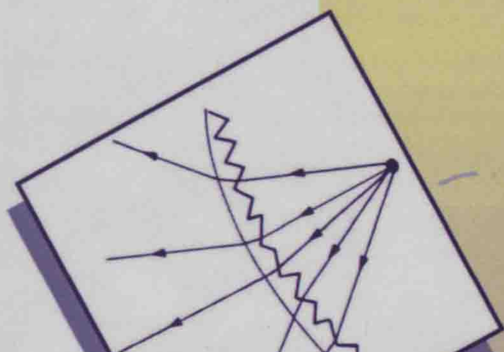
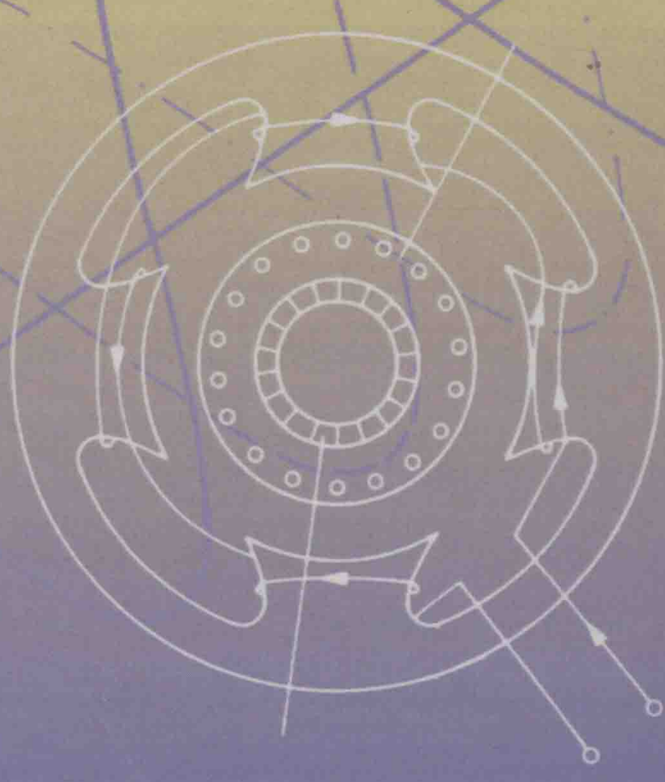
Electrical Power Technology

DAVID W. TYLER





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Preface

This book has been written for the Advanced GNVQ in Engineering, covering the BTEC Optional Unit 12, Electrical Power Technology, and the City & Guilds Optional Unit 19, Electrical Power. It also covers the BTEC NII level objectives in Electrical Applications U86/330. To understand the applications, a knowledge of the underlying principles is needed and these are covered briefly in the text.

Throughout each chapter are worked examples and **Test your knowledge** questions. When reached, the examples should be worked through and the questions attempted before moving on. The **Test your knowledge** questions are mostly very short and require information given up to that point in the chapter. They enable you to check whether you have learnt the salient points of the preceding work. Answers to these questions are given at the end of the book.

At various stages in the chapters there are **Activities** which will require much more effort to accomplish. These will create work suitable for a portfolio of evidence, and also provide opportunities to develop Key Skills in Communications, Information Technology and Application of Number. It is not envisaged that all students will tackle all of the **Activities**; which ones are attempted will be determined at least in part by the equipment you have at your disposal.

At the end of each chapter there is a further selection of problems given with mathematical answers in brackets. Answers to questions requiring descriptive answers will be found by looking back through the text. Concluding each chapter, a section of **Multiple choice questions** provides practice material for GNVQ end-of-unit tests.

In a subject such as this, many pieces of work require you to describe operations or effects. A good diagram is worth many words and this book aims to promote the use of diagrams by the inclusion of over 200 throughout the nine chapters.

I wish to thank the Institution of Electrical Engineers for permission to quote from the Regulations for Electrical Installations. Any interpretation placed on these regulations is mine alone.

In these days of ever-increasing use of computers, there is a growing tendency to regard any piece of equipment without a screen as being in some way deficient. I would like to remind those who have this impression that, without power equipment and 'power men', the rest of the industry would not exist.

