E4.39

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2004

EEE PART IV: M.Eng. and ACGI

ENVIRONMENTAL & ECONOMIC ISSUES IN POWER SYSTEMS

Thursday, 29 April 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

Corrected Copy

All questions carry equal marks

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible	First Marker(s) :	B.C. Pal, D. Popovic
	Second Marker(s) :	D. Popovic, B.C. Pal

[4.39]

1. (a) Write a 500-word essay on 'The Energy Consumption in the UK' focusing on overall primary and final energy consumption and factors affecting changes in consumption. [8]

   (b) Outline the principle of operation of a gas turbine. What are the ways to increase a gas-turbine power plant efficiency? [6]

   (c) A summer camp is located near a 16.7m waterfall. Tests show that the stream delivers a minimum of 7.645 m^3/min in the course of a year. It is proposed to install a 3-phase induction motor and drive it as a generator. Calculate the approximate power of the motor in kW that could harness 80% of the capacity of the falls. [6]

2. (a) Describe the principle of operation, main characteristics, use, advantages and research needs of microturbines. [10]

   (b) Discuss briefly the basic concept of harnessing power from the wind, and the main advantages and disadvantages of using wind power to generate electricity. [10]

3. (a) What are the main reasons for introduction of markets in electricity industry? [5]

   (b) Write a 900-word essay on the Nord Pool vs NETA. Describe their main characteristics and differences in terms of market structure, operation and pricing. [10]

   (c) What is market power? Explain why and how the presence of market power can influence the efficiency of market operation. [5]

[4.39]

4. Every item in column I in the following table has only one matching item in column II. Associate with each item in column I the relevant item from column II, e.g. if item [1] in column I relates to item [C] in column II, then write **[1]⟶ [C]**.

I	II
[1] In the context of OPF, the loads P and Q	**[A]** is purely inductive
[2] In DC load flow, the Y-bus	**[B]** are assumed fixed parameters
[3] Static Var Compensator (SVC)	**[C]** deals in linear objective
[4] Line MVA limits	**[D]** are state variables
[5] Lagrange parameter vector λ in OPF	**[E]** imposes limit on control variable
[6] Constraining transformer tap movement	**[F]** employs thyristor switching technology
[7] Unified power flow controller (UPFC)	**[G]** employs GTO switching technology
[8] Newton's method in OPF formulation	**[H]** independently controls of P and Q through lines
[9] Static Series Synchronous Compensator (SSSC)	**[I]** are treated as control variables
[10] Interior point method in OPF formulation	**[J]** deals in non-linear objective
	[K] are taken as constraints in OPF
	[L] are related to bus incremental costs

[20]

[4.39]

5. (a) What is *loop flow* in an interconnected system? What consequence does it have on operational efficiency of the network? [5]

   (b) What is thermal capacity of a line? Is it possible to load a 500 miles long, 400 kV line to its thermal limit without any control or compensation? [5]

   (c) What are the structural and functional differences between a thyristor controlled series capacitor (TCSC) and a static synchronous series compensator (SSSC)? [5]

   (d) Discuss various technical benefits of FACTS technology. [5]

6. (a) Very briefly describe the applications and benefits of optimal power flow (OPF). [5]

   (b) In the context of OPF, outline various limits associated with control and state variables. [2]

   (c) Figure 6.1 describes a 3-bus power system model. The load at bus 3 is $(3 + j1.5)$ p.u. The generation at bus 2 is fixed at 1.5 p.u. All the bus voltage angles are expressed with respect to that of swing bus, i.e., bus 1. The line parameters are shown in the diagram. For an objective of minimising total power loss in the system:

      (i) Identify state variables (**x**), control variables (**u**) and fixed parameter (**p**) vectors. [4]

      (ii) Formulate the objective function f(**x,u,p**), constraint vector function **g(x,u,p)** with the variables and network parameters. The following general formulae can be used for calculating flows out of any bus k in an N bus power system:

$$P_k = \sum_{m=1}^{N} V_k V_m [G_{km} cos(\theta_k - \theta_m) + B_{km} sin(\theta_k - \theta_m)]$$
$$Q_k = \sum_{m=1}^{N} V_k V_m [G_{km} sin(\theta_k - \theta_m) - B_{km} cos(\theta_k - \theta_m)]$$

      where $Y_{km} = G_{km} + jB_{km}$. [5]

      (iii) Find the expressions $\frac{\partial f}{\partial \mathbf{x}}$ and $\frac{\partial f}{\partial \mathbf{u}}$ and evaluate them around an operating point $V_1 = V_2 = 1.05\,p.u, V_3 = 0.99\,p.u$ and $\theta_1 = 0^0,\ \theta_2 = 4.4642^0,\ \theta_3 = -3.4317^0$. [4]

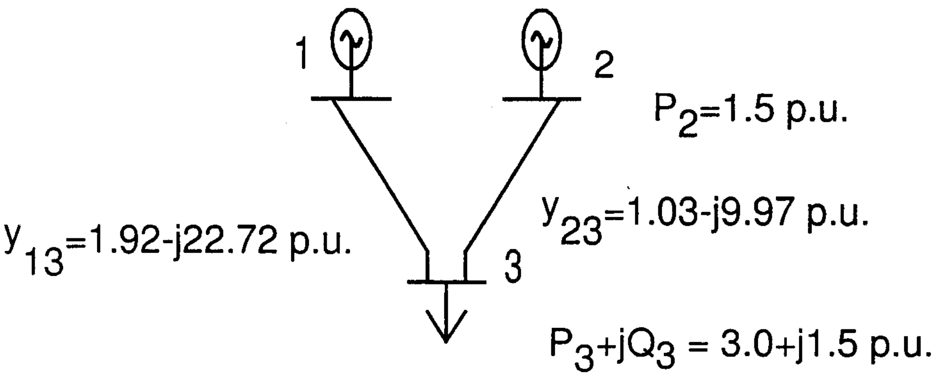

Figure 6.1

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IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE
UNIVERSITY OF LONDON

Department of Electrical and Electronic Engineering

Examinations 2004

MODEL ANSWERS

E 4.39 Environmental and Economic Issues in Power Systems

Authors: Dr D.Popović and Dr. B. Pal

1 (a) (Bookwork ; www.dti.gov.uk/energy/)

