no



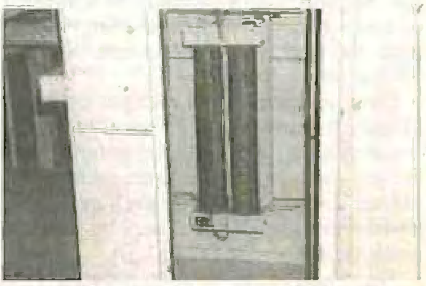
Exposed equipment with safety earth wires fitted during maintenance.



How all exposed steel framework is soundly interconnected with copper bars and also earthed.



A typical armoured-cable terminator, note the steel armour which is the "protective earth".



The "neutral resistor" is designed to limit fault currents in the generator. It connects between the star point and earth.

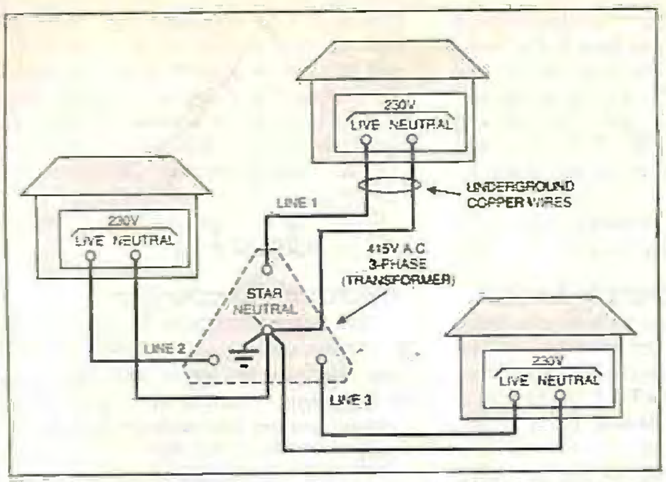


Fig.15. How a 415V 3-phase system is utilised to distribute 230V to the end user. Each "house" uses one phase in order to balance the loading on the substation (ref. Fig.14b).

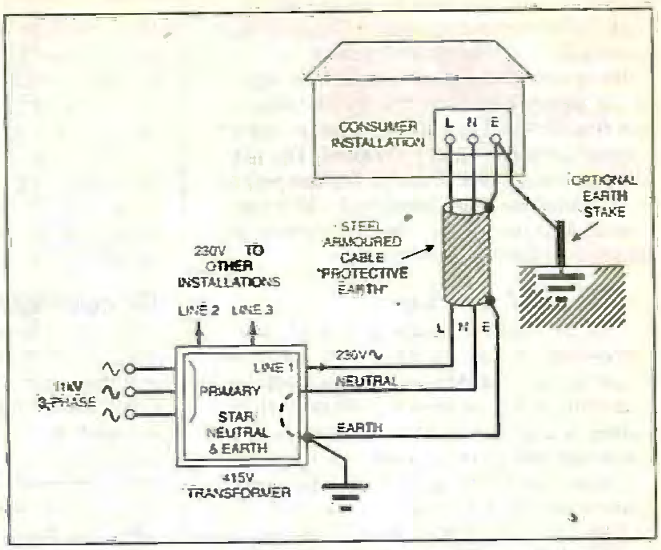


Fig.16. How an earth connection is routed through to a consumer installation. The steel armoured cable ensures a good earth continuity between the installation and the transformer star/neutral earth. It is connected via a brass cable gland which terminates the cable.

earth has been provided at all by the electricity supply authority. There are other variations on house wiring as defined in the *IEE Regulations* with which a competent electrician will be familiar, and who should be consulted if individual doubts exist. In the case of overhead domestic supplies, the earth terminal of the property might only be connected to earth but not to neutral.

Getting Down to Earth

We have now shown how a 230V a.c. supply is derived from a 3-phase 415V transformer, noting also that a consumer's neutral wire connects to the transformer's star/neutral point. A separate "protective" earth (the steel armour of the underground cable) runs between the consumer's earth terminal and the (earthed) star point of the transformer as well. What is the point of all this "earthing"?