I wish all my readers success in their studies and hope that all, including those who are not following a formal course, will find the material in this book useful, interesting, and perhaps most of all, approachable.

David W. Tyler

Contents

1 Electricity supply

Summary

This chapter looks at energy sources for generation of electrical energy and the basic cycle employed. It explains why transmission is carried out at very high voltages and shows how the various pieces of equipment are interconnected using switchgear and transformers to give maximum efficiency together with practical user voltages. It compares the use of underground cables with overhead lines. The purpose of switchgear is described together with the equipment found in distribution substations. The reasons for the adoption of the three-phase system is explained and the losses in feeder systems examined.

Synchronous generators

Virtually all the generation of electrical energy throughout the world is done using three-phase synchronous generators. Almost invariably the synchronous generator has its magnetic field produced electrically by passing direct current through a winding on an iron core which rotates between the three windings or phases of the machine. These windings are embedded in slots in an iron stator and one end of each winding is connected to a common point and earthed. The output from the generator is taken from the other three ends of the windings. The output from a three-phase generator is therefore carried on three wires. In many three-phase diagrams single line representation is used when each line on the diagram represents three identical conductors. Figure 1.2 is drawn using this method.

All such generators connected to a single system must rotate at exactly the same speed, hence the description *synchronous* generator.

They are driven by prime movers using steam generated by burning coal or oil, by nuclear reactors, water falling from a higher to a lower level, or aircraft-type gas turbines burning oil or gas. A very small amount of generation is carried out using diesel engines.

Generators range in size from 70 MVA (60 MW at 0.85 power factor) at a line voltage of 11 kV which were mostly installed in the 1950s, through an intermediate size of 235 MVA (200 MW at 0.85 power factor) to more recent machines of 660 and 1000 MW which generate at 25.6 kV. The very large machines are quite rare; many modern power stations employ a combined cycle where gas turbines running on gas produce electricity, and the extremely hot exhaust gases raise steam in a boiler which is used in a further turbine to generate more power. Such combined cycle stations have an efficiency about 50 per cent greater than a straight steam power station but individually are of lower rating.

Energy sources

- **Coal.** Coal is plentiful worldwide and there are sufficient known reserves to last for centuries. It may be deep mined or extracted from open cast mines. Open cast coal is generally of lower quality than deep mined coal but is more easily extracted since once the top overburden is removed it can be scraped out by very large diggers. Open cast mining is opposed on environmental grounds because of the huge areas of land involved and the dust produced. When coal is burnt it produces sulphur oxides which combine with water to form sulphurous and sulphuric acids which are very corrosive. The term *acid rain* is used in this context. Large amounts of ash are produced which need to be disposed of, filling in quarries and marshes etc. To plan and build a coal-fired power station takes several years and it must be accessible to bulk transport to bring in the coal (5 million tonnes annually typically for a major station) and to get rid of the ash which may be up to one tenth of the coal input.
- **Oil.** This may be residual oil from refineries or refined products.
  - (a) Residual oil. When oil from the well has been refined and the petrol, paraffin and diesel oil taken off, the refinery is left with a tar-like substance which is only liquid when kept hot. This may be burnt in power stations to produce steam in the same manner as coal. It should be cheap since the refineries need to get rid of it but is sometimes costed as coal equivalent for heat production. It contains all the impurities of the original raw oil and produces large amounts of sulphur oxides but little ash. It needs special transport to keep it hot and must be maintained hot at the power station since once cold it cannot be pumped.
  - (b) Refined oil. This may be kerosene for use in gas turbines or diesel oil for use in reciprocating engines. This is a very clean fuel but relatively expensive. It burns mainly to water vapour and carbon dioxide although in common with all high-temperature processes there will be some nitrogen oxides produced which are also associated with acid rain. Stations burning refined fuel are generally much simpler to construct than those involving solid fuels.
- **Natural gas.** This is comparable to refined oil but is richer in hydrogen so that when it burns it produces more water vapour and less carbon dioxide and is therefore favoured by those concerned with the effects of carbon dioxide on the global atmosphere (global warming). Stations using refined fuel are quick to start and shut down and so are often used for supplying short peak demands.