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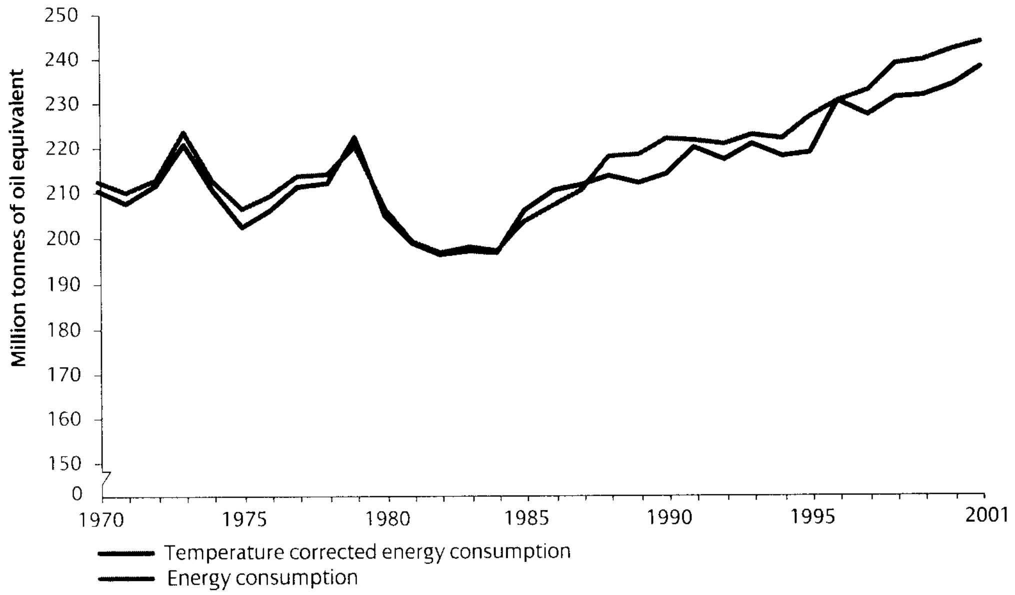
Overall energy consumption

1.1 Energy consumption in 2001 was higher than in any other year over the last thirty years. Overall energy consumption for energy use in the UK has increased by 13 per cent since 1970 and by 11 per cent since 1990. Since energy consumption is partly dependent on the weather, in a cold year more energy is consumed to maintain a consistent internal temperature than in a warmer year, energy consumption is adjusted for temperature to identify the underlying trend. On this basis, energy consumption increased by 15 per cent between 1970 and 2001 and by 10 per cent between 1990 and 2001. Chart 1.1 shows how energy consumption has changed over the last thirty years on both unadjusted and temperature corrected bases.

Chart 1.1
Total primary energy consumption, 1970 to 2001

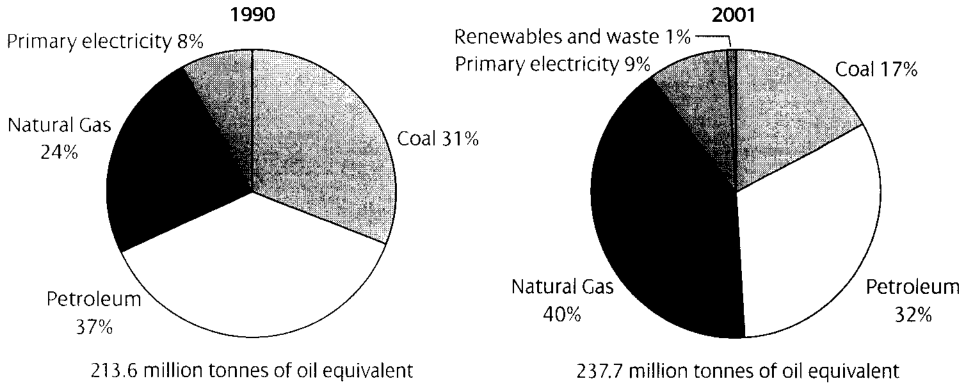


Source: DTI

- Primary energy consumption increased by 13 per cent between 1970 and 2001 and by 11 per cent between 1990 and 2001.
- On a temperature corrected basis, energy consumption increased by 15 per cent between 1970 and 2000 and by 10 per cent between 1990 and 2001. Over the last 20 years it has been steadily increasing at about 1 per cent a year.

1.2 Chart 1.2 shows how much fuel was consumed in 1990 and 2001. In 2001 natural gas made up two-fifths of all energy consumption in the UK. Since 1990, while use of natural gas has increased by 86 per cent, solid fuel consumption fell by 38 per cent and accounted for 17 per cent of all fuel consumed in 2001. The increase in natural gas consumption is due to its use in generating electricity, Combined Cycle Gas Turbine power stations were introduced in 1992.

Chart 1.2
Primary energy consumption by fuel, 1990 and 2001

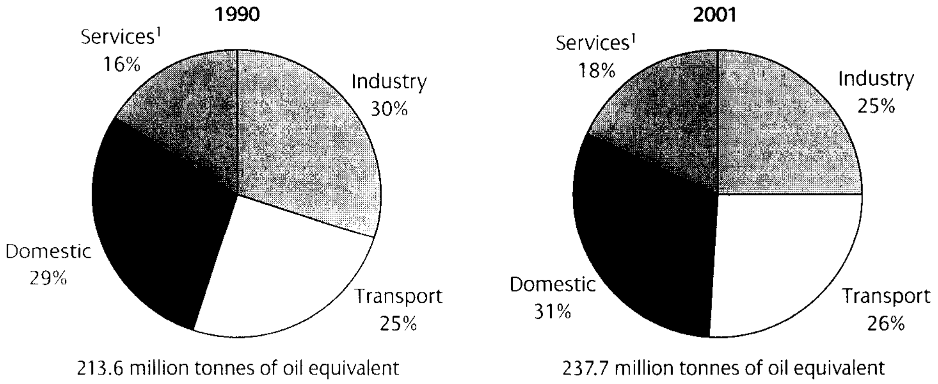


Source: DTI

- Natural gas contributed towards 40 per cent of total primary energy consumption in 2001.
- Petroleum contributed towards 32 per cent of total primary energy consumption in 2001.

1.3 The total amounts of energy consumed by sector in 1990 and 2001 (in primary energy equivalents) are shown in Chart 1.3. Industrial energy consumption fell by 5 per cent between 1990 and 2001 while energy consumption in the transport, domestic and service sectors increased by 18 per cent, 17 per cent and 19 per cent respectively. In primary energy equivalents in 1990 industry was the largest sub-sector, followed by the domestic sector. A decade later the domestic sector was the largest, with transport second. Paragraph 1.6 provides more information about the contribution that each sector makes in final energy terms.

Chart 1.3
Final energy consumption, by sector, in primary energy equivalents, 1990 and 2001



Source: DTI

1. Includes agriculture.

- The domestic sector contributed towards 31 per cent of final energy consumption, in primary energy equivalents in 2001.
- The transport sector contributed towards 26 per cent of final energy consumption, in primary energy equivalents in 2001.