It is widely understood that the need for "earthing" (or "grounding" in the USA/Canada) is a safety measure designed to prevent electric shock due to wiring faults or insulation breakdowns. More accurately, earthing is used as a method of ensuring that no open or exposed metalwork can accidentally become "live" should an internal insulation fault arise. This aspect is now examined in greater detail, and it's useful to start (courtesy of National Power) by seeing what happens in our adopted power station, Killingholme "A", before we look at the situation in a domestic residence.

In the field of electricity generation any voltages expressed are always understood to be *between phases* rather than with respect to earth or "ground". A 415V three-phase supply has 415V *between phases*, not between a phase and ground (between which, 230V a.c. exists). Recall how a 9·1kV generator coil produces 15·75kV between phases, and it is this latter voltage which everyone talks about.

However, the ground or earth plays a fundamental safety-related role. Remembering that the power generator's output takes the form of a star connection, the star point has a net voltage and current of zero. In practice, the generator's star point is connected to earth via a *"neutral"* resistor.

In the case of the generators used at Killingholme "A", this resistor fills a metal cabinet (see photo), but in older plants the resistor can actually be in liquid form, made from a tankful of potash and capable of handling kilo-amps of current. *However, it should be realised that the only currents which ever flow to earth are* **fault** *currents.*

All exposed metal work, instrument racking, chassis, cabinets and even the metal girders of the power station's buildings are heavily interconnected with straps and bonding wires and also physically connected to the earth. This "ring of steel" ties all of the open metalwork together to form the escape route down which fault currents can flow. It means also that all earthed parts are at the same potential – zero or very nearly so.

If any fault develops in the generator – such as a failure in insulation – then if any part of the exposed metal work becomes "live" there will be an immediate short to

Heartfelt Shock and First Aid

THE HUMAN BODY is a water-filled resistor of approximately 3 kilohms value, and is a good conductor of electricity. Since one side of the mains power supply is grounded, then it is possible to receive fatal electric shocks if your body comes into contact with high voltages – the body will complete a circuit and current will flow through the body back to earth.

The human heart is a muscle which happens to be most susceptible to stimulation at a frequency of 50Hz. Perversely, this is also the frequency of the UK mains supply.

The effects of shock depend on the level of current which flows from a device (and where it flows through the body). Once a certain threshold is reached, you will have no control over the actions of muscles, which means that you may be unable to release your grip on a device and may suffer electrocution.

A list of effects which would arise if you grasped a "live" apparatus or wire is as follows:

1mA	Tingling
9mA	Probably still able to release the device
16mA	Borderline on ability to release the device
20mA	Unable to release the device
16mA to 50mA	Pain, possible unconsciousness. Heart and respiratory functions probably continue.
> 100mA	Heart tremor, asphyxia due to respiratory paralysis. Severe shock and burns. Possible death.

Burns are caused when current passes through the skin tissue, and because of their penetrating action, electric burns can be much deeper than their size might suggest. Extremely serious burns can result from contact with high voltage power lines.

First Aid

In the event of a person receiving a suspected electric shock from the domestic mains supply, you should act quickly and calmly to help the victim, without exposing yourself to the same risk of electrocution.

- Avoid touching the victim if he or she may still be in contact with the mains. Switch off and unplug, or use an insulating wooden pole or wooden chair to push the victim clear of the supply.
- If the victim has stopped breathing, you should apply artificial respiration immediately.
- Then treat burns immediately. Relieve pain and reduce tissue damage by cooling the affected area with plenty of clean cold running water, or apply ice, frozen produce etc.
- Remove any items of a constrictive nature (rings, watchstraps, bracelets) before swelling starts.
- Apply a sterile dressing for protection from infection. Do not apply lotions, creams or ointments nor prick blisters.
- Seek medical attention.

No attempt should be made to help victims of high voltage electrocution unless it is certified that the power source has been completely isolated. See the section *"Leaps and Volts"* for more information.

earth, because the star point is connected to earth as well. The neutral resistor will limit the current and prevent a serious failure.