- **Nuclear.** Heat produced by nuclear fission of uranium derivatives is used to produce steam and the cycle then continues as with burning any other fuel in a boiler. Nuclear power stations are immensely expensive to plan, construct, fuel up the initial charge and to bring on line. However, once running they produce electricity at virtually zero incremental cost, the main charge being paying off the investment. Therefore nuclear stations are ideally suited to run on base load, maintaining their output 24 hours a day for months at a time. The principal disadvantage will probably turn out to be the cost of decommissioning the stations at the end of their life. Once the turbines and external pipework have been removed the reactors will need to be boxed up and kept secure for centuries before anyone can finally dismantle them.
- **Water.** Very large quantities of water falling through a short distance can be used to drive Francis-type water turbines connected to generators. Again, smaller quantities of water falling through perhaps several hundred metres can be used with Pelton Wheel turbines to the same end. In Britain the possibilities are quite small; there are hydroelectric stations in Scotland and in Wales but their outputs are small compared with fuel-fired stations. There are some very large installations in other countries, a very famous one being the Hoover dam on the Colorado river in the USA.
- **Wind.** In situations where strong winds can be guaranteed for long periods wind turbines are being installed. Generally they involve a two- or three-bladed rotor driving an alternator rated at up to 500 kW set on a single tall pillar. These are often arranged in groups of 10 to 15. Once running they have zero fuel input charge, the whole of their output producing revenue which has to pay off the original investment.
- **Refuse, sewage sludge, peat, wood chippings, straw, vehicle tyres, garbage.** Refuse tips produce large quantities of methane gas which has caused problems when it leaked into houses causing potentially explosive situations. This can be piped away and allowed to burn off uselessly but there are now many instances where it is used to drive diesel-type engines with some oil backup to produce electricity. The same is true of gases produced from sewage sludge. The power produced is used to supply the sewage works, any excess being exported to the system. Willow wood grows very quickly and in very wet areas, Ireland typically, this can be coppiced, chipped and then burnt as coal in specially designed boilers to produce steam and electricity. Peat is also used. Now that farmers are no longer allowed to burn straw in the fields in Britain there is a move to use this as a fuel. Boilers are available which burn whole bales, several at a time, but of course the ratings are fairly small. Huge numbers of vehicle tyres need to be disposed of annually and plants are being developed to burn these to produce electricity and steel scrap from the reinforcement at the same time. Household garbage is also burnt to produce power in some cities.

Generation cycles

Single cycle

In the cases of wind and hydro generation the prime mover is connected directly or through a gear box to the alternator. Where there is a heat input the straight system involves:

1 a boiler
2 a superheater
3 a turbine
4 a condenser
5 auxiliary plant such as feed heaters, air ejectors, evaporators and possibly cooling towers.

We will examine these in more detail in conjunction with Figure 1.1.

- **Boiler.** Power station boilers comprise a tall, rectangular open space (like a large luggage lift shaft without the lift with a floor and perhaps four or five storeys high). The walls are of firebrick inside a sheet-steel casing. Inside the firebrick and supported by it all round the walls are vertical steel pipes typically 10 cm in diameter and spaced at 20 cm centres. All the tubes are expanded into one or two large steel drums at the top and smaller ones at the bottom. When operating, the top drums are half full of water so that the tubes and bottom drums are completely full of water.

  The fuel being burnt feeds in through ports near the bottom of the boiler and in burning boils the water and brings it up to the required pressure.
- **Superheater.** Across the top of the boiler there are several layers of spaced tubes through which the combustion products, still very hot, pass. Steam is taken from the top steam drum and fed into these tubes. In passing through it becomes hotter, up to 550 °C being typical.
- **Turbine.** This comprises many sets of blades on its rotor matched by similar sets with opposite pitch on the fixed casing. The steam from the superheater is fed though nozzles on to the first set of rotating blades which creates a force and motion. As the steam exits from this set of blades it is redirected by a fixed set on to the next rotating blades etc. After many such redirections through blades which are longer at each stage the steam approaches the condenser.
- **Condenser.** This is a large vessel across whose width a large number of small tubes pass. These are fed with a constant supply of cold water. The steam in striking these tubes turns rapidly into water which since it has only approximately 1/1700 times the volume of the steam creates a near-perfect vacuum. This very strong suction causes the steam to expand much more than if it exhausted into the atmosphere as in a steam railway locomotive and so to do much more work, making the turbine more efficient. In addition, we have regained the water which can now be pumped back into the boiler to create more steam.
- **Auxiliary plant.** Rather than pump cold water directly back into the boiler it is heated using some of the steam passing through the turbine. At various stages in the turbine there are

