Chapter 1

Electric power transmission and distribution systems

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1.1 Nature and development of transmission and distribution systems

1.1.1 Nature of transmission and distribution systems

Today, in all countries in the world that utilise electricity as an efficient source of light and energy, some form of a transmission and distribution system exists. Both systems carry electric current, albeit at different voltages and they are connected to each other. They are part of the bulk transport and distribution system that essentially delivers and distributes the electrical energy, converted from primary energy sources, to the end users. The only clear differences between the two systems is based on the perception of their end use and functionality.

Transmission systems provide the bulk transport paths for electrical energy from generation centres located close to the primary energy sources to the major load centres within a large geographical area, thus facilitating economic and efficient bulk power transfer. On the other hand distribution systems are concerned with the delivery of electrical energy to individual customers within a smaller geographical area. In this respect a distribution system may have a number of delivery points to its major load centres, from one or more transmission systems and/or elements of a transmission system, the final shape of the system structure being dependent on the magnitude and the pattern of demand within its geographical area. It is also usual for transmission systems to be interconnected to enable shared economic benefits and operational access to generating capacity.

Generally modern transmission systems transport electrical energy by alternating current (AC) at a frequency of 50 or 60 cycles per second operating at voltages of 220 kV and above, with other standard voltages of 275 kV, 330 kV, 400 kV, 500 kV, 765 kV and 1000 kV. As systems develop, each time a new transmission voltage is added the lowest transmission voltage level reverts to play more of a distribution network role. For example, the 132 kV transmission network developed in the early days in the UK assumed a distribution role after the addition of 275 and 400 kV transmission networks. It is usual for one or more of these standard voltage networks to be employed with transformers connecting parts of the transmission system at each voltage level. Generators with output voltages of around 10–25 kV are usually connected onto the transmission system(s) via generator transformers and directly feed electrical energy into one or more transmission lines. The delivery from the transmission to the distribution systems is via transformers located at substations marking the interface boundary between the two energy delivery systems as shown in Figure 1.1. High voltage direct current (HVDC) up to ± 600 kV is also used for bulk transmission of electricity either over long distances or across sea crossings where AC transmission is either technically or economically possible. The DC transmission is also used for interconnection of two AC systems or areas each operating at a different nominal frequency or for providing an asynchronous interconnection between two AC systems.

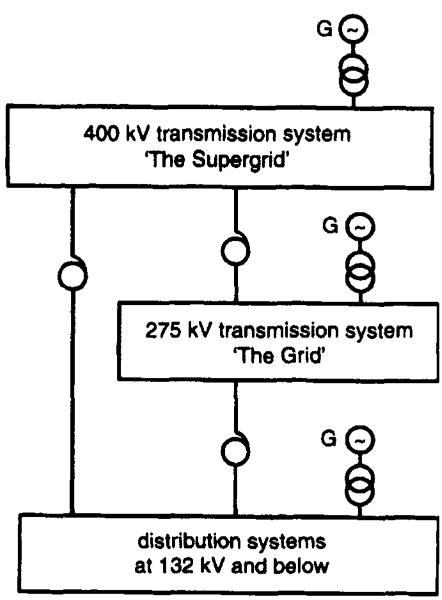

Figure 1.1 The transmission and distribution system structure in England and Wales

Beyond the transmission interface boundary the distribution system is built in a layered structure with each consecutive layer supplying decreasing amounts of power. The primary voltage level for distribution systems is usually around 132 kV, with other standard distribution voltages at 66 kV, 33 kV, 11 kV, 3.3 kV and 2.4 kV with 240/110 V at the customer terminals. The distribution system, at its highest voltage level, is directly connected to the transmission system via one or more transformers with sizes dependent on the magnitude(s) of demand(s) to be supplied. The distribution system also differs from the transmission system in terms of the complexity of interconnectivity between load centres. The complexity in distribution networks arises from the numbers of connections that are required at each voltage level and successive voltage levels, dependent on the distribution of demand and individual customer demand magnitudes. The interconnectivity needs are less pronounced compared with transmission systems as mainly radial feeders are used at lowest demand levels to pool together sufficient magnitudes of demand that can then be secured by connections to alternative supply points. The major power station sites and demand centres which have influenced the structure of the transmission and distribution systems in England and Wales are shown in Figure 1.2.

1.1.2 Early developments (1880–1930)

The basic human need for safe, efficient and affordable light was the primary driving force in the development of electric power systems. In 1882 Thomas Edison initiated first large-scale use of electricity by what became known as 'Edison's Illuminating Companies'. The most famous of these was the Pearl Street System, which was a system comprising of a

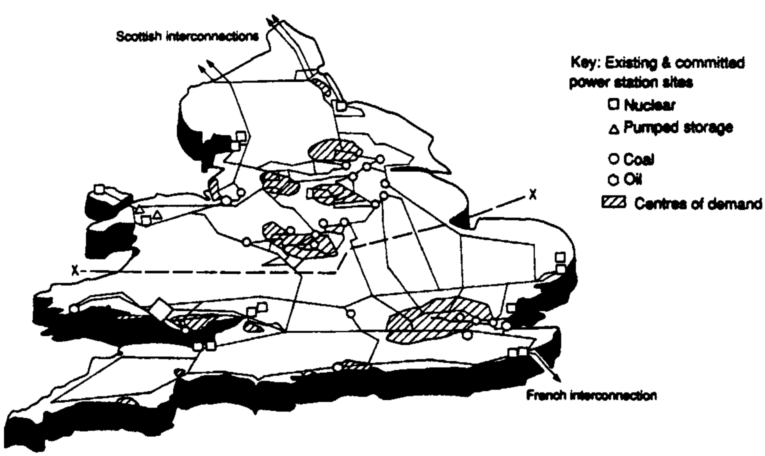

Figure 1.2 Major power station sites and centres of demand

load of approximately 400 incandescent lamps invented by Edison each consuming about 83 W, and provided electric lighting for Lower Manhattan.

At about the same time in England, the Holborn Viaduct Generating Station, constructed under the provisions of Electricity Lighting Act 1882, provided 160 kW of power for customers who had mixed lighting and motor loads. It is worth noting that both these systems relied on DC generation with the power being directly distributed by underground or surface laid cables. Under the 1882 Act any local authority, company or person licenced by the Board of Trade could install a supply system, and an individual consumer had the right to demand a supply without discrimination between consumers.

