ENVIRONMENTAL + ECONOMIC ISSUES IN POWER SYSTEMS 1

Department of Electrical and Electronic Engineering Examinations 2002 **Confidential**

Model Answers and Mark Schemes First Examiner: POPOVIĆ; PAL

Paper Code: E4.39 Second Examiner: PAL, POPOVIĆ

SOLUTIONS 2003

Question Number etc. in left margin | Mark allocation in right margin

1. a) (Bookwork)

Primary energy: fossil fuels (coal, gas, oil), biofuels (wood, straw), nuclear power, renewables

Primary energy supply today (2000-data) ≃ 10000 Mtoe, more than 50% from OECD countries, about 10% from Asia, China and former USSR (each). Within OECD, North America contributes ≃ 50%.

Among fossil fuels:

- oil & natural gas – estimated reserves for next 9-10 years (in USA). Worldwide, ≃40 years oil reserve & ≃ 60 years gas reserve. 2
- coal – estimated reserves are very large (peak not predicted to occur until 23rd century), enough for next 200 years but coal use is not expected to grow rapidly due to environmental & health issues/concerns, transportation problems.

Fuel share in total primary energy supply (worldwide):

- oil 35%
- gas 21%
- nuclear 7%
- coal 23.5%
- renewable 11%
- hydro 2%

Oil share is even larger in OECD countries (≃ 40%), coal & gas = 20% each. But renewables contribute very little (only ≃ 3.5%)

Primary energy consumption – similar picture to supply – again OECD countries dominate. Total consumption ≃ 7000 Mtoe (1 TWh = 0.086 Mtoe) 2

Electricity generation ≃ 15000 TWh (worldwide). Among fossil fuels, coal dominates (≃ 40%), then gas, nuclear, hydro = 17% each 2

1. a) (cont)

OECD countries generate more than 60% of total electricity generation (≈ 15000 TWh), while Asia, China & former USSR contribute ≈ 8.5% each.

Since world population doubled in past 50 years (to 6 billion) and the estimate for the rate of growth is 1.3%/pa over next 50 years (to approx 10 billion in 2050), electricity role will increase significantly. The estimate is that we would need ≈ 1000 kWh per year as a minimum energy required for education, economic development, environmental development 2

Department of Electrical and Electronic Engineering Examinations 2002 **Confidential**

Model Answers and Mark Schemes First Examiner: POPOVIC ; PAL

Paper Code: E4.39 Second Examiner: PAL ; POPOVIC

Question Number etc. in left margin Mark allocation in right margin

1. a) (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) Direct fuel burning

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) Gas generator with low press. turbine

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

Department of Electrical and Electronic Engineering Examinations 2002 **Confidential**

Model Answers and Mark Schemes First Examiner: POPOVIC ; PAL

Paper Code: 4.39 Second Examiner: PAL ; POPOVIC

Question Number etc. in left margin | Mark allocation in right margin

1. b) (cont)

Since GT efficiencies are ≃ 30%, 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

Combined-cycle gas-turbine (CCGT) plant: 3

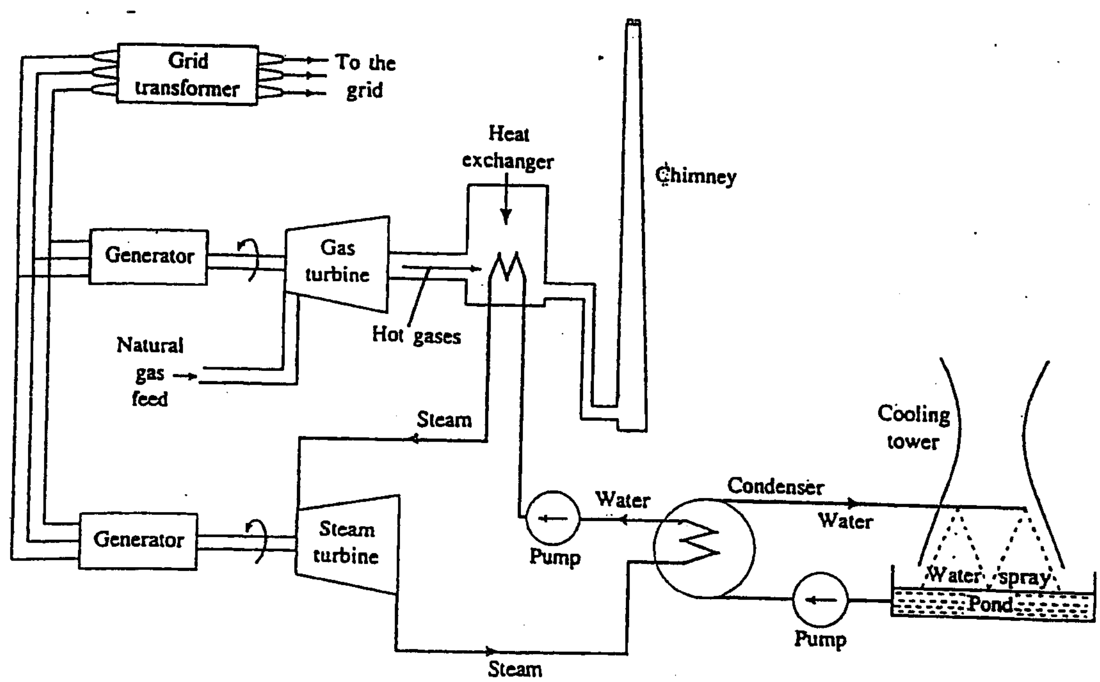


Figure 1.8 Schematic diagram of a combined-cycle gas-turbine power station (Reproduced by permission of Butterworth/Elsevier)