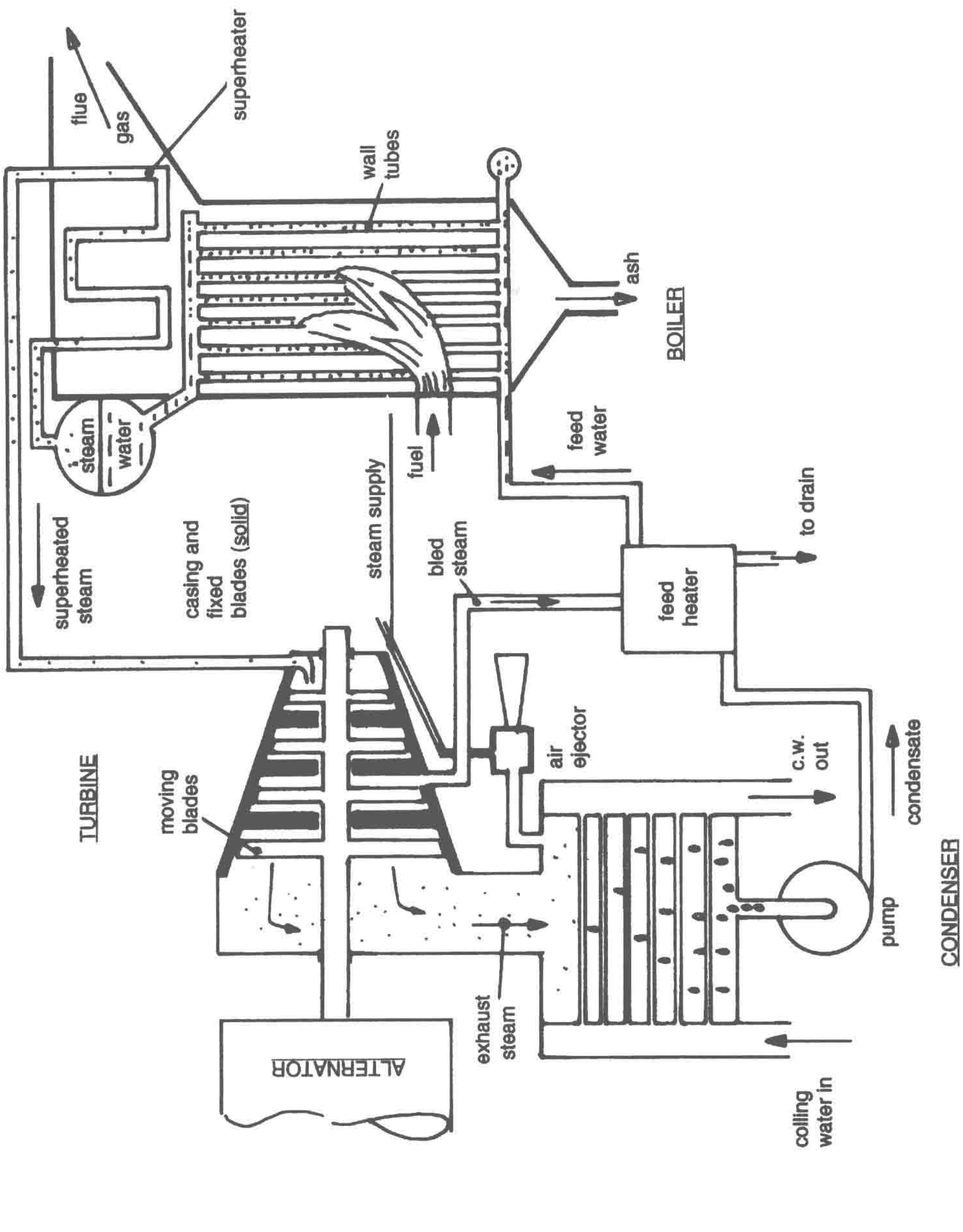
flue
gas
superheater
wall
tubes
ash
BOILER
feed
water
fuel
steam
water
superheated
steam
casing and
fixed
blades (solid)
steam supply
bled
steam
to drain
feed
heater
TURBINE
moving
blades
air
ejector
c.w.
out
condensate
ALTERNATOR
exhaust
steam
pump
CONDENSER
colling
water in