Throughout the first decade of the electric lighting age, the demand for electricity grew at a phenomenal rate, but towards the end of the 19th century came the revolution which influenced the way in which electricity has since been generated and transmitted. Up to this point in time, many industrial drive systems, including the direct current generators, had been powered by steam engines or complicated mechanical linkages to water wheels. This resulted in the majority of industry dependent on electricity being sited close to riverbanks and bringing its associated pollution problems.

There had been a lot of debate on the merits of DC and AC generation and transmission. However, with the invention of the transformer and the induction motor, the advocates of AC generation and transmission prevailed, and gradual development of AC transmission systems started in 1896 with the 25 Hz three-phase generation and transmission system from Niagara to Buffalo in USA.

Gradually, in towns and cities all over the industrial world, generating stations were developed to a point that they were able to supply the demand within their own area. This, however, resulted in a situation where each electricity authority defined their own parameters of supply, such as frequency and voltage.

At the turn of the 20th century, electricity began to be regarded as a product and service that should be available to all. Thus its generation and distribution became the subject of debate between the authorities/companies who produced and sold electricity and their respective Parliament, who laid down the laws for all industry.

There had also been a lot of debate on the fossil fuel reserves available to the electricity industry and on the effects of pollution, which was excessive in urban and new industrial conurbations. In 1918, the Williamson Committee in the UK reported to the President of the Board of Trade that 'the cheap supply of electricity, on town conditions in particular, would be most marked. The reduction of pollution by smoke would result in a lower death rate from bronchial diseases'. The Committee also recommended that the concentration of larger generation units in fewer and bigger power stations was the only solution to reducing the costs of electricity to industry to an absolute minimum. The need for more efficient power stations to help conserve fossil fuel reserves was also recognised. However, lack of compulsory powers in the 1919 Electricity Act handicapped progress at the required scale.

Along with this report and many others produced for the government of the day, it was soon realised that something was going to have to be done to the electricity industry to ensure its efficient, economical and effective development. These extensive debates had sown the seeds for the development of electric power systems for 'overall public benefit' in the industrialised nations on both sides of the Atlantic. Lord Weir, a leading UK entrepreneur in his time, was invited to head a committee to investigate 'the national problem of the supply of electrical energy' by the newly elected Conservative government in 1925. Weir completed his report in four months and considered three ways in which the electricity supply industry might operate. These three suggestions were:

1. Power could be bought and sold by a 'Transmission Board', buying only from the cheap suppliers and allowing inefficient plant to close down.
2. A 'Transmission Board' would act as a carrier for electrical power and leave the buying and selling negotiations to the producer and purchaser.
3. The control of all generation should be brought under the Transmission Board.

All of these suggestions were rejected by the government of the day. Nevertheless it is interesting to note that the present structure of the present UK Electricity Supply Industry is in fact based on a combination of these recommendations. The additional recommendation of the Committee that was finally adopted for implementation was the establishment of a 'Gridiron' of high voltage power lines covering the whole country.

1.1.3 Development of the transmission grid concept

A public corporation, the 'Central Electricity Authority (CEA)' was formed under the Electricity Supply Act 1926 to erect the necessary transmission lines that would interconnect a limited number of 'selected' power stations where generation of electricity would be concentrated. The Board would purchase the output of the selected stations and sell it on to the local distribution undertakings. For the first time in the UK, customers benefited from the use of the cheapest power generation stations supplying their electrical energy needs. Between the Electricity Supply Act of 1926 and the Second World War, the idea of 'public ownership' or 'nationalisation' of the Electricity Supply Industry increasingly gained favour. In 1934, the Fabian Society produced a document entitled 'The Socialisation of the Electricity Supply Industry'. The principles advocated by this document, whilst causing concern amongst the municipal companies and being regarded as radical, were adopted in the 1947 Electricity Act. The existing 560 generation and distribution undertakings in England and Wales were formed into a single Generation Board, the 'British Electricity Authority (BEA)', responsible for bulk generation, transmission and central co-ordination/policy direction, with 12 'Area Electricity Boards' responsible for retail distribution of electricity to customers.

The first transmission grid system, operating at 132 kV (shown in Figure 1.3), was planned and built in the early 1930s and interconnected major generating sites in England and Wales by 1948, as shown in Figure 1.4. Over the first decade or so of nationalisation, the central planners of the industry had many claims of poor project management laid at their feet for the inability to build new power stations. Demand was growing so fast that proposals were put forward to divide the grid system into three sections.

Arguments for and against this were many, but the then President of the Institution of Electrical Engineers, T.G.N. Haldane, suggested an increase in the grid voltage. Economic studies carried out then, which are still applicable today, showed that it was cheaper to build power stations on the coalfields and transmit the electricity via high voltage lines.

Figure 1.3 The 132 kV grid system in 1934

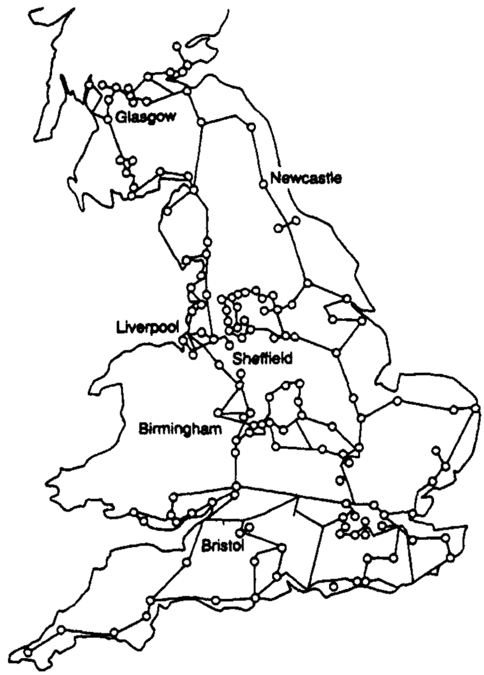

Figure 1.4 The 132 kV transmission system in 1948

Common sense prevailed, and plans for the construction of the '275 kV Supergrid' [1] were put forward in the early 1950s and were implemented by the publicly owned 'Central Electricity Generating Board (CEGB)', which under the Electricity Act 1957 took the responsibility for bulk electricity generation and transmission from CEA. At the same time the 'Electricity Council' taking the co-ordination role from the BEA, was formed. Generating stations with larger capacities were built, and these tended to be concentrated around the coalfields and close to large rivers, which facilitated easy access to their fuel and cooling water needs.