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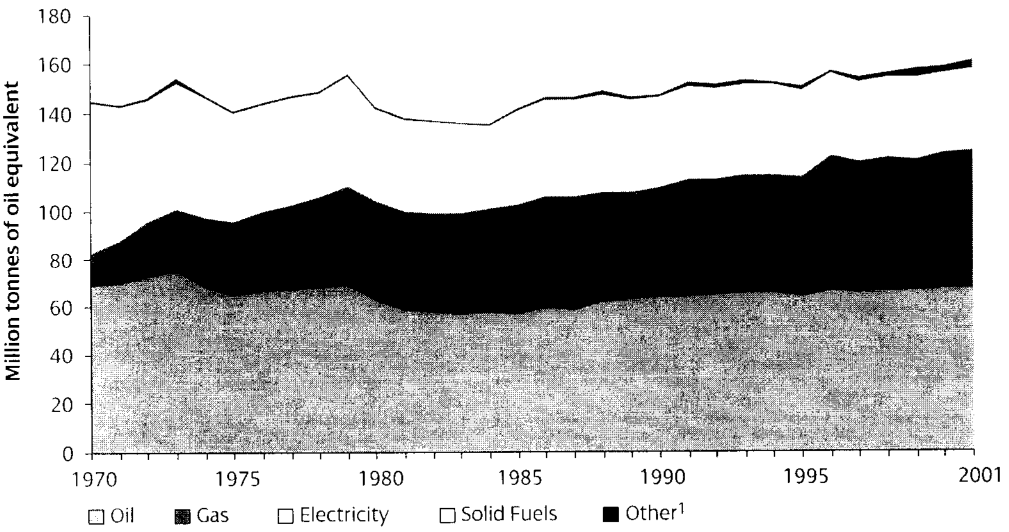
1.4 Some of the fuel consumed in the UK is transformed into electricity and other manufactured fuels, which result in energy losses. On average for every 2½ energy units of fuel that goes into power stations, approximately 1 energy unit of electricity is produced. Since electricity is used for a wide range of uses and trends in electricity consumption determine the levels of energy required to generate it, the rest of this chapter focuses on final energy consumption. Final energy consumption covers the final fuels that are consumed by users so the final amounts of electricity and manufactured solid fuels are measured rather than the amount of fuel used to generate or manufacture them.

1.5 Final energy consumption in the UK in 2001, shown in Chart 1.4, was at a higher level than any in other year over the last thirty years. Overall energy consumption has increased by 10 per cent since 1970 and by 9 per cent since 1990. The fuel mix has changed significantly since 1970 as natural gas consumption has replaced coal. In 1970 natural gas accounted for 3 per cent of total overall final energy consumption and in 2001 for 36 per cent. Electricity consumption has increased by 74 per cent over the period. Over the last 20 years it has grown steadily at 2 per cent a year.

Chart 1.4:
Final energy consumption by fuel, 1970 to 2001

4



Source: DTI

1. Includes coke oven gas, heat, renewables and waste.

- Gas energy consumption (including town gas in 1970) increased by 300 per cent between 1970 and 2001
- Consumption of solid fuels has fallen by 90 per cent between 1970 and 2001.

1.6 In final energy terms by sector (rather than primary energy equivalents which were discussed in paragraph 1.3), the transport sector was the largest single consumer of energy in 2001, accounting for 34 per cent of the total. The domestic sector was responsible for a further 30 per cent and industry for another 22 per cent. The remaining 14 per cent was consumed by the service sector (13 per cent) and the agriculture sector (1 per cent). Chart 1.5 shows that since 1990, the contribution that each of these sectors has made to overall energy consumption has not changed greatly, although

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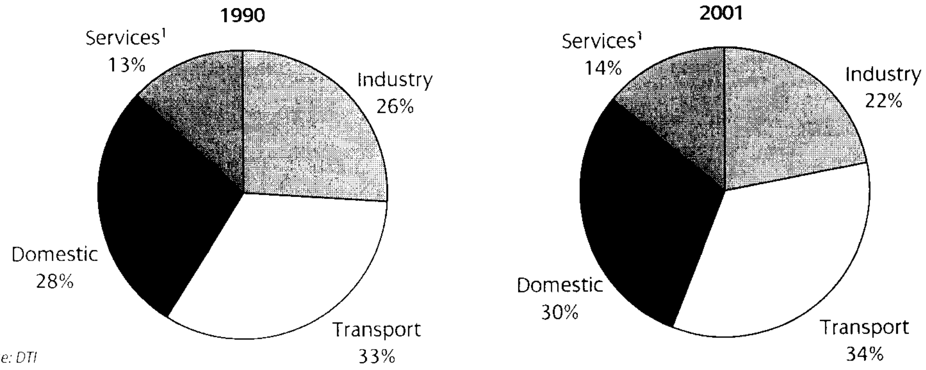
there have been more major changes since 1970, reflecting the shift from energy-intensive industry to the service sector and growth in the transport sector.

Chart 1.5
Percentage sector shares in total energy consumption, 1990 and 2001

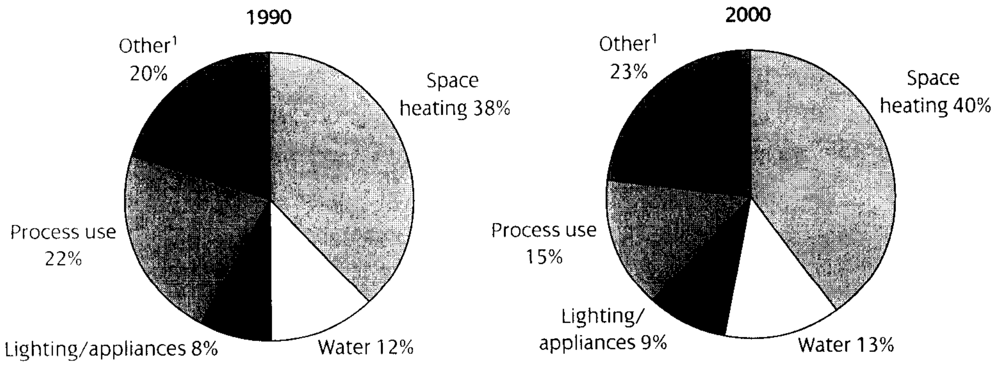


Source: DTI
1. Includes agriculture.

- The transport sector contributed towards 34 per cent of overall energy in 2001.
- The domestic sector contributed towards 30 per cent of overall energy in 2001.

1.7 The amount of energy consumed by each sector can be analysed by how it is used. In 2000, 40 per cent was used for space heating, and 15 per cent for process use. Space heating and hot water accounted for 82 per cent of domestic use of energy and 64 per cent of commercial use of energy in 2000. Chart 1.6 shows how energy consumption by end use changed between 1990 and 2000.

Chart 1.6
Final energy consumption by end use, 1990 and 2000



Source: DTI estimates derived from data provided by FES and BRE
1. Includes cooking, catering, motors, drivers, drying and separation.

