Lecture 3: Generation I

3.1 Overview

Generation is the process by which a source of energy is converted into electrical energy:

Primary fuel(coal, oil, gas, nuclear) → Heat → Mechanical → Electrical.

Renewables: Wind, solar, hydroelectric, tidal.

UK breakdown of electricity generation (%):

	2022	2010	1990
Gas	38.4	40.4	0.05
Coal	1.5	32.3	67
Nuclear	15.5	17.6	19
Wind	26.8	2.9	0
Solar	4.4	0	0
Biomass	5.2	3.4	0
Hydro	1.8	1.7	2.6
Oil	0	1.5	7
Imports	5.5	0.2	4.35
Storage	0.9	0	0

UK total electrical energy consumed in 2010: 363 TWhr = 363×10^9 kWhr, 2022: 275 TWhr

2022 capacity 76 GW, peak demand 48 GW.

The next four lectures are concerned with the process of generating electricity. In this lecture we will start by gaining an overview of this process, and look at the special properties of electrical energy which impact on the engineering aspects of generation. We will also consider the basic physical principles which underlie the generation of electricity, and see in detail why electricity is generated as three-phase.

The process of generation is the means by which some source of energy is converted into electrical energy. In the case of generation using fossil fuel this process involves burning the fuel to produce heat energy. In coal fired generation, the heat is used to produce steam, whereas in gas-fired generation (which has become very popular in recent years - the so-called 'dash for gas') the working fluid is air. In both cases, the working fluid is at high temperature and pressure from burning the fuel, and can then be used to drive a turbine, which is mechanically coupled to the electrical generator. Thus, the flow of energy is: Primary fuel → heat → mechanical → electrical.

Increasingly other possibilities for generating electricity which do not rely on this series of conversions are becoming mainstream, but a substantial proportion of electrical power in the UK is generated in this manner.

Examples of other types of generation using renewable energy sources are hydroelectric, wind , solar, tidal and wave, and biomass. Of these, most viable sites for hydroelectricity have been exploited, but the growth in both onshore and offshore wind capacity continues at an increasing pace. Biomass also makes a substantial contribution, and solar PV is growing rapidly.

3.2 Features of electrical energy

1. No easy means of bulk storage - pumped storage schemes are the only form of ‘storage’ which makes a significant impact.

⇒ Generated power must equal consumed power at all times ⇒ need to react instantly to changes in demand ⇒ use ‘pooled spinning reserve’.

2. Supplier has no control over variations in demand (except through pricing).

⇒ Capacity of generation must exceed maximum demand.

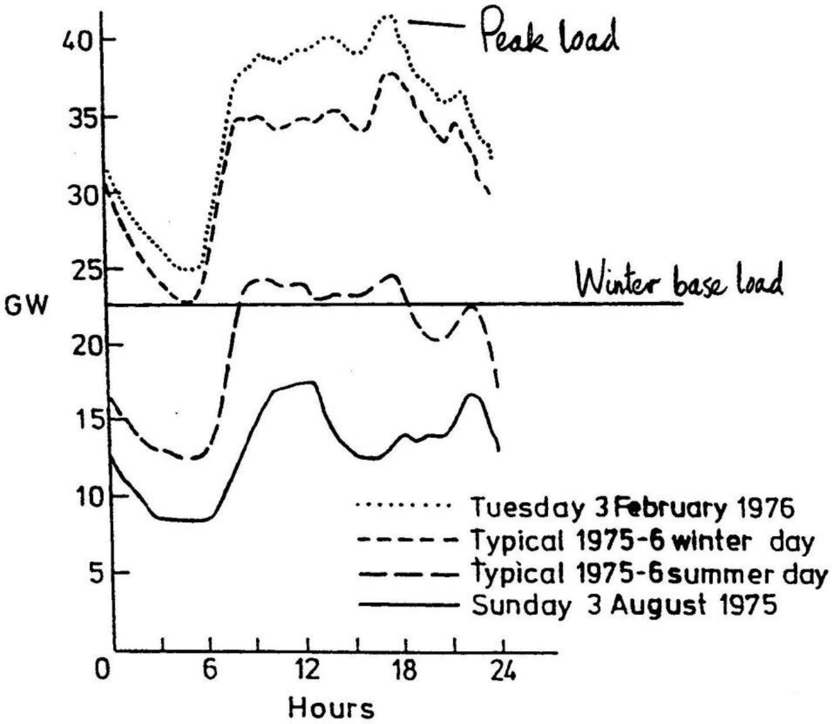

Fig. 3.1

In this section we briefly consider some of the features of electrical energy which have implications for the overall process of generation.