By the early 1960s it became evident that even the 275 kV supergrid system, shown in Figure 1.5, would not be capable of carrying the predicted power flows, and plans for the construction of a further supergrid at 400 kV were accepted [2, 3]. The progress in the construction of this supergrid to adequately address the electrical energy transmission needs in England and Wales is illustrated in Figure 1.6.

While these vast changes to the transmission system within the UK progressed there was very little change to the distribution system structures. The 12 nationalised regional distribution companies formed at the same time as the CEGB took power from the major transmission bulk supply points close to their load centres and distributed it to individual

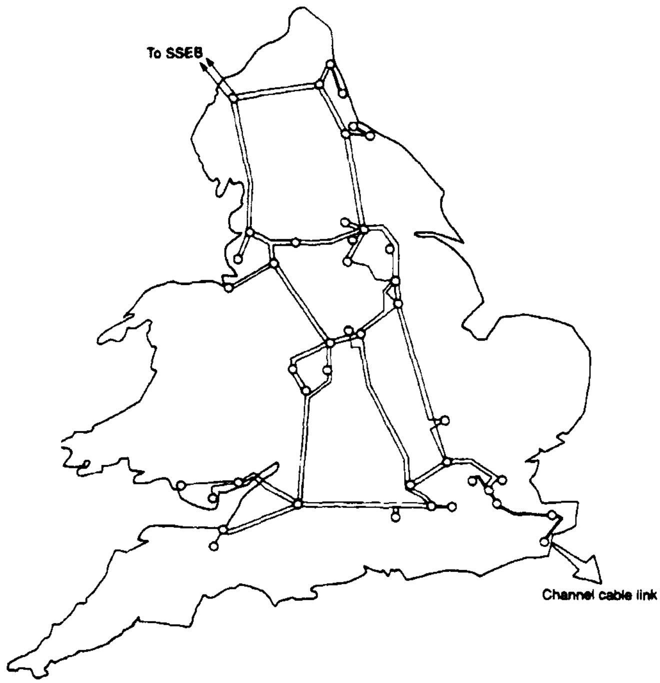

Figure 1.5 The 275 kV system in 1961

customers. The largest change to the distribution systems was in the number of customers now connected to an electricity supply. In 1948, approximately 9½ million domestic premises or one-quarter of the domestic properties in the UK were connected to a supply of electricity. By the way of comparison this figure had risen to 20 million domestic premises in 1989 [4]. In the same period, domestic electricity consumption alone had risen from 11 TWh to almost 80 TWh.

Elsewhere in the world electric power transmission systems developed along similar lines largely influenced by the availability and location of the primary fuel resources in relation to major load centres. Availability of hydro resources far from load centres led to development of sophisticated high voltage long distance AC and DC transmission systems, while in countries with population centres separated by large distances development of integrated generation, transmission and distribution systems based on locally available primary energy resources gained favour. These regional systems were interconnected to other similar systems at a later stage to enable sharing of accruable financial benefits. The need for long distance transmission revived the fortunes of high voltage DC transmission as the developments in technology increased its reliability and economic competitiveness for a wider spectrum of transmission applications in the late 1960s.

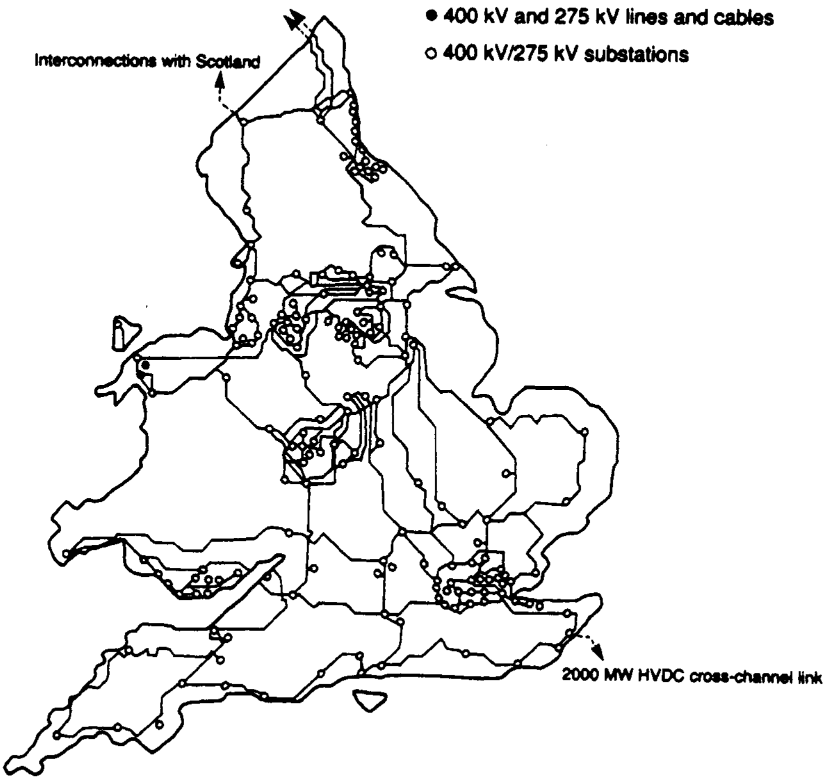

Figure 1.6 The National Grid system today

Thus the 'overall public benefit' concepts [5] developed in the first quarter of the 20th century led to the development of transmission and distribution systems which were:

(i) optimum for a large region or country and not just for a specific region or area
(ii) based on technology to optimally meet public needs over a long time spectrum counted in at least a quarter to half a century in terms of the longevity of its capital equipment
(iii) to present least cost penalties in the development of associated generation and distribution systems
(iv) of sufficient reliability to justify public dependence and confidence
(v) at an overall cost to meet the public need and interest.

Across the world the development of transmission systems broadly followed four distinct stages:

(i) *isolated plant stage (1885–1910)* – where isolated generating plant fed a specific local area

(ii) *individual systems stage (1910–1935)* – where isolated plant based systems around a major population centre were connected to each other
(iii) *regional/national systems stage (1935–1960)* – where individual systems were connected
(iv) *inter-regional/international systems stage (1960–1985)* – where AC and DC interconnections between a multiplicity of systems were developed and will continue in the foreseeable future.

The transmission developments went ahead due to one or more of the following 'diversity factors' offering more optimal use of assets for 'overall public benefit':

- demand
- outage
- fuel source
- generation capacity and transmission outage risk
- generation and demand uncertainty.