Although a fault current will now flow, this will be detected by earth fault relays, current transformers, circuit breakers or other devices. In the case of a major generator fault, the neutral resistor is capable of withstanding many tens of amperes for five seconds, at a potential of some 10kV or more.

Ground Force

In the simple example of Fig.17, a generator phase has shorted to an imaginary steel girder, one end of which is connected to earth. It will be seen that the neutral limiting resistor now forms the load for the winding and a fault current will flow down to earth and through the resistor, which limits the current.

In his several days on-site at Killingholme "A", the author saw countless examples of all kinds of earth straps and leads which are designed to ensure high tension fault currents find their way directly to earth. It clearly makes a great deal of sense to make it easy for fault currents to flow through a massive conductor – the ground – and trip a circuit breaker in the process to disconnect the supply. A similar form of protection is used in the home.

Remembering that the power station also uses electricity itself for its own systems, it is interesting to note that even if the worst happened and power was lost entirely, the power station has a Battery Room containing several very large banks of lead-acid accumulators which offer 48V, 110V and 220V d.c., sufficient to power auxiliary equipment for many hours. Safety regulations (danger caused by sparks) prevented any photography in this area.

Greetings, Earth Links

We can draw parallels with the preceding principles to examine the need for earthing at a domestic or commercial installation. The "neutral" wire of a 230V a.c. supply is provided by the star/neutral point of the transformer and is therefore always close to zero volts with respect to the incoming "live". The star/neutral point is also earthed as shown in Fig.14b and Fig.15. A separate good quality metal earth connection usually runs between the installation's earth circuit back to the transformer (e.g. to its metal body, which is also earthed).

The arrangement for domestic/commercial installations is virtually identical to that used by the power station generators to isolate failures in the insulation or other faults. If every piece of exposed non-live metal is earthed, then it will be very easy for "escaping" fault current to flow to earth as well; it will strive to complete the circuit back to the earthed star point of the 415V transformer. In so doing, a massive current will flow which will melt an in-line fuse or operate a circuit breaker. (A separate box out *"Fuses – The Race to Protect"* gives a little more background to domestic circuit breakers and fuses.)

Heated Exchange

Taking the example of an ordinary electric heater (see Fig.18), its metal casing is connected to the earth terminal of the mains plug. Alternating current flows between the live and neutral wires when the heater functions normally.

If a live wire should come adrift within the heater and touch the metal cabinet, then a heavy current will flow to earth which will melt the fuse in the mains plug, thereby disconnecting the supply. Such action prevents the user from being able to touch a "live" metal cabinet and acquire a potential, because he or she could be fatally injured by the fault current flowing through the human body en-route to earth.

Fuses – The Race To Protect

Fuses are the "last gasp" and sometimes the only protection found in most domestic electric appliances as well as electronic circuits. A fuse is primarily used in a mains plug-top to oversee the mains cable (power cord) and will "melt" if the cable is severed or damaged, when an excessive current could flow. The fuse is also intended to disconnect the mains supply should an insulation fault, such as a short to earth, arise within the apparatus.

Fuses are the most rudimentary type of over-current protection and rely on a wire melting to interrupt the supply. They offer little protection to human beings in preventing electric shock, other than to disconnect the supply if an overload condition (e.g. a short to earth) occurs.

Old open-type fuses found in some fuseboards contain bare wire which will melt if the rated current is exceeded. However, fuse wire can eventually start to oxidise which may cause premature failure. An HRC (High Rupture Capacity) fuse uses a sand-filled ceramic cartridge to prevent oxidation and also to extinguish the arc. These are typically found in UK mains plugs but larger versions are used in industry. Continental fuseboards use such ceramic cartridge fuses as well.

Electronic equipment often utilises a variety of glass-bodied cartridge fuses: 20mm × 5mm for up to 10A current, whilst larger 32mm (1¹/₄in.) types are produced with ratings exceeding 25A. Some types are anti-surge, meaning that they will not "nuisance trip" when equipment surges during first powered up. *It is always very important that fuses are replaced with the same type, size and rating.* Failure to do so may cause both a fire and an electrocution hazard.