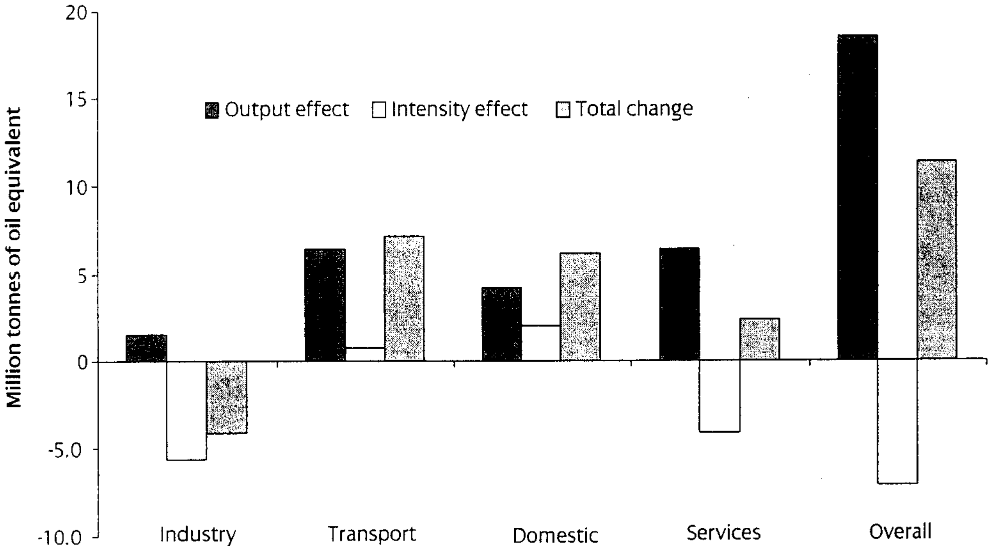
- Space heating contributed 40 per cent of all non-transport energy consumption in 2000.
- Process use contributed 15 per cent of all non-transport energy consumption in 2000.

Factors affecting overall energy consumption

1.8 Overall energy consumption increased by 11.4 million tonnes of oil equivalent between 1990 and 2000. If the energy required to produce a unit of output was the same in 2000 as in 1990, then it is estimated that energy consumption would have risen by an additional 7.1 million tonnes of oil equivalent. This 7.1 million tonnes of oil equivalent is due to a combination of structural change and changes in efficiency (called an intensity effect). The difference between the intensity effect and the actual value, an increase of 18.5 million tonnes of oil equivalent, can be attributed to changes due to output. The largest fall in intensity, of 5.6 million tonnes of oil equivalent, occurred in the industrial sector. The service sector also experienced a fall in intensity of 4.1 million tonnes of oil equivalent. Increases in output in both the transport and domestic sectors resulted in increased energy consumption of 6.4 and 4.2 million tonnes of oil equivalent respectively. The next section describes the change in intensity in more detail.

4

Chart 1.7
Factors affecting changes in final delivered energy by sector between 1990 and 2000



Source: DTI estimates

- Of the overall increase in energy consumption between 1990 and 2000 of 11.4 million tonnes of oil equivalent, it is estimated that changes due to output resulted in an increase of 18.5 million tonnes of oil equivalent which was partly offset by a fall in intensity of 7.1 million tonnes of equivalent.

1 (b) (BOOKWORK)

Increasing availability of natural gas (methane) and competitive price ⇒ increased use of prime movers based on the gas turbine

High efficiency (high temperatures can be obtained by gas combustion) ⇒ comparable with a steam turbine

2 main types used for electricity generation:

(i) <u>Direct fuel burning</u>
fuel injected into combustion chamber
-> gases impinge directly onto turbine blading
=> produces rotary motion

3

Units up to 200 MW built
-> life limited by corrosion of turbine blades
-> at high temps (> 1000°C) & speeds (6000 rpm)
Various fuels used:
oil
gas
pulverised coal

(ii) <u>Gas generator with low press. turbine</u>
More successful design
-> essentially uses aircraft type jet engines
-> generates gas at sufficient press.
-> feeds separate turbine
=> drives gen. at 3,000 or 3,600 rpm

1. (b) (cont)

Since efficiency ≈ 30% is low, need for improvement.

Improvements :

Addition of exhaust gas heat exchanger
-> preheats combustion air
=> regenerative cycle much more efficient
(produces lower exhaust gas temps)

Better use via "*combined cycle*" operation

3

Combined-cycle gas-turbine (CCGT) plant:

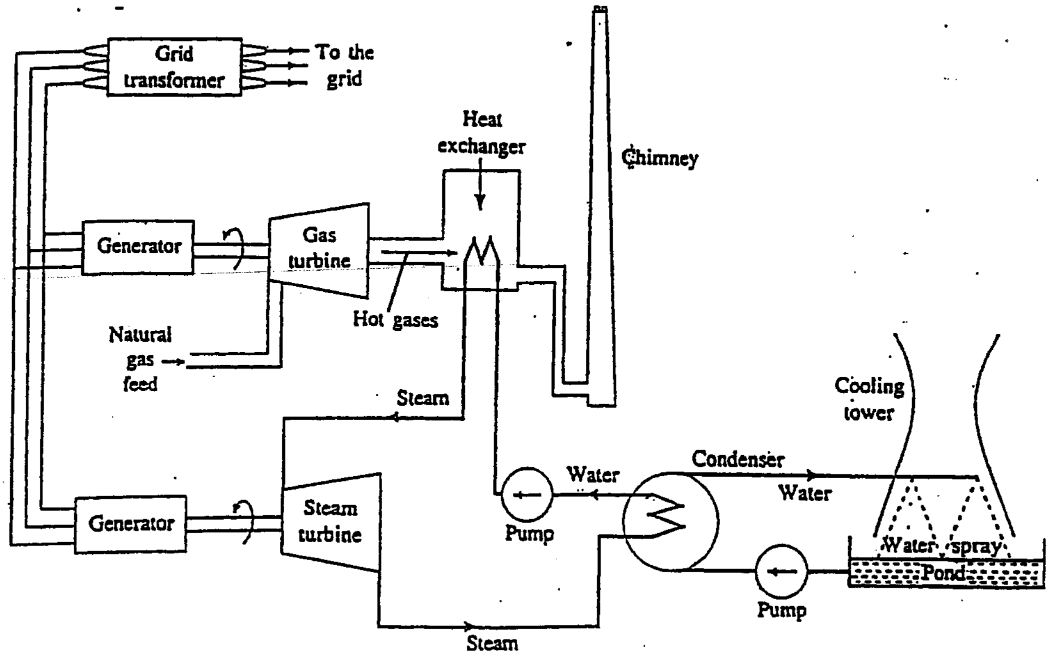


Figure 1.8 Schematic diagram of a combined-cycle gas-turbine power station (Reproduced by permission of Butterworth/Elsevier)

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Paper Code: E4.39 Second Examiner: B. PAL (Ques 1, 2, 3)

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Question Number etc. in left margin

Mark allocation in right margin

1 (c) (application of theory) 1

$P = 9.81\, q\, h$

$q = 7.645\ m^3/min = 7.645 \frac{m^3}{60s} = 0.1274\ m^3/sec$

$h = 16.7\ m$

$P = 9.81 \cdot 0.1274 \cdot 16.7 = 20.8\ kW$ 3

$80\% \Rightarrow 0.8 \cdot 20.8 = 16.6\ kW$ 2

So, a 16.6 kW motor operating as an asynchronous generator would be satisfactory.