The transmission developments produced both public and private company benefits arising from the pooling of generation capacity, generation reserves, scheduling of lowest cost generating plant, making best use of available plant sites and achievement of better supply security at near optimum cost. These developments also enabled management of the security of supply under adverse primary fuel supply conditions resulting from a prolonged coal miners' industrial dispute experienced in mid 1980s [6]. The electricity industry structure which progressed all the transmission and distribution developments in England and Wales, between 1957 and 1990, is illustrated in Figure 1.7.

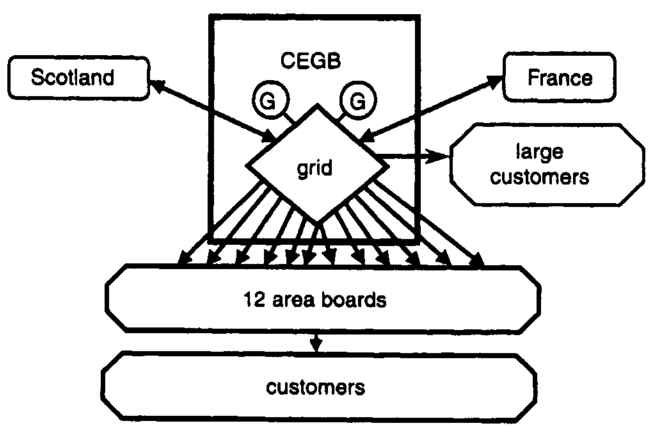

Figure 1.7 The electricity industry structure in England and Wales from 1957 to 1990

1.1.4 Recent developments

The 1983 Electricity Act conferred new rights to privately owned generation companies to:

(i) construct new or extend their existing power stations
(ii) secure purchase of their electricity by CEGB or an Electricity Board
(iii) secure their use of the transmission and distribution system.

Under this act the CEGB and the area boards were obliged to set use of system tariffs and provide access to their systems as well as purchase the electricity produced by the private generators. The governmental and European Community ban on extensive use of natural gas for generation of electricity meant that there was no great rush of private capital to construct large and high capital cost coal, oil or nuclear power stations. In addition complex tariff structures for the purchase of the generated output and use of system did not provide any incentives.

In February 1988 the government published proposals to privatise the electricity supply industry by separating the ownership of the generation, transmission and distribution by:

(i) ending the CEGB's monopoly in generation through splitting its generation activities into separate companies
(ii) ending the CEGB's obligation to provide bulk supplies of electricity
(iii) permitting existing and potential private generation companies to operate on the transmission and distribution systems
(iv) maintaining the transmission activities as the National Grid with the retained central role in scheduling and dispatch of generation
(v) privatising the 12 area boards as 12 distribution companies each with an obligation to supply in its area with rights to generate.

The privatised electricity industry structure shown in Figure 1.8 became effective from 31 March 1990. It is interesting to note that this structure is basically the same as that set out in the Weir Committee Report of 1925 and as amended by the Fabian Society Report of 1934.

Thus although the assets of the transmission and distribution systems and their main functionality remained the same, the concept of electricity trading over these assets have altered from a 'monopoly wholesaler/monopoly retailer' to 'competition in generation and supply via regulated monopolistic transmission and distribution assets' at the customer interface. Competition in generation and supply, together with regulation promoting competition in areas of natural monopoly, i.e. transmission and distribution, are the key factors towards driving down the cost of electricity to the customers.

As the 'owner and operator' of the high voltage transmission system in England and Wales, the National Grid Company (NGC) operates within a demanding framework of statutory and regulatory requirements. Its two major obligations under the 1989 Electricity Act are to:

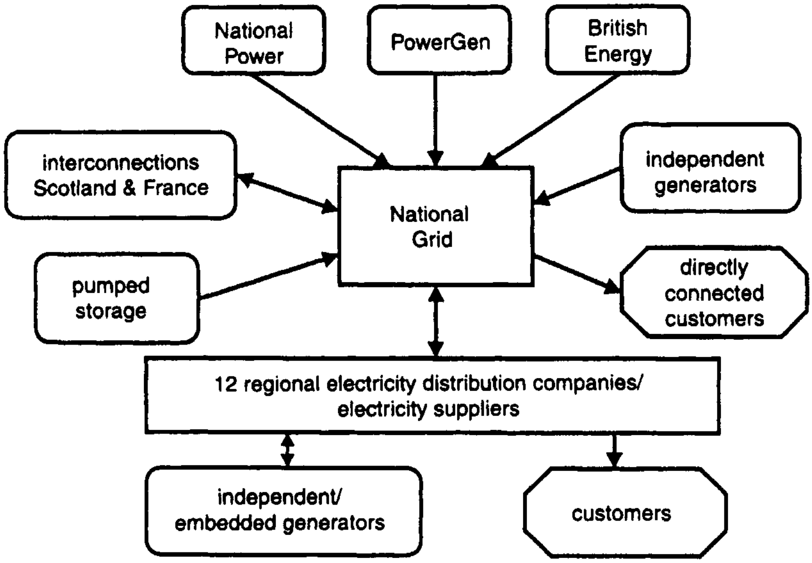

Figure 1.8 *The current electricity supply industry structure in England and Wales.*

(i) develop and maintain an efficient, co-ordinated and economical transmission system
(ii) facilitate competition in the generation and supply of electricity.

These obligations are specified in detail in the transmission licence, which requires NGC to:

(i) schedule and despatch available generation in merit order to meet demand
(ii) establish, implement, comply and ensure compliance with a grid code
(iii) develop and operate the transmission system to meet defined security and quality of supply standards, including statutory levels of system frequency and voltage
(iv) contract for ancillary services (reactive power, MW reserve, black start) from most economical sources to meet system security requirements
(v) set nondiscriminatory connection and use of system charges within regulatory framework
(vi) set charges for the use of interconnectors based on return on capital
(vii) administer the settlements process, particularly the complex computer systems needed to calculate payments due as a result of daily trading in the electricity market or 'pool'.

It was recognised from the outset of the industry restructuring process that freedom of access to the transmission and distribution systems would be the key to effective competition in generation and supply. Major national and international debates on the practicalities of ensuring open transmission access have taken place since and still continue particularly on ensuring adequate technical co-ordination between different entities within the structure and maintaining the security of supply.