Figure 1.1

points between the fixed blading from which steam can be extracted after doing part of its useful work in driving the shaft. Figure 1.1 shows one such stage but in practice there will be five or more separate steam tap-off points, each one at a higher pressure and hence greater temperature than the last. The steam is taken to tubed water heaters, the feed water to the boiler passing over the steam heated tubes increasing its temperature in each so that when it enters the boiler it is at close to boiling point already.

The vacuum inside the condenser would gradually run down due to air leakage into the casing through the turbine shaft seals so that some of the boiler steam is used to operate an air ejector, constantly sucking air out of the steam space.

There will always be leaks of steam out of the turbine since no seal at the high-pressure end of the shaft is perfect. Gradually there will be less and less water available to pump back into the boiler. Again a small part of the steam passing through the turbine is taken away and used in another heater to evaporate river or sea water which then condenses into pure water for use in the boiler. This evaporator is not shown in Figure 1.1.

The cold water passing through the condenser becomes heated by perhaps 8 °C. Where river or sea water is used this is a once-through process, the hot water returning to its source. Where water is in short supply it has to be cooled down and reused. This is done in cooling towers. The water is pumped through nozzles situated about halfway up the tall tower. The fine spray falling comes into contact with the air which, in being heated, rises to the top of the tower giving the characteristic plume which comes from a cooling tower. The same plume is apparent in cold weather on the top of tall buildings with air conditioning where excess heat is dumped using this method.

When the flue gas leaves the superheater it is still at a very high temperature. It goes on to pass through air heaters which heat the incoming air which is drawn from the top of the boiler house so that it is already warm. Where pulverized coal is used as the fuel the hot air is used to dry the coal so that it may readily be milled into dust which burns with more hot air in a similar manner to a gas or oil flame. Where gas or oil is used the hot air is fed in with the fuel, so maximizing flame temperature and thus efficiency. Where coal is the fuel the flue gas is finally cleaned using some form of dust removal such as an electrostatic precipitator to minimize dust pollution. The chimney temperature is of the order of 140 °C.

Combined cycle

A more efficient use of energy is possible by either producing electricity and useful heat at the same time or generating electricity in two stages. Where heating and electricity are required this can be accomplished in two ways: (1) Use the same cycle as above but extract more steam from the turbine at various bleed stages to heat water for buildings or an industrial process. (2) Instead of using a condenser, cause the steam to leave the turbine at a pressure suitable for any process in mind. For example, a paper works might want a supply of steam at 12 bar to dry the wet paper. The turbine can be designed to exhaust at this pressure using steam from the boiler at, say, 40 bar, thus we get electricity and heat from the system.

Electricity may be generated in two stages by using a gas turbine followed by a conventional boiler. A gas turbine fired with natural gas or oil produces a very hot exhaust at the jet pipe and this jet from a single engine or two engines may be used to drive a turbine connected to an alternator. Aircraft jet engines are available which are capable of generating over 15 MW each. The gas as it leaves the generating turbine is still hot enough to raise steam in a conventional boiler so that another generating stage as above can be added or the boiler heat used in an industrial process.

A very simple electricity/heat combined cycle could involve simply using a diesel engine to drive an alternator whilst using the cylinder cooling water to heat a building or water for industrial process use etc. The heat from this water is radiated into the atmosphere as waste when the engine is associated with a vehicle.

Economics of generation and transmission

The power in a single-phase circuit = $VI\cos\phi$ watts where V and I are the r.m.s. values of circuit voltage and current respectively and ϕ is the phase angle between the current and voltage.