(However the turbine speed is determined by hydraulic considerations and a gear box may be needed to couple the motor to the turbine.)

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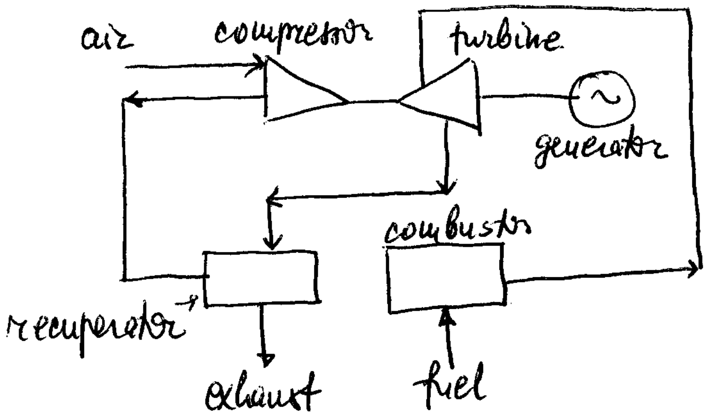
2. a) Microturbines

Small gas turbines with a few moving parts (typically only one rotating shaft)



2

Size: 30-75 kW; modular 1

Suitable for customers with loads ≥ 30kW (commercial & industrial)

For sizes ≤ 30kW, losses do not decrease as rapidly as output, so efficiency falls significantly + component costs do not decrease as rapidly as size decreases ⇒ cost per kW increases (⇒ not suitable for small residential use) 2

Installed at $750 - 1000/kW (target is $350/kW)

Microturbine of 75kW: $\eta = 30\%$, speed 90000-100000 rpm; approx. 40000 hours of reliable operation 1

Strong points: high reliability, capable of unattended operation at a customer side; heat recovery can be incorporated 2

Needs
- increase efficiency (single-stage compressor & uncooled turbine blades are the largest limitations)
- reduce cost (power electronics, compressor)
- further development of equipment that uses waste heat to provide heating & cooling

2

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2 (b) (Bookwork)

Wind – after hydropower, the next most popular source of green electricity around the world.

2000: 17500 MW is the worldwide wind energy capacity
12800 MW – in Europe (70%) – to meet domestic needs of 5 million people

The European Wind Energy Association has a target of 60000 MW of installed capacity by 2010 and 150000 MW by 2020 (50 000 MW to be offshore).

Modern wind turbines typically have availabilities exceeding 98% and perform with capacity factors 35-40% in good wind resource areas.

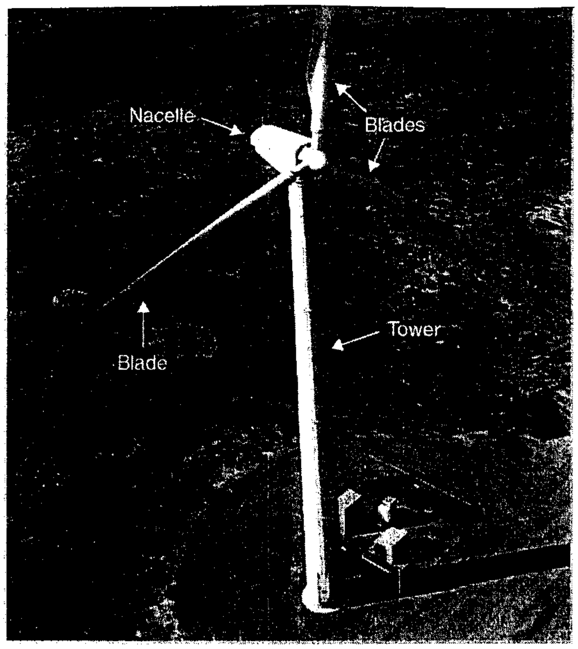
The cost of wind-generated electricity has declined over the last 20 years. Today, large new wind farms at excellent wind sites generate electricity at a cost of 4-6 c/kWh (US$) – competitive with that of electricity from new conventional power plants. 5

When connected to the grid, wind turbines contribute to stability, voltage control & frequency control, as well as to the system balancing. This is especially important when large numbers of turbines are connected to a system during periods with low loads and high wind speeds – importance of penetration level & wind turbine type is crucial here.

UK: already >1000 turbines in Scotland, Wales, Cornwall, North England
Plans for large offshore developments & windfarms of machines individually capable of generating 5MW each (enough to power 4000 homes)

Electricity from Wind

Wind turbines can be classified into two major groups: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). For the HAWT machine, the axis of rotation of blades is horizontal, whereas for the VAWT, it is vertical. While for the HAWT the turbine is located at higher height to take advantage of greater wind speeds, VAWT must be mounted close to the ground. All of the commercially available wind turbine generators (WTGs) today are HAWT. There are also some differences between WTGs used in different applications. For home-owners who want to install WTGs to supply part or all of their power, setup and operation of the WTG will be much less complex than that of a utility that wants to install a number of WTGs to supply grid power.



large-scale wind turbine generator.

DOI

The basic concept of harnessing power from the wind has not changed much over the years, but the specific realization of this goal has. Though there are several different manufacturers of wind turbine generators, each with their own specific designs and applications, the overall design is fairly consistent. Major components of the WTG as well as the integral parts of these components are shown in Figure 6. The nacelle (which houses the gearbox, generator, and the associated controls) is mounted on the tower. The rotor assembly (including the blades) is connected to the gearbox mechanism. The nacelle is under yaw control and is free to rotate around on a vertical axis to always face the incoming wind as closely as possible. The pitch angle of the rotor blades can be controlled to harness more or less wind, thus optimizing the energy capture and controlling the speed in the event of excessive winds. The hub and blades are connected to a low-speed shaft that drives a gearbox. In the gearbox, the shaft speed is increased to drive the generator generally to a speed somewhere between 1,200 and 1,800 rpm. A high-speed shaft connects the gearbox to the generator.

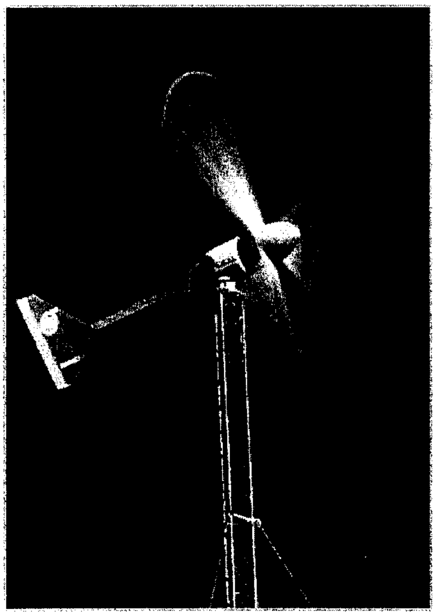


Figure 7. stand-alone individual-scale installation: 10 kW BWC EXCEL wind turbine.