In England and Wales, the overriding aim has been to provide a 'level playing-field' such that the would-be entrants to the electricity market, irrespective of location or size, are able to connect to and use the transmission system without discrimination or privileges in rights of access. Thus NGC was set up to be operationally independent of generators, suppliers and all users of its system. It was also set up to earn sufficient revenue from the operation of its energy transport system to ensure the capability to invest in new connections, reinforcements and maintain existing assets to required standards and to earn a reasonable return for its shareholders.

Transparency of information is essential to create the right conditions for open access to the transmission system. Therefore NGC is obliged to make available to existing and prospective users of the transmission system detailed information including:

(i) *annual statement of charges* for connection to and use of the transmission system
(ii) *seven year statement* – NGC's annual snapshot of the development of the system in each of the seven years ahead, which provides essential background information for investment decisions by generators and suppliers
(iii) *the Grid Code* – comprehensive technical and operational requirements for all plant connected to NGC's system and for NGC's own plant which helps to guarantee access for all users without discrimination.

NGC is obliged by its licence to provide access to its transmission system to all parties who agree to abide by the Grid Code and to pay appropriate charges for their use of the transmission system. Devising equitable charges which accurately reflect the costs of providing the NGC transmission system has been a major challenge, bearing in mind that before the 1989 Electricity Act transmission and generation were operated as an integrated system, the costs of which were recovered through a single, uniform tariff.

NGC's use of system charges seeks to reflect the investment costs of providing a system which can accommodate the bulk power transfers which result from regional/local imbalances between generation and demand in England and Wales. Zonal differentials in the charges aim to create financial incentives for generators to locate new plant near to load centres where there is inadequate generation, and conversely for demand to locate in zones where there is currently a surplus of generation. The transmission charging principles are regularly reviewed to ensure appropriate financial messages to the users.

Although NGC provides both technical and financial messages to the users on the optimum areas of the system for the location of new generation and demand, it is, nevertheless, obliged by its licence to provide connection to, and use of, the system to *any applicant*, irrespective of their locational choice. Furthermore, technical and financial terms for connection to the system need to be provided within three months of application by a prospective user – a dramatic change from past practice. The demands of the new commercial environment require multidisciplinary teamwork practices, bringing together engineers, lawyers, accountants and economists to ensure a timely and effective response to customer needs.

Since transmission and generation development in England and Wales is no longer centrally co-ordinated, NGC must plan and operate its system, without full knowledge of the intentions of its customers. In contrast with new connections, which may be signalled to NGC some years in advance, closure of older power stations can take place at short notice. This new background of uncertainty, together with regulatory controls on income, means that the need for new investment in the transmission system is subjected to more rigorous scrutiny than ever before and more effort is focused on making existing assets work harder.

Where the need for new investment is established, procurement practices have changed significantly towards greater flexibility and innovation in transmission system engineering. As an example, NGC is increasingly investing in both traditional and new technologies, e.g. mechanically switched reactive compensation, quadrature booster transformers, static VAr compensators (SVCs) and 'flexible AC transmission systems (FACTS)' technologies, for controlling the power flows arising from the continuously changing generation and demand pattern. Application of these technologies also enables deferment or removal of the need for certain costlier system reinforcements. Wherever there is a clear cost benefit, transmission line reconductoring, live line working techniques and on-line capability monitoring equipment is utilised to improve the availability of transmission equipment, enabling more efficient and flexible use of the transmission system.

The reorganisation of the industry has also put similar pressures on the 12 privately owned 'regional distribution companies' operating the distribution systems. This led to a separation of providing the 'wires' to ensure flow of electricity to the customer on demand and the 'supply' function concerned with the customer being provided with the quality of service level of his choice from a supplier of his choice. The technical design and operation of the wires are subject to rules in the 'Distribution Code' that has been developed along parallel lines to the Grid Code, any subsequent changes in the rules being reflected, in many cases, simultaneously in both codes. Regulatory pressures to drive the cost of supply to the customer down has affected both functions of the distribution businesses.

When the Government initially announced the new industry structure separating ownership of generation, transmission and distribution there was concern that the security of the supplies might be undermined. Since the restructuring of the industry, however, the new structural arrangements have been dramatically tested on a number of occasions, demonstrating that there has been no reduction in supply security levels.

System security has been maintained despite the unbundling of the industry because:

(i) all users of the transmission and distribution systems, as a condition of access, agree to abide by the technical and operational rules set out in the Grid Code and the Distribution Code
(ii) NGC and distribution companies continue to plan and operate the transmission and distribution systems according to the standards of security observed by their predecessors, the CEGB and the area boards
(iii) as a condition of its licence, NGC purchases the ancillary services (reactive power, black start capability and reserve) which are needed for maintenance of system security and stability, from generators.

However, the most important factor is that all companies in the industry generators, suppliers and transmission/distribution network operators have a vested interest in ensuring a high quality of supply to customers.

1.2 Structure of transmission and distribution systems

Several key factors heavily influence the development and operation of the electricity transmission and distribution systems.

First, since electricity cannot be stored, the electricity generated must continually be adjusted to meet the continually varying demand, plus the system losses. Failure to maintain this balance results in a change in system frequency, which could in turn result in widespread demand loss across the system. It is the role of the control engineer to continuously meet the demand by scheduling sufficient generation to maintain the system voltage and frequency. An illustration of the dimensions of this task is given in Figures 1.9 and 1.10, which show the impact of major events on demand and typical seasonal demand curves for England and Wales.

Second, the demand for electricity is growing as illustrated in Figure 1.11. Although in some parts of the world electrical energy consumption may have slowed down or reversed into decline during certain periods, the