As an example consider a power of 1 MW at 240 V and a power factor of 0.8 lagging. (1 MW = 1000 kW = 10^6 watts.)

$$240 \times I \times 0.8 = 10^6$$

$$I = \frac{10^6}{240 \times 0.8} = 5208 \text{ A}$$

By increasing the voltage to, say, 20 000 V the required current falls to 62.5 A. The voltage drop in a transmission line due to the resistance of the line = IR volts.

The power loss = voltage drop multiplied by the current flowing

$$= IR \times I$$
$$= I^2R \text{ watts}$$

Using the above values of current it may be deduced that:

1 for a conductor of given size and resistance, the line losses at 240 V and 5208 A will be very much greater than at the higher voltage; or
2 if the losses are to be the same in both cases the conductor for use at 240 V will need to have a very much lower resistance and hence have a much greater cross-sectional area than for use at the higher voltage.

Example 1.1

Each core of a two-core cable feeding a load 200 m distant from the supply point has a resistance of 0.05 Ω. The voltage at the load end of the cable is 230 V. The power developed in the load is 19.3 kW at 0.85 power factor lagging.
Calculate: (a) the current in the cable; (b) the losses in the cable; (c) the supply voltage; (d) power input to the cable.

(a) Load power = $VI \cos\phi$ watts
Hence $19\,300 = 230 \times I \times 0.85$
Load current (= cable current)

$$I = \frac{19\,300}{230 \times 0.85} = \mathbf{98.7\ A}$$

(b) Losses in the cable = I^2R watts
where R = total resistance, go and return
$= 2 \times 0.05$
Losses $= 98.7^2 \times 0.1 = \mathbf{974\ W}$

(c) Supply voltage = load voltage + volt drops in cable
$= 230 + 2(98.7 \times 0.05)$
$= \mathbf{239.9\ V}$

(d) Power input to cable = load power + cable losses
$= 19\,300 + 974$
$= \mathbf{20\,274\ W}$

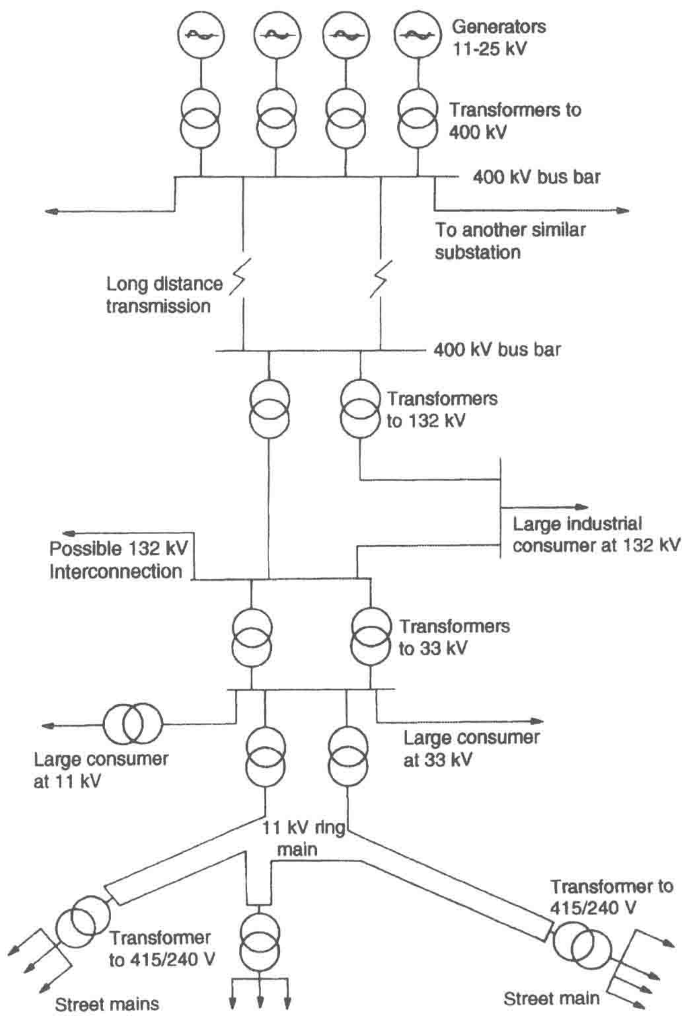

Figure 1.2