Firstly, there is no easy means of bulk storage. This differs from other sources of energy which we routinely use, such as gas and petrol. One possibility is the storage of electricity in the form of potential energy by pumped-storage schemes. There are a number of these schemes in the U.K. such as Dinorwic in Wales, and Cruachan in Scotland. The basic idea is that electrical energy is used in off-peak periods to pump water up to a high-level reservoir. The potential energy thus stored is released during a period of high demand, to produce electrical energy. However, the majority of electricity has to be generated in ‘real time’. In turn, the ability to react to sudden changes in demand is vital (e.g. when you all get back to college after an exhausting day of lectures and supervisions, and switch on the kettle !). This is achieved in practise by having a large number of generators ‘running light’ i.e. spinning around but not producing any electrical power, but ready to do so.

Variations in demand depend on many factors. There are seasonal variations e.g. there is more demand for electrical power in Winter - heating, people tend to stay in more, gets dark earlier. There are daily variations e.g. little power is used between midnight and 6 am , and there are peaks at breakfast, and in the evening. These points are illustrated in fig. 3.1. The variations in demand are usually predictable. However, suppliers are occasionally caught out - in the Winter of ‘95/’96 it was necessary to import power from France to meet the demand ! The only control the supplier can exert is through variable pricing.

3. Future demand predicted to increase greatly.

⇒ Ongoing need to anticipate changes in demand and develop and integrate new sources into the grid.

4. Economic and environmental considerations are important.

⇒ Continual investment in clean energy.

⇒ Nuclear power used for ‘base’ load, then renewables, then CCGT, then coal.

5. Security of supply also important.

⇒ Large degree of interconnection ⇒ synchronised power supply with a common supply frequency.

Economy 7 is an example of this which the domestic consumer can take advantage of. Basically, between 1 am and 8 am, typically, the cost of electrical energy is about a third of its normal cost, thus encouraging consumers to use more off-peak power.

The strategy to get to overall nett zero by 2050 includes replacing passenger vehicles by all-electric ones, and phasing out gas boilers. It is estimated that this will require a doubling in electricity generation capacity.

Economic generation of electrical power is important for customers and for wider economic health. But environmental considerations aimed at reaching nett zero emissions for electricity generation by 2035 means a very rapid and large investment in renewable energy and supporting grid infrastructure.

Nuclear power takes a long time to bring online (and to run down) so it is used to supply base load (meaning the load that is always present).
All renewable sources are deployed too, if necessary importing/exporting power via high voltage DC (HVDC) links, or increasingly using stored energy (pumped storage, batteries). Combined cycle gas turbines, which are about 60% efficient are used for peak load. Coal-fired power stations are used as an absolute last resort. Note that some coal-fired generation have been converted to biomass.

Power supply failures range from mildly irritating to catastrophic; security of power supply is therefore very important, and is achieved by a large degree of interconnection between suppliers and users, via the National Grid. This means that the whole of the power supply must operate at a single frequency, and in synchronism.

3.2 A.C. Generators - Basic Principles

Generator consists of a stator and a rotor.

Stator is stationary, rotor is supported by bearings and is free to rotate when driven round by the prime-mover.

D.C. current is fed into the rotor coils via slip-rings and brushes.

This sets up a magnetic field.

The field follows the closed path:
rotor core → air-gap → stator core → air-gap → rotor core.

Air-gap field varies sinusoidally with θ.

$$B(\theta) = \hat{B}\cos(\theta) \qquad \text{(rotor stationary)} \qquad (3.1)$$

Drive the rotor round at ω_r rads/sec:

$$B(\theta,t) = \hat{B}\cos(\omega_r t - \theta) \quad \text{(rotor rotating)} \qquad (3.2)$$

Consider a stator with only one coil. The flux linking that coil is obtained by integrating the flux density over the coil area:

The conversion of mechanical power into electrical power is achieved by the a.c. generator, and in this section we consider the fundamental principles of its operation.

The generator consists of a rotating part, called the rotor (fig. 3.1), and a stationary part, called the stator (fig. 3.2). The rotor is supported by bearings, so that it is free to rotate when driven round by the source of mechanical power, which is termed the prime-mover from now on. The rotor is mounted within the stator, and is concentric with it. There is a small gap between the two, known as the air-gap, fig. 3.3.