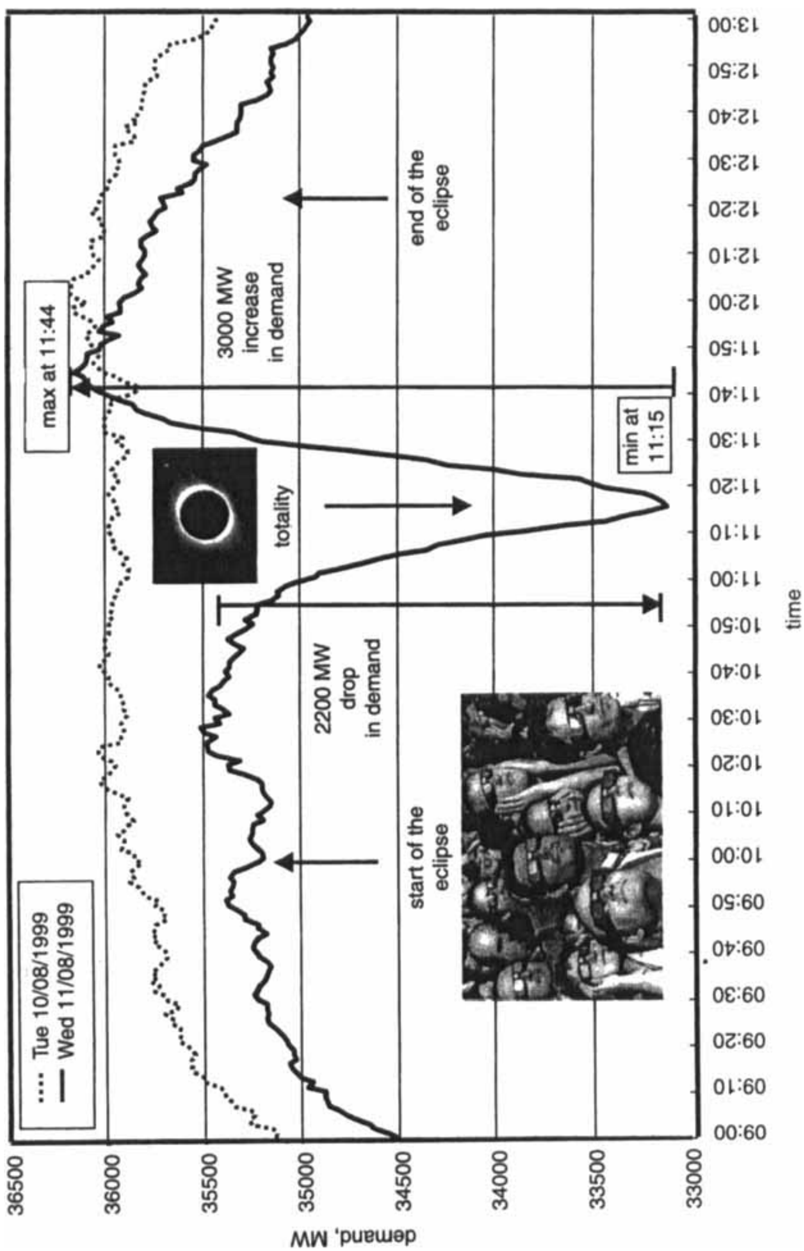

Figure 1.9 Effect of the total solar eclipse on NGC demand, 11 August 1999

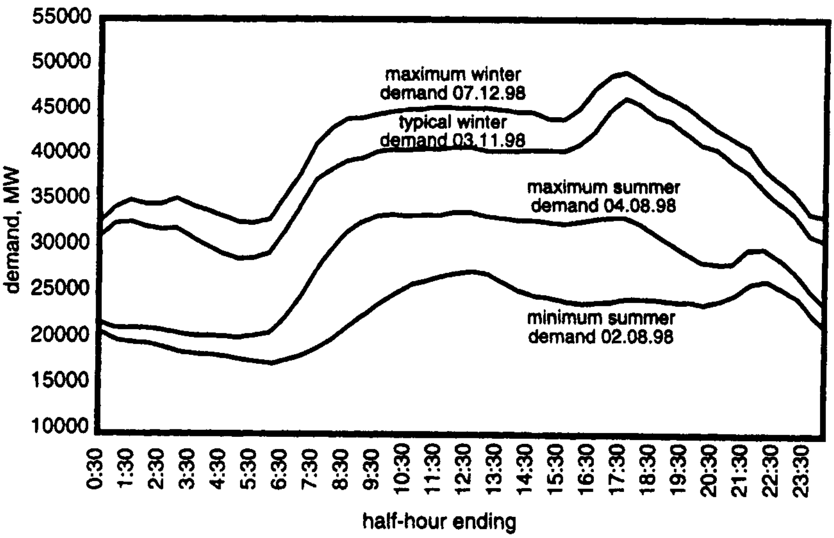

Figure 1.10 Typical seasonal power demand variations

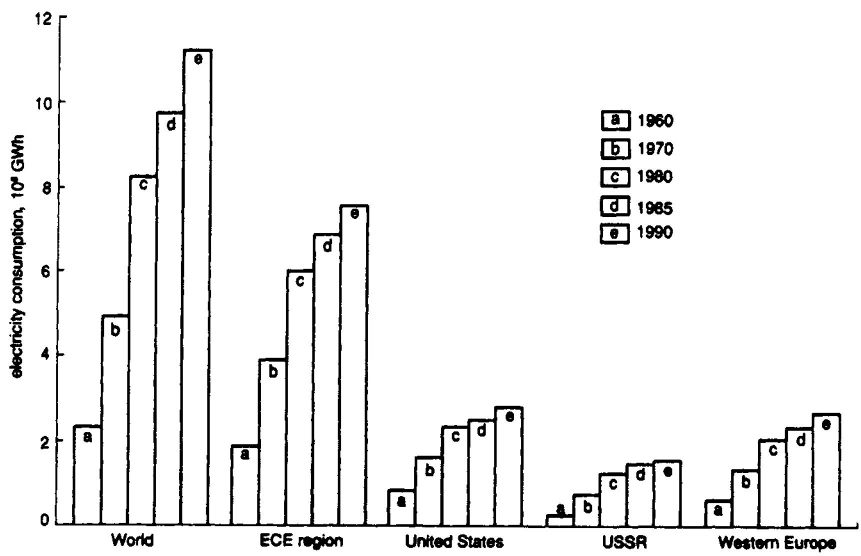

Figure 1.11 World and regional consumption of electricity, 1960–90. ECE–United Nations Economic Commission for Europe

Source: Annual Bulletin of Electric Energy Statistics for Europe, 1992 (United Kingdom) overall trend still shows annual increase in the 1 to 10% range for countries with mature and growing economies, respectively. This means that the transmission and distribution system planners have to accurately anticipate this growth several years in advance to ensure that the networks are capable of meeting the increased requirements. Furthermore, the long economic life of the transmission and distribution equipment requires particular attention to selection of investments and technologies best suited to meet the system need over such periods.

Finally, since electricity is generated from primary fuel sources, the nature and location of these resources is an important factor in influencing the structure of a transmission and distribution system. This is due to the fact that transportation of energy in the form of electricity over high voltage lines is more economic than the transportation of other primary energy sources. Large power stations also have a requirement for large amounts of cooling water for use within the steam cycle and thus tend to be sited on the coast or by large rivers. Furthermore, other environmental factors such as emissions of harmful gases and acceptability of certain types of structures in the countryside are increasingly playing an important part in the siting, physical characteristics and installation principles of generation, transmission and distribution systems.