The miniature circuit breaker (or MCB) is a resettable form of fuse or "trip switch" which will act to open the circuit when an excessive current is drawn by the load. The best form of protection though is Residual Current Device or RCD, also known as an earth leakage circuit breaker (ELCB) or Ground Fault Circuit Interrupter (GFCI) in the United States.

These devices "look for" an imbalance between the currents flowing in the live and the neutral wires. If any difference arises, any losses must be due to current leaking to earth, and an RCD will typically trip within 40ms of detecting an earth leakage current of 30mA.

Not to be confused with an MCB, a Residual Current Device offers the best personal protection against electrocution and is a wise investment when using outdoor power tools. Most RCDs now offer "double-pole" protection which disconnects both the Live and the Neutral wires to ensure total isolation, and feature a test button. Fuseboards fitted with RCDs are now quite common.

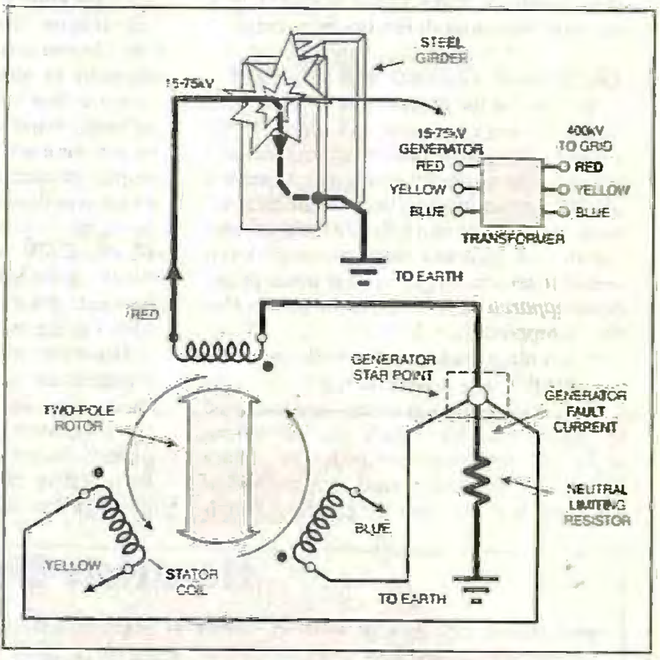


Fig.17. A "neutral" resistor connects the generator star point to the earth to limit any fault currents. Here, the Red phase has shorted to earth, via a steel girder in this simple example.

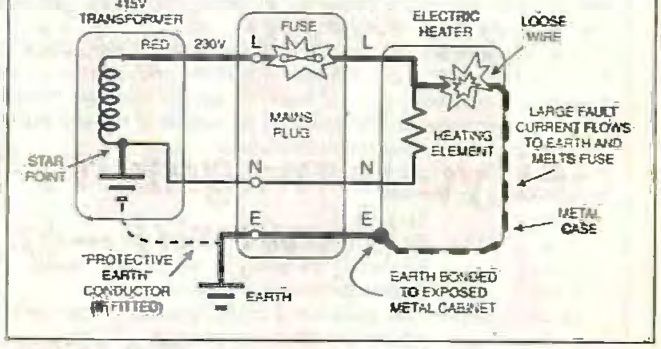


Fig.18. How earthing ensures that any insulation breakdowns will cause a fuse to melt, thereby disconnecting the supply. A large fault current flows to earth, when a loose wire shorts the 230V live wire to earth, via the earthed metalwork.