The rotor has a coil of copper wire mounted on it in slots, fig. 3.1. This coil is connected to a d.c. voltage source via slip-rings and brushes, and so d.c. current flows in it. This current is known as the field, or excitation current. The purpose of this is to produce a magnetic field, as shown in fig. 3.3. This field follows the closed path: rotor → air-gap → stator core back →air-gap → rotor. By careful design of the rotor coil, the air-gap field can be made to vary sinusoidally with θ, equation 3.1. This magnetic field, known as the rotor-driven field, is ‘fixed’ to the rotor. Therefore, when the rotor is driven round by the prime-mover, this magnetic field rotates with the rotor. Consequently, a rotating magnetic field is established in the air-gap of the machine, equation 3.2. Equation 3.2 is the standard wave equation, except with linear displacement replaced by angular displacement i.e. rotating as opposed to travelling in a constant direction. We will return to this point in more detail in the next lecture.

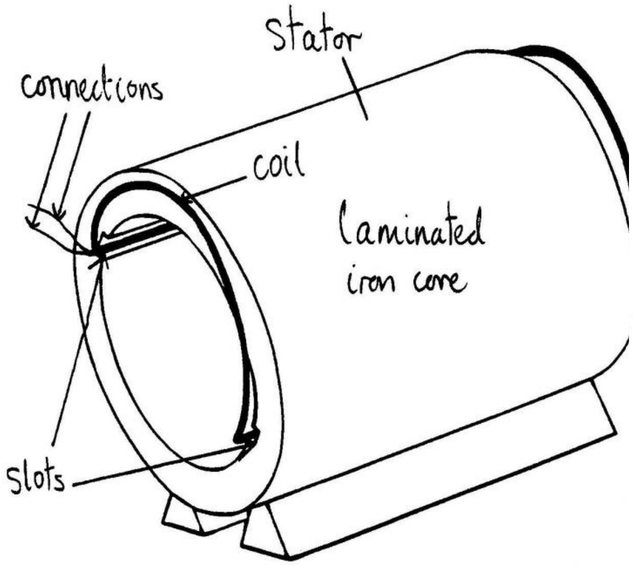

Fig. 3.2

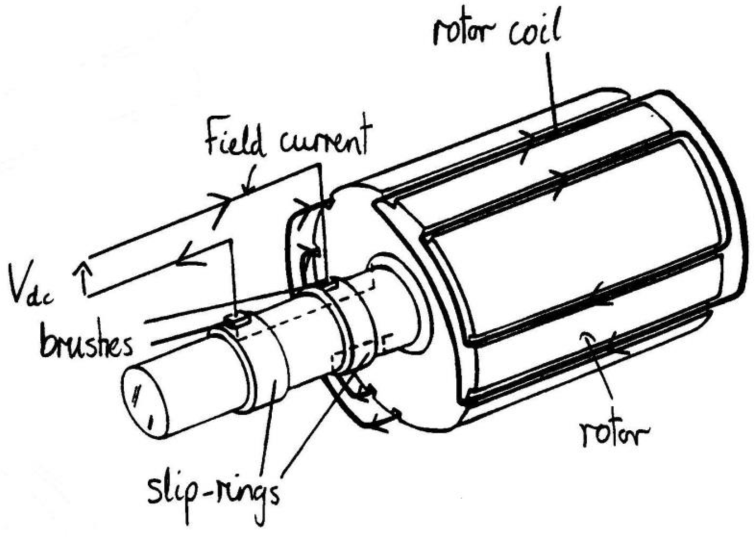

Fig. 3.3

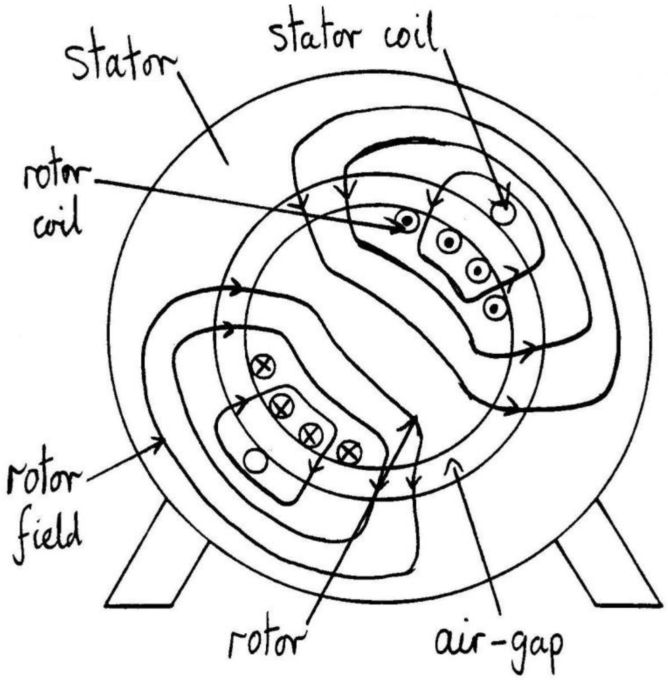

Fig. 3.4

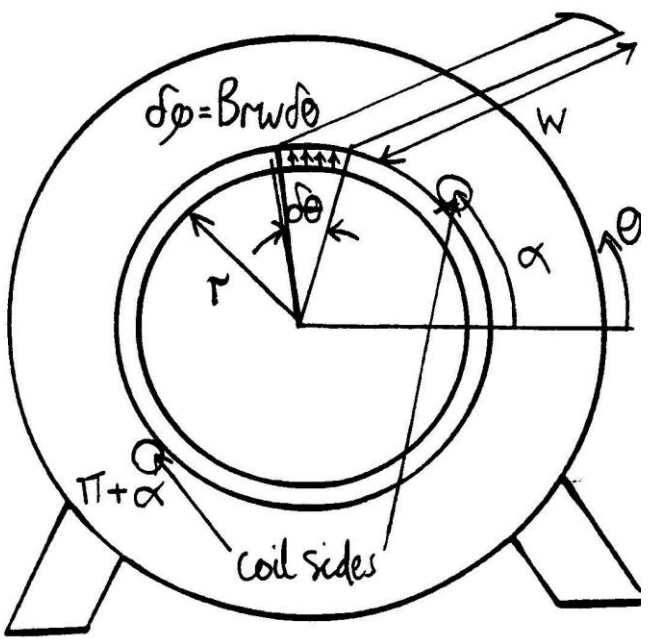

Fig. 3.5

$$\delta\phi = B\,\delta A = B\,wr\,\delta\theta = \hat{B}\,wr\,\cos\left(\omega_r t - \theta\right)\delta\,\theta$$

$$\therefore \quad \phi = \int_{\alpha}^{\alpha+\pi} \delta\,\phi = \hat{B}wr \int_{\alpha}^{\alpha+\pi} \cos\,(\omega_r t - \theta)\; d\theta$$

$$= \hat{B}wr\left[-\sin\left(\omega_r t - \theta\right)\right]_{\alpha}^{\alpha+\pi} = 2\hat{B}wr\sin\left(\omega_r t - \alpha\right) \tag{3.3}$$

This flux changes as the rotor rotates. Therefore, by Faraday's Law, an emf is induced in the stator coil:

$$e = N\,\frac{d\phi}{dt} = 2N\hat{B}wr\,\omega_r\cos(\omega_r t - \alpha)$$
$$= \hat{E}\cos(\omega_r t - \alpha) \tag{3.4}$$

<u>Conclusions</u>