1.2.1 Typical characteristics of transmission and distribution systems

The modern AC transmission and distribution systems transport the electricity generated at a frequency of 50 or 60 Hz from the generators connected via generator transformers. The choice of either frequency was governed by the necessity to ensure that there is no annoying visual flicker in incandescent lighting. This choice was also compatible with the manufacture of transmission and distribution equipment based on technologies at near optimal overall cost to meet public needs and present least cost penalties in the establishment of such systems (see Section 1.3). The DC transmission systems within the AC transmission utilise convertors at their points of connection with the AC system. These operate in the rectifier mode for conversion to DC and inverter mode for reconversion back to AC. Due to the specific capabilities of the convertors the DC connections are capable of connecting two AC systems operating at different nominal frequencies or providing asynchronous connection between the systems.

One of the most important characteristics of a transmission or distribution system is the security of supply which, by implication, means a supply of electricity which is continuous and of the required quantity and quality, especially in terms of frequency and voltage. This in turn means that the generation, transmission and distribution systems have sufficient in-built flexibility to maintain supplies under conditions of plant breakdown or weather induced failures for a wide range of demand conditions.

The frequency of the system is governed by the speed at which the generating plant operates. The quality of the frequency generated is conditional on the transmission system operator scheduling sufficient generation to meet the demand plus the losses of the transmission and distribution systems. This quality is further assured by holding generation in reserve for immediate availability in the event of unplanned plant losses. In this way, the level of the frequency can be maintained to pre-determined levels. In the UK, the statutory frequency is 50 Hz with ±1% permitted variation. The DC interconnection with France provides an asynchronous connection in that the systems at either side of the connections are isolated from the frequency variations in the other system.

The other important characteristic of transmission and distribution systems is the voltage quality which is also governed by the generating plant. Whilst the frequency of a system will be substantially constant at all points, the voltage levels will differ at different locations on the system. This difference is governed by the capacitive and inductive characteristics of the 'wires', i.e. the overhead lines and underground cables, forming the systems and the customer demand. At times of low power flow through the wires, the capacitive effect dominates and causes the voltage at the end of transmission and distribution lines to rise. At times of high power flow, the inductive effect dominates and the voltage tends to fall along the length of a line. Through the installation of capacitive or inductive compensation plant termed 'reactive compensation' it is possible to limit variations in voltage beyond pre-defined limits. This ensures that the customer equipment does not suffer any undue interruptions and the customer does not have to invest undue amounts in purchasing equipment designed to operate over very wide voltage variations. Statutory voltage variations permitted on transmission and distribution systems are usually around ±5% and ±10%, respectively. The manual and automatic control facilities put in place to achieve compliance with these performance criteria are shown in Figure 1.12.

The above technical principles and characteristics are applicable to virtually any transmission and distribution system around the world. The only difference between transmission and distribution utilities is related to the organisational structures of the companies which control the various types of systems.

1.2.2 Organisational structures of transmission and distribution systems

In essence, the electricity supply industries or utilities around the world based on their structure and ownership can be classified under four main headings:

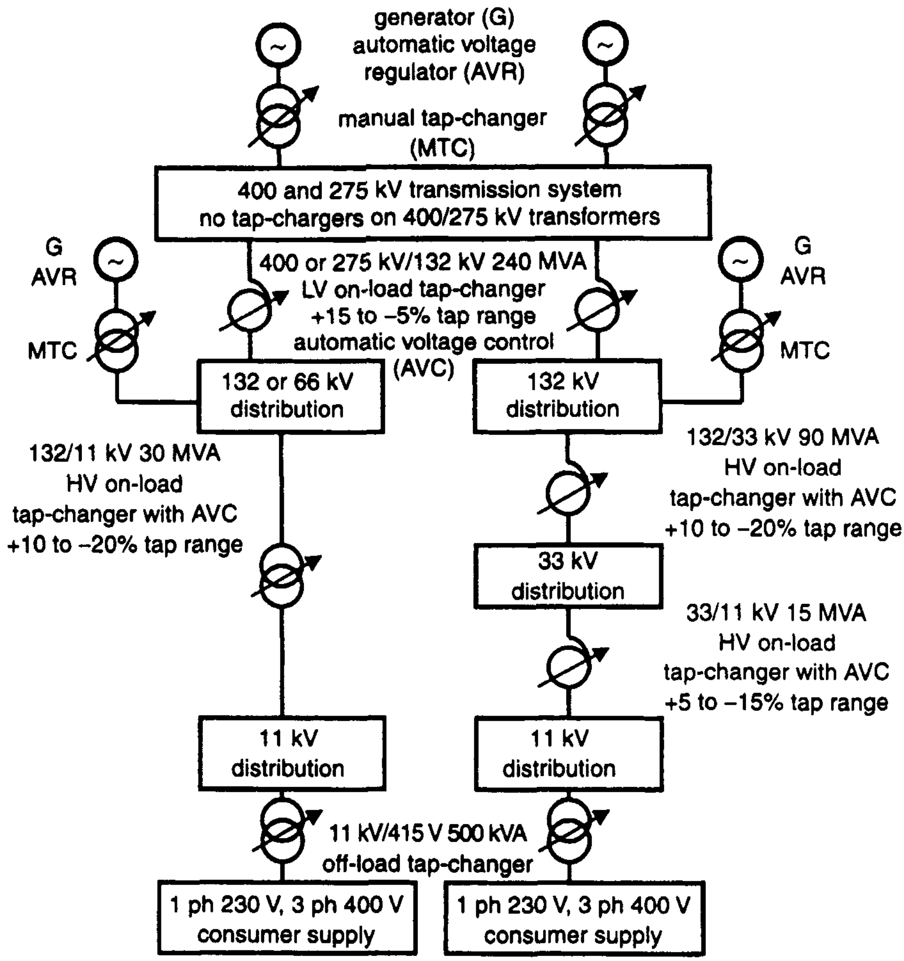

Figure 1.12 Transmission and distribution system voltage control facilities

- vertically integrated
- horizontally separated
- privately owned
- publicly owned.

In a vertically integrated industry, the whole industry, i.e. generation, transmission and distribution is controlled by a single authority. This authority may be wholly or partially owned publicly or privately. Essentially it is able to carry out integrated generation, transmission and distribution planning and operation within a defined geographical area. Currently within the UK, the only vertically integrated electricity utilities are in Scotland and Northern Ireland. These entities are privately owned.