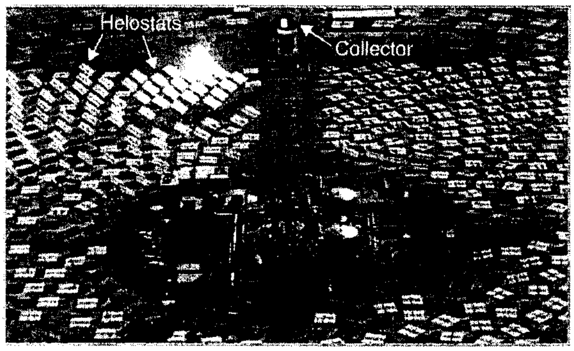
DOE/NREL

The blades are, of course, where the wind is caught. Significant design efforts have gone into designing them to improve the amount of energy extracted from the wind. The tips of the blades are generally rounded, as experimentation has shown that a rounded blade tip will reduce the minimum speed needed to start the WTG. A rounded tip also increases the peak aerodynamic efficiency. The rotor assembly consists of three major subassemblies: blades, hub, and the pitch-change mechanism. Each blade is attached to the hub through a three-row, cylindrical, roller bearing that permits the full pitch of the blade from the power position (0°) to the feather position (90°). Blade pitch is controlled by hydraulic actuators operating through a mechanical linkage with sufficient capacity to feather the blades.

Wind power applications can be broken down into two large categories: utility-scale installations and individual-scale installations. For utility-scale projects, many very large wind turbines (>1 MW each and similar to ones shown in Figure 6) would generally be installed in a given location. This is a huge endeavor, as the towers can be 70 m or taller, and the diameter of the blades can be 70 m or more. Stand-alone WTGs are also on the market designed to power a single house, a remote cabin, etc., as seen in Figure 7. The structure supporting the WTG is the tower, and it can take many forms. For smaller systems, it can be as simple as a pole and perhaps with some guy wires, but, for larger WTGs, the requirements are considerably greater. Large concrete pads have to be poured and sometimes 70 m tall towers have to be built on site. Most utility scale WTG's are perched on solid towers as shown in Figure 6.

5

A certain amount of wind speed is necessary for the WTG to overcome the mechanical inertia and provide enough rotational motion for the generator to start producing electrical power. This is known as the cut-in speed and can be as low as 3 m/s for small WTGs. The WTG produces variable power between cut-in and rated speeds. When the rated wind speed is attained, the WTG produces full power as it reaches its design rotational speed. Any speed higher than the design rotational speed resulting from a wind speed higher than V_R may cause damage to the mechanical couplings, gear boxes, and electric generator. Thus, as the wind speed exceeds V_R, a constant blade rotational speed is maintained by changing the pitch angle of the blade, thereby catching only a part of the energy available in the wind. There is, however, an upper limit to the ability of the pitch control mechanism to maintain a fixed rotational speed of the wind turbine as the wind speed keeps on increasing. When that limit is reached, i.e., as the wind speed reaches the furling speed, the WTG is turned off. For many machines, this speed can be as high as 30 m/s. Failure to stop the WTG under high wind speeds will cause mechanical as well as electrical damage to the machinery.



DOE/NREL

Figure 3. large-scale, central receiver, solar thermal installation: 10 MW Solar Two installation in the Mojave Desert, California.

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3 (a) **(Bookwork)**

A traditional central utility model is based on a vertically integrated monopoly structure and regulated price of electricity (tariff).

Motives for the restructuring:

- Market imperfections under the regulated monopolistic structure, and therefore inefficient use of the interconnected transm. and gen. systems
- Many utilities have been limited by regulation with regard to profits and expansion
- development of new technologies in generation and IT (e.g. allow low-cost plants owned by IPP to enter).

COST-BASED SYSTEM → MARKET-BASED SYSTEM

- cost price → market price (reflects real costs according to use)
- regulation → competition ⇒ economic efficiency (⇒) improve and maintain the quality of customer services, monitorcosts more closely, invest in and deploy new technologies)

Aims of deregulation/restructuring:

- remove barriers to trade
- lower the ultimate price of electricity
- offer better products and services
- long-term gains in efficiency
- greater assurance of future adequacy of supply
- influx of private capital (including freeing up public funds and collecting cash from the sale of industry assets)
- (not openly admitted:) free utilities from political meddling, push through reorganization and downsizing enforcing efficient business practices

5

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3. (b) **(Bookwork)**

England and Wales Electricity Pool

In 1990, British electricity supply industry (ESI) was privatized. In England and Wales, Electricity Pool opened for trading. Separate companies to provide competition in generation and to transmit energy at HV (NGC). 12 Regional electricity companies (RECs) to distribute and supply energy to consumers. Nuclear power stations remain with Nuclear Electric. In Scotland, Scottish Power and Hydroelectric companies continue as vertically integrated who could sell power to England and Wales competitively. Nuclear stations belong to Scottish Nuclear.

Transmission and Distribution are recognized as monopolies.

The Regulator was established to fix the profit that the NGC and RECs could earn.

1. Each generating unit has to declare by 10am its availability to the market + the price at which it is prepared to generate for each and every half-hour of the following day
2. NGC call units to generate in ascending order of price. The most expensive unit establishes the System Marginal Price (SMP) which all other generators supplying electricity receive for that half-hour . Another pricing mechanism is designed to provide an incentive for the provision of generating capacity (capacity payment).

   Pool Purchase Price (PPP) = SMP + (capacity payment) is calculated the day before trading and published the following day in FT.
3. Suppliers purchasing electricity via the Pool buy at the Pool Selling Price PSP = PPP + Uplift (uplift charges for ancillary services which ensure that system remains stable and secure)

Form of virtual real-time pricing (may lead to volatility in prices) . To overcome this, the Pool introduced short and long term contracts to make capacity and energy prices more predictable for both customers and suppliers (so-called Contracts for Differences - involve an agreed 'strike price' ie an agreed price/kWh for a specified quantity of electricity and a specified period of time. 5

Main features:

Compulsory: all the electrical energy produced and consumed has to be traded through the Pool

One-sided: only the generators submit bids (which include startup and no-load costs as well as availability and flexibility parameters). Consumers are represented by a load forecast that ignored the price elasticity of demand. So, generators are paid on the basis of the forecast, not the actual demand and consumers pay for 'forecast error'

Complex bids: not simple price-quantity pairs but a set of parameters designed to reprsent the cost and technical constraints associated with generating el.energy with a specific unit

Day-ahead centralized scheduling: an "optimal" gener. schedule is determined centrally for the day-ahead on the basis of bids and the load forecast

Day-ahead centralized pricing: at each half-hour the adjusted marginal price of the marginal unit in this schedule sets the System Marginal Price (SMP). All of the electrical energy generated was purchased at the SMP for that half-hour

In theory, not bad system but only if there is enough competition (ie only in that case the generators' optimal bidding strategy is to bid their marginal cost.)