1. A rotating, sinusoidally-distributed air-gap flux density induces a sinusoidally time-varying emf in a stator coil.

2. Frequency and magnitude of the emf are proportional to the rotor speed, ω_r.

3. Phase of emf, α, is the same as the angular position of the stator coil.

The stator of the generator, like the rotor, also has copper coils fixed to it, mounted in slots, fig. 3.2. For the present, we will consider that there is only one such coil and that it subtends an angle of 180^0 as shown in fig. 3.4. The magnetic field produced by the rotor links this coil, and to determine the total amount of magnetic flux linking the coil, we must integrate the flux density over the coil area (Part 1A Electromagnetic Fields course showed that flux=flux density times area - this becomes an integration when flux density varies over the area through which the total flux is to be found). The appropriate elemental area is that of a thin strip subtending an angle $d\theta$ at the centre of the machine, and of length l into the paper, fig. 3.4. The magnetic field, however, is only a function of θ and time, t i.e. it does not vary along the length of the machine. Consequently, the integration becomes w.r.t. θ only. The limits correspond to the angular positions of the coils sides, α and $\alpha + \pi$, as shown in fig. 3.4. Performing the integration gives equation 3.3, showing that the flux linking the coil varies with time at the frequency equal to the angular speed of the rotor. By Faraday's Law, when a coil is linked by a time-varying magnetic flux, an emf is induced in it. This is given by equation 3.4, by differentiating the flux in equation 3.3 w.r.t. time. This emf, like the flux density which induced it, varies sinusoidally with time. Its magnitude is proportional to the rotor speed, as is its frequency. Also, the phase of the induced emf depends on the angular position of the coil w.r.t. the air-gap field.