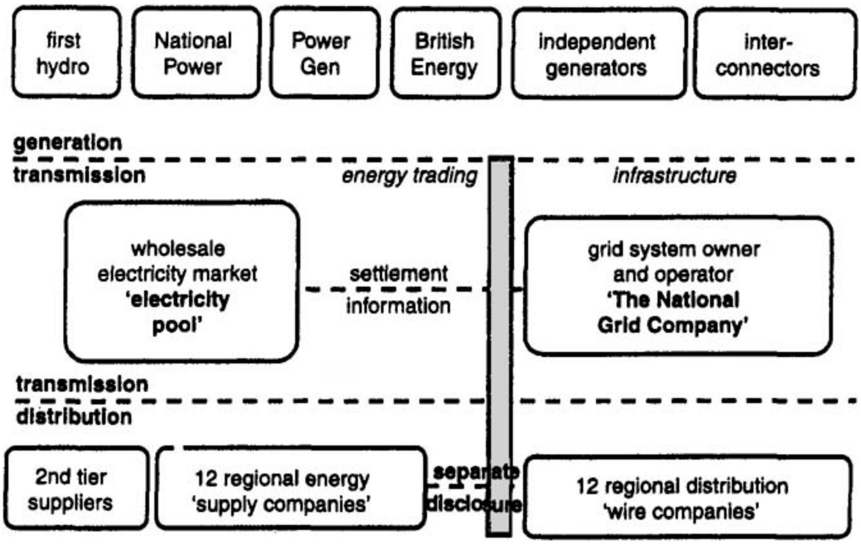

Figure 1.13 *Electricity supply industry structure in England and Wales since 1990 – energy trading and infrastructure*

At present Électricité de France and ENEL (Italy) are typical examples of publicly owned vertically integrated utilities.

For the privately owned utility companies that are vertically integrated within a certain geographical area the regulatory pressures on the 'natural monopolies' of transmission and distribution result in a clear definition of the costs of each part of the company activity. The traditional single tariff structures in the publicly owned vertically integrated utilities are not designed to clearly differentiate between the costs of generation transmission and distribution activities. Cross-subsidies between these activities are also more common in such utilities.

The electricity industry structure in England and Wales, with both energy trading and transmission/distribution infrastructure components, shown in Figure 1.13, is horizontally separated by virtue of privately owned generation, transmission and distribution companies being separated from each other. This method allows for the private ownership of all or parts of each function in 'wires' and 'supply'. However, it is the independence of the transmission utility from all others that tends to be the essential mechanism by which a horizontally separated system structure operates in a secure and economic manner. The natural pivotal role of a transmission company is to provide a transmission and operational infrastructure by which power can be securely transported across the system and hence facilitate the trading between generators, distributors and suppliers. This also allows access for other interconnected electricity utilities outside the immediate geographical area. Two further models

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of horizontally separated industry structures implemented around the world are shown in Figures 1.14 and 1.15 for Argentina and State of Victoria, Australia, respectively.

Transmission system interconnections extend customer access to more sources of electricity supply. Availability of technologies at

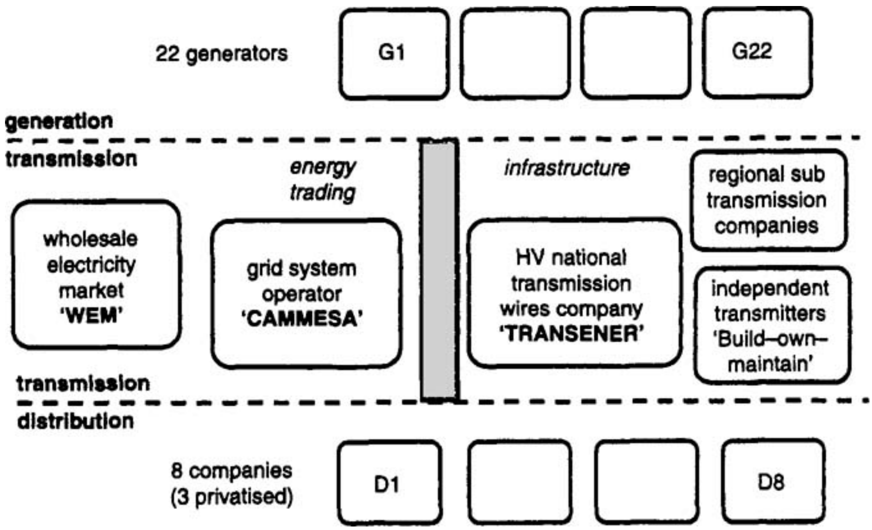

Figure 1.14 The new electricity industry structure in Argentina

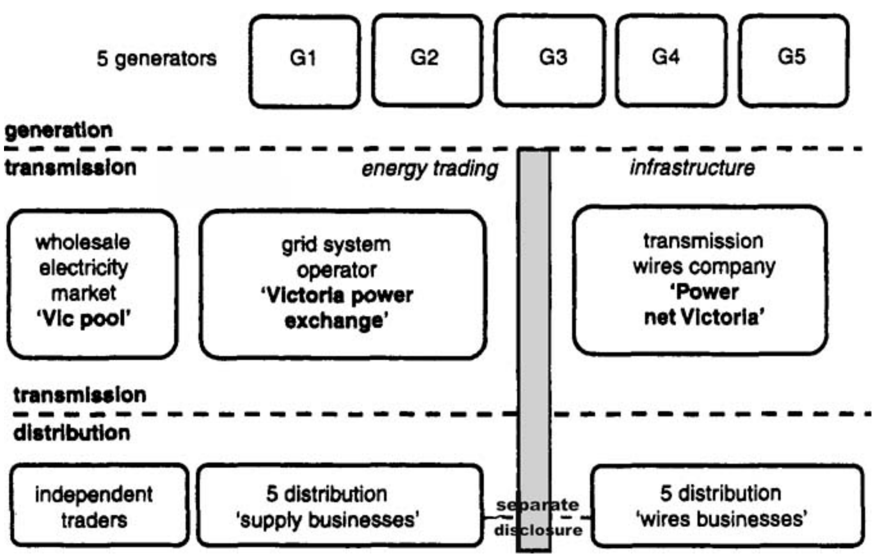

Figure 1.15 The new electricity industry structure in State of Victoria, Australia