In practice, there wasn't enough competition. Actually, only two: National Power and PowerGen; only they owned the intermediate (mid-merit) plants that normally set the SMP. The other four, EdF, Nuclear Electric, Scottish Power and HydroElectric were only interested in providing base generation. Result: temptatation to adopt a bidding strategy that will increase the SMP (ie push SMP up by raising bids of intermediate units) ie manipulation of prices (**market power**).

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The Regulator (OFFER, now OFGEM) started investigating the problem:

1994: price regulation was imposed
National Power and PowerGen should bid in such a way that the average SMP over a period of several months would not exceed a given ceiling. At the end of the period, the average SMP turned out to be exactly equal to the set ceiling, demonstrating that the generating companies had precise control of the market-clearing price.

1998/99: the Regulator forced National Power and PowerGen to divest themselves of a significant proportion of their mid-merit plants. A single company, Eastern Group, acquired control of all of the divested plants.

Expectation: divestment should have prevented the generating companies from controlling the prices

Reality: not quite so; more divestures were needed. In addition, even though there was an overall drop in prices of primary fuels, electricity prices did not drop as much.

NordPool

A sucessful example of electricity deregulation - primarily because market power has not been an issue (as it was in the E&W Pool). Most liberal electricity market

Market participants: generators, utilities with distr/gen capacity, end users. SOs

NordPool as central PX (or market operator); comprises Norway, Sweden and Finland, with Denmark soon to join. Responsible for the market clearing process in the spot market (24h market) and the futures market, accounting and invoicing.

Energy markets consist of

1. the short-term spot and regulating markets

   Spot market: settled daily at noon for delivery next day. NordPool accepts generator offers and demand bids for each hour of the following day. System (claring) price = equilibrium point (where aggregate demand curve meets the aggregate supply curve) *(ex ante pricing)*

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   Regulating market: compensates power imbalances. Generators can submit buyback bids after the day-ahead market trading is finished: how much a generator is willing to pay to buy back the surplus or to produce the deficit amount of power. In real-time operation, SO selects the cheapest generator (regulator) from a merit list. All the regulators receive the price of the marginal regulator. *(ex post mechanism)*

2. the longer term futures and options financial markets
   Weekly time resolution; settled against uncongested spot market clearing price

3. bilateral contract markets
   90% electricity contracts are transacted through bilateral contracts

NordPool does not include a centralized scheduling, pricing and dispatch, instead scheduling is responsibility of individual generating companies on the basis of individual profit maximization

There are 3 different SOs (each associated with a national grid company. In Norway, transmission network is owned by Statnett which is SO for the regulating market. In Sweden, Svenska Kraftnat is SO.) Also, different (but coordinated) solutions to tariffs, congestion management etc.

Problems: different transm. tariffs can give a competitive advantage to generators in one country compared to another. Establishment of one ISO (an institution independent of the transm. owners) has been discussed.

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3. (c) **(Bookwork)**

In a perfectly competitive market:
  - no participant is large enough to affect the price
  - all participants act as 'price takers'

A price-taking firm will sell as long as the market price is above the marginal cost of production.

A firm exercises market power when
  - it reduces its output (withholds capacity), or
  - it raises its offer price

in order to increase the market price.

A generation company that frequently finds itself within a region/zone of the power system that is limited in ability to bring a less expensive energy is said to be able to exercise "market power" (eg it can raise prices almost to any level and customers will pay for it if they need electricity)

When is market power more likely?
  - Price elasticity of demand is low
  - Price elasticity of supply is low (highly variable demand so that all capacity is used OR output cannot be stored)

Unilaterally reducing output or increasing offer price to increase profits is legal.
Collusion between firms to achieve the same goal is not legal.

Other ways to exploit market power: 5

1. exploiting network characteristics using generators at different locations
2. using financial contracts when firms are vertically integrated
3. using physical bilateral contracts
4. raising the price of natural gas (NY Times, 2001)

Market power interferes with the efficient dispatch of generating resources (cheaper generation is replaced by more expensive generation). It is especially critical if congestion is present in the system. In such operating conditions, some generators can exercise an unlimited market power (e.g. they can increase their bid as much as they want, and the customers do not have any option than to buy from them).

High average prices + high volatility of prices indicates/raises concerns about the abuse of market power by generators

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Model Answers (Dr. B. Pal)

4 Solution

(a) (**Bookwork**)
$1 \longrightarrow B$
$2 \longrightarrow A$
$3 \longrightarrow F$
$4 \longrightarrow K$
$5 \longrightarrow L$
$6 \longrightarrow E$
$7 \longrightarrow H$
$8 \longrightarrow J$
$9 \longrightarrow G$
$10 \longrightarrow C$

[10x2=20 marks]

5 solution

(a) (**Bookwork**) In an interconnected network power flows satisfying ohms law. A particular load point can be reached from a particular generation point through more than one root. The total current flows and hence the power flow will be shared by these paths in inverse proportion to their impedance and power frequency. Some time, the point of delivery may not be located physically far, but because of the interconnection, portion of the power would come in a circuitous root involving many transmission line sections. The power wheels through various sections in a transmission system before reaching the load point. This is known as loop flow. Because of the finite conductivity of the transmission conductors carrying current, I^2R loss is inevitable. The extent of loss depends on the magnitude of current and resistance. For longer paths which is encountered in loop flows, losses are more. The reactive power loss proportional to I^2X, has also to be supplied either from the sending or from the receiving end of the contract if the other arrangement of compensation with in the network is not made. All these lead to higher operational losses and the cost of these losses are a significant proportion of total cost of operation. If loop flow is avoided by proper design of the transmission system, or retrofitting it with FACTS controller, significant price reduction can be achieved that can easily be passed on to the customers. **[5 marks]**

(b) (**Bookwork**) The heat produced by current flow in a transmission system has two undesirable effects

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(i) Annealing and gradual loss of mechanical strength of the aluminium conductor caused by continued exposure to temperature extremes.

(ii) Increased sag and decreased clearance to ground due to conductor expansion at higher temperatures.

The second of the above two effects is generally the limiting factor in setting the maximum permissible operating temperature. At this limit, the resulting line sag approaches the statutory ground clearance. The maximum allowable conductor temperatures based on annealing consideration is 127 degree Celsius for aluminium conductor. The allowable maximum current (i.e the ampacity) is dependent on ambient temperature, wind velocity. The thermal time constant is of the order of 10 to 20 minutes. Therefore the distinction is always made between short time rating during contingency and normal continuous rating. It is once again an empirical relation to assume thermal limit of a 50 mile long line to be 3.0 times the surge impedance loading (SIL).