3.4 Multiple-coil generator

Real generators have many coils evenly distributed within the stator.

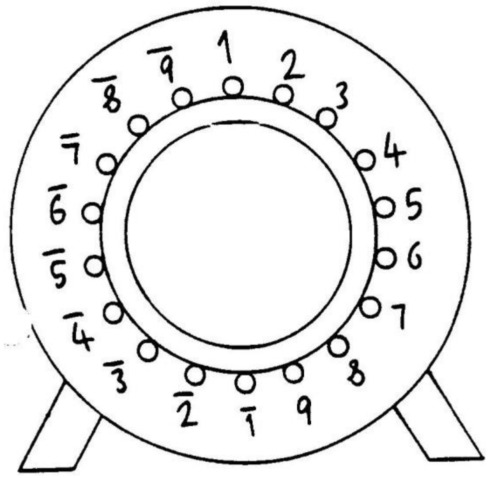

Fig. 3.6

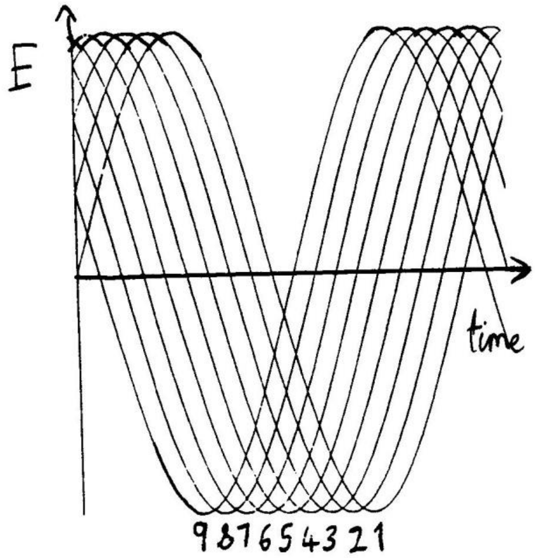

Fig. 3.7

Let I_{max} = maximum current per coil (heating).

n coils $\Rightarrow$ 2n coil ends !! For typical n, this would lead to an unfeasible system, so connect coils to form a three-phase supply