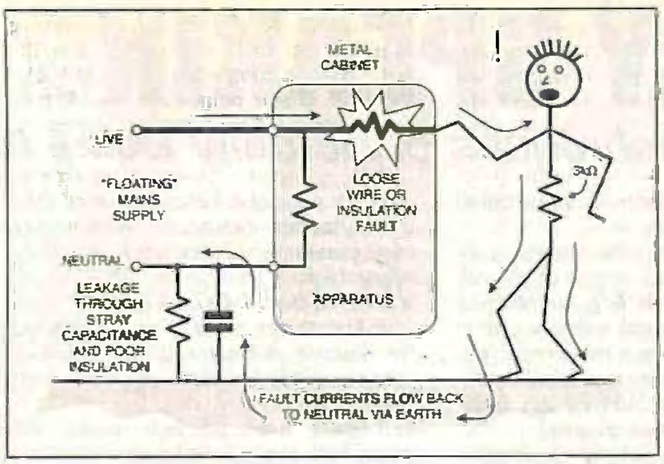


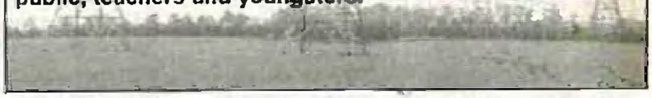
Fig.19. A "floating" (unearthed) supply can still give rise to electrocution risks caused by stray capacitance or poor insulation completing a path back to neutral. (Adapted from Guide to IEE Wiring Regulations (15th Edition) – J. F. Whitfield.)

Acknowledgements

The author is extremely grateful to those at National Power Killingholme "A" without whose assistance this article would not have succeeded in its objective of exploring the world of electricity from pipelines to pylons. Thanks again to Station Manager Keith Ulyett and Richard Power for their valuable and enthusiastic support. The National Grid PLC kindly permitted reproduction of several photos.

Several readers contributed technical information to this feature when the subject of mains earthing was raised in our *Circuit Surgery* (Oct. 1997) pages. The author is grateful to I. J. Goldfinch, B. J. Taylor and R. H. Ogilvie for their input.

Internet users can view the National Power PLC web site at www.national-power.com. The National Grid web site at www.ngc.co.uk offers more background information, data, real video clips and more! The web site of the Yorkshire Electricity Group at www.yeg.co.uk contains a considerable amount of material which will be of general interest to the public, teachers and youngsters.



There is a counter-argument which states that if no earth were installed, then even if a human being *did* accidentally touch a live terminal, no ill effects could arise because there would be no reason for current to flow through the body to earth. The body would merely be "floating" at the live voltage but no potential difference would exist across him or her, and no harm would be done.

Anyone who has suffered at the hands of a very cheap open-type mains transformer will know that standards of electrical insulation are sometimes less than 100 per cent, and leakage currents can occur. This means that the earth (or, say, the chassis of an apparatus) could still *not* be completely isolated from the supply even if the supply has no *apparent* direct connection to earth and is supposed to be "floating". Poor insulation allows a leakage current to flow given a suitable opportunity.

There are other ways in which the earth can form a return path for fault currents, even if the supply is supposed to be "floating". As IEE guidelines state, electrical insulation can itself be thought of as a capacitor dielectric, with the live wiring forming one "plate" and the earth forming the other.

This *stray capacitance* could form an adequate route for an a.c. fault current to pass, should a human body accidentally contact a live wire (see Fig.19). There is thus the prospect of receiving an electric shock from earth fault currents even if it is thought that the mains supply is floating and supposedly unearthed.

In Shock

Still on the subject of accidental electrocution, the human body, being full of water, is the walking equivalent of a 3 kilohm resistor and it only takes a current of 20mA to pass through a muscle to cause uncontrollable spasms and render the body unable to release a live wire. A separate box out entitled *"Heartfelt Shock"* explains some things about the human body and its reaction to electric shock, and there is also some useful first aid advice to help with cases of suspected electrocution.

There are various earthing configurations permitted under the UK Institute of Electrical Engineers' Wiring Regulations, but how earthing is achieved in an installation depends on whether the incoming supply is via undergroud cables or from an overhead supply. Due consideration is also paid by installers to the method by which earthing has been implemented in the locality by the supply authorities.

It should be again emphasised that the domestic electricity supply should NEVER be interfered with except under expert guidance. ☐