No it is not possible in the absence of any control or compensation to load a 500 miles long 400 kV line to operate close to its thermal limits. The stability related issues will restrict the loading far below to its SIL value.

[5 marks]

(c) (**Bookwork**)TCSC is a thyristor based controller series compensation device. It can be realised as part fixed and part controllable through thyristor. Some time it can be part fixed capacitor and thyristor controlled reactor and capacitor type. The commutation is natural. SSSC is voltage sourced based converters. The voltage is a balanced and of system frequency. The magnitude is controllable. Forced commutation (GTO) is used. It is placed in series with the line. The amount voltage drop across a TCSC is function of line current and hence the reactive power generated by TCSC is function of line current. The power transfer is increased by a fixed percentage of the value of the uncompensated line for the same angle. The injection of voltage of SSSC is independent and controllable and does not depend on line flow but it can be operated in constant impedance mode if required. The angle of the voltage to line current is fixed either at +90 degree or -90 degree. When at +90 degree it can behave as controllable inductor as opposed to capacitor at -90 degree. So compensation in both directions is possible. The amount of power transferred is increased by a fixed percentage of the maximum power transfer value of the uncompensated line. The short term overloading capability is very useful during high current condition and comes as a very useful benefit in first swing stability performance of the network. At fault, the voltage developed across the series capacitor is dangerously high and can be damaging to the costly thyristor switches if over-voltage protection arrangement does not act. The TCSC cannot be useful during contingency (faults) conditions. **[5 marks]**

(d) Various benefits of FACTS technology include the following:

- (i) Control of power flow as ordered and suit to follow a contract. This is very important from the present day operating scenario of the power system. Contracts are agreed between the suppliers (generation companies) and the distribution companies based on the bidding on the market. This does not take care of transmission constraint that is the responsibility of the transmission operators. FACTS can ensure contracted service by properly controlling power flow in the lines.
- (ii) Increase the loading capability of lines to their thermal capabilities including short term and seasonal.
- (iii) Increase the system security through raising large and small signal stability margin and limiting short circuit current.
- (iv) Provide secure tie line connections to neighbouring utilities and reasons thereby decreasing overall generation reserve requirements on both sides. Phase angle regulator at times become handy to create power flow conditions amongst neighbouring utilities through tie lines.
- (v) Providing greater flexibility in siting new generation
- (vi) Upgrade of lines
- (vii) Reduce reactive power flows thus allowing lines to carry more active power. FACTS devices can generate reactive power to supply local requirement thus eliminating the need of var generation by the generators
- (viii) Reduce loop flows
- (ix) Increased utilisation of lowest cost generation

[5 marks]

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6 solution

(a) (**bookwork**) The various applications and benefits of optimal power flow (OPF) are as follows:

- (i) Calculation of optimum generation pattern, as well as control variables, to achieve the minimum cost of generation subject to meeting transmission system limitations
- (ii) Can provide preventive dispatch if security constraints are incorporated
- (iii) Can provide corrective dispatch when, during the operation system, overloaded or bus voltage limits are violated.
- (iv) Can be used periodically to find optimum setting for FACTS control under varying generation and load pattern.
- (v) Used in planning studies to determine transmission system capacities to future power flow scenarios
- (vi) Can be used for evaluating transmission pricing through bus incremental costs (BICs)

[5 marks]

(b) **bookwork** Commonly encountered limits in OPF are:

- (i) Generator output power limit
- (ii) Generator reactive power limit
- (iii) Generator voltage limit
- (iv) Bus voltage limits
- (v) Line flow limits
- (vi) FACTS control limits

[2 marks]

(c) (**bookwork and computed example**) From the statement of the problem it is clear that only reference bus power is variable hence minimisation of loss is simplified to minimising reference bus power output. The bus voltage magnitudes can be used as control variable. The constraints are load flow equation comprising of bus 2 real power injection and real and reactive injection at bus 3. The bus 1 angle is assumed reference.

- (i) Hence the control variables(u) are bus voltage magnitude V_1 and V_2 of bus 1 and bus 2. state variables (x) are bus voltage angle of bus 2 and bus 3 and fixed parameters (p) are bus 2 real power P_2, bus 3 real and reactive power P_3 and Q_3 and reference angle θ_1 of bus 1 . **[4 marks]**

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(ii) The objective and constraint functions are:

$$L = f(x,u,p) + \lambda^T g(x,u,p) \tag{6.1}$$

$$f(x,u,p) = P_1 = V_1\, V_2[G_{13}cos(\theta_1-\theta_3)+B_{13}sin(\theta_1-\theta_3)]+G_{11}V_1^2 \tag{6.2}$$

$$g(x,u,p) = \begin{bmatrix} P_{2,cal} - P_{2,sch} \\ P_{3,cal} - P_{3,sch} \\ Q_{3,cal} - Q_{3,sch} \end{bmatrix} \tag{6.3}$$

$$P_{2,cal} = V_2V_3[G_{23}cos(\theta_2-\theta_3) + B_{23}sin(\theta_2-\theta_3)] + G_{22}V_2^2 \tag{6.4}$$

$$\begin{aligned} P_{3,cal} = {} & V_3V_2[G_{32}cos(\theta_3-\theta_2) + B_{32}sin(\theta_3-\theta_2)] + G_{33}V_3^2 \\ & + V_3V_1[G_{31}cos(\theta_3-\theta_1) + B_{31}sin(\theta_3-\theta_1)] \end{aligned} \tag{6.5}$$

$$\begin{aligned} Q_{3,cal} = {} & V_3V_2[G_{32}sin(\theta_3-\theta_2) - B_{32}cos(\theta_3-\theta_2)] - B_{33}V_3^2 \\ & + V_3V_1[G_{31}sin(\theta_3-\theta_1) - B_{31}cos(\theta_3-\theta_1)] \end{aligned} \tag{6.6}$$

$$\lambda = [\lambda_1, \lambda_2]^T \tag{6.7}$$

[5 marks]

(iii) The partial derivative of objective f(**x,u,p**) and constraint g(**x,u,p**) around the operating condition given in problem are obtained as:

$$\frac{\partial f}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_2} \\ \frac{\partial P_1}{\partial \theta_3} \\ \frac{\partial P_1}{\partial V_3} \end{bmatrix} = \begin{bmatrix} 0.0 \\ -23.721 \\ -0.584 \end{bmatrix} \tag{6.8}$$

$$\frac{\partial f}{\partial \mathbf{u}} = \begin{bmatrix} \frac{\partial P_1}{\partial V_1} \\ \frac{\partial P_1}{\partial V_2} \end{bmatrix} = \begin{bmatrix} 3.48 \\ 0.0 \end{bmatrix} \tag{6.9}$$

[4 marks]