$$\Rightarrow \quad |\tilde{V}_A| = |\tilde{V}_B| = |\tilde{V}_C| = V$$

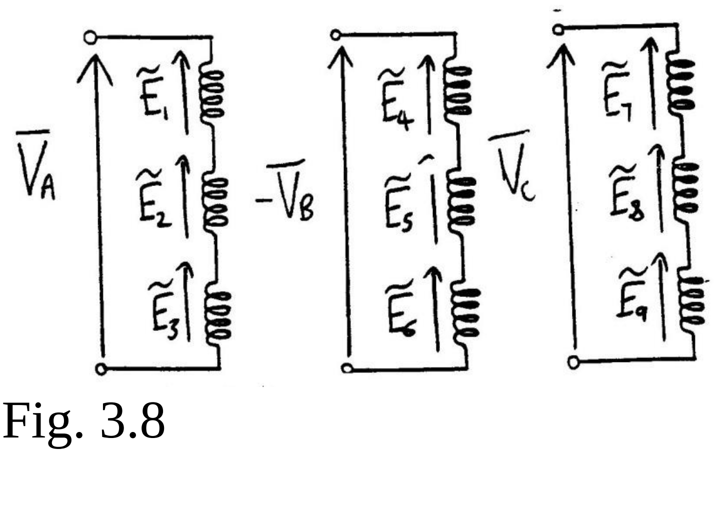

Fig. 3.8

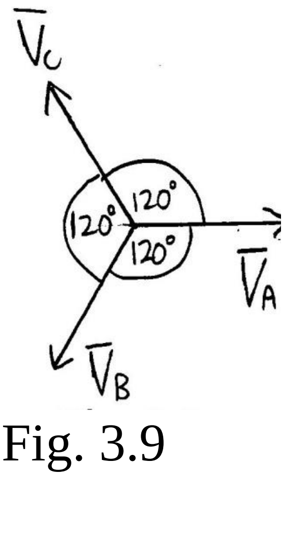

Fig. 3.9

In reality, generators do not have only a single stator coil, but have many identical coils evenly distributed in slots around the periphery of the stator, fig. 3.6. This improves the utilisation of space within the generator, allowing more electrical power to be converted for a given generator size. From equation 3.4, all coils will have emfs of the same magnitude induced in them, but the phases will differ by 180^0/n. This is illustrated in fig. 3.7 for a 9 coil stator, showing that adjacent coil emfs are 20^0 out of phase with each other.

However, it would not be feasible to connect each coil to its own electrical load in a practical power system - there would be far too many connections, and far too many wires required to transmit the power ! We therefore need to consider other alternatives. The coils cannot be connected in parallel, because the coil emfs are instantaneously different.

What if we try connecting the coils together to form a balanced three-phase supply ?

By definition, the output voltage of each phase would be the same, and so the maximum output power of the three-phase generator would be $3VI_{max}$. This is because the power is maximised when the generator is operating at its maximum allowable current, at unity power factor. The factor 3 is because there are three phases, each of which is supplying VI_{max} power.

Maximum output power is $P_{max}=3VI_{max}$

Now connect coils to give single-phase supply.

The output voltage would then be the sum of the three voltages of the three-phase supply.

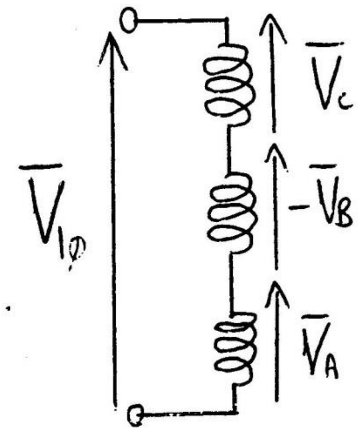

Fig. 3.10

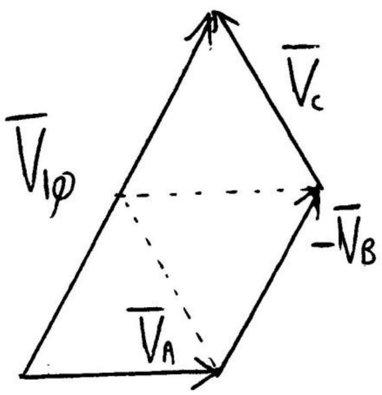

Fig. 3.11

$$\therefore \quad \left|\tilde{V}_{1\varphi}\right| = 2V \text{ and } P_{\max_{1\varphi}} = 2VI_{\max}$$

Conclusion: Only get 2/3 output power of equivalent 3-phase generator !!

Also, power losses are the same in each case, so efficiency is worse for single-phase device.

No. of phases	No. of wires	Output(%)
1	2	66.7
2	3	94.2
3	3	100.
4	4	102.

Now consider what would happen if all the coils were connected in series to provide a single-phase supply. This is equivalent to connecting the three-phase voltage supply so that the three voltages are in series, fig. 3.10. The output voltage of this supply is obtained by vector addition of the voltages, fig. 3.11. This figure shows that the voltage phasors form three sides of a hexagon. Therefore, by considering the 'semi-hexagon' as three equilateral triangles, it is seen that the output voltage of this single-phase supply is twice the voltage of one of the original three-phase voltages. However, the maximum allowable current is still I_{max}, and so the maximum power output of the single phase generator is only $2VI_{max}$.
This means that:
i) for the same physical size of generator the output power is only 67 % of what it would be if the generator had three phases.
ii) for the same power losses the output power is much reduced, resulting in much poorer efficiency.

On the bright side, we only need two connections, and two wires to transmit the power produced, but the price paid is unacceptable.

What about other phase numbers ? The table opposite shows the percentage difference in output when compared with a three-phase generator, and also the number of wires required to transmit the power. Going to a four, five or more phase system only brings about marginal increases in output power when compared to three-phase, but adds additional conductors to transmit the power (table opposite). Consequently, three-phase is a good compromise between these conflicting requirements, and is adopted throughout most of the world.