Department of Electrical and Electronic Engineering Examinations 2002 **Confidential**

Model Answers and Mark Schemes First Examiner: POPOVIC; PAL

Paper Code: E4.39 Second Examiner: PAL; POPOVIC

Question Number etc. in left margin | Mark allocation in right margin

1. (c) (Bookwork)

Thermal plants produce electricity from the heat released by the combustion of coal, oil or gas.

The efficiency is lower because of the inherent low efficiency of the turbines.

Max efficiency of any machine which converts heat into mech. energy is

$$\eta = (1 - T_2/T_1) \cdot 100 \quad [\%]$$

where T_1 – temp. of the gas entering the turbine [K]

T_2 – temp of the gas leaving the turbine [K]

(In most thermal plants the gas is steam.)

T_2 – cannot be lower than the ambient temp ($\approx 20°C$)

$\Rightarrow T_2 \approx 293K$ 6

For high efficiency, (T_2/T_1) should be as small as possible.

$\Rightarrow T_1$ should be as high as possible but we cannot use temperature above those that steel & other metals can safely withstand, e.g $T_1 \approx 550°C = 823K$

$$\rightarrow \eta = \left(1 - \frac{293}{823}\right) 100\% = 64.4\%$$

Due to other losses, some of the most efficient steam turbines have efficiencies of 45%.

20

E4.39

2. (a) **(Bookwork)**

Fuel cells - Invented in 1839, only minor advances were made until 1959 when a 5kW alkaline fuel cell was developed

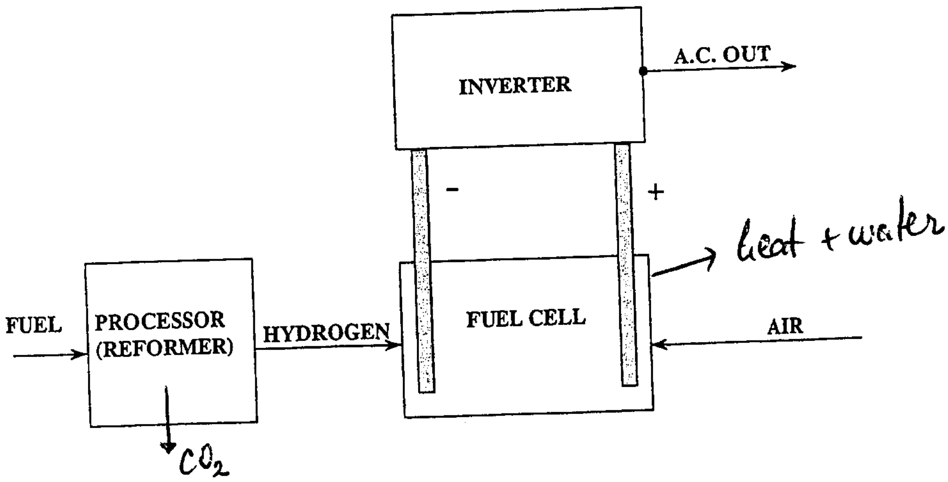
Size: 1kW - 200kW and greater than 1MW; modular

Larger units (targeting commercial/industrial customers) generally can use the waste heat

Very expensive at the moment ($4000-5000/kW); should enter the market within 1-3 years

Efficiency is higher than in case of microturbines

Fuel cells can essentially be described as batteries which never become discharged as long hydrogen and oxygen are continuously supplied. The hydrogen can be supplied directly, or produced (reformed) from natural gas or liquid fuels such as alchocol or gasoline.



Strong points:

8

- they can be more easily scaled to residential size (competitive advantage)
- efficient in handling the load profile of residential customers
- quiet, clean (low emmision) and efficient

Needs:

- cost reduction
  - reduce cost of the fuel processor (reformer)
  - reduce cost of power conditioning electronics
  - develop inexpensive and efficient methods for manufacture
  - prove/increase reliability, performance and fuel cell stack life
  - reduce total cost to customer (both cost of the fuel cell system and the connection to the customer's gas, electric and hot water system)
  - develop/improve efficiency of high-temp. FC most interesting for CHP applications

Department of Electrical and Electronic Engineering Examinations 2002 **Confidential**

Model Answers and Mark Schemes First Examiner: POPOVIC ; PAL

Paper Code: E4.39 Second Examiner: PAL ; POPOVIC

Question Number etc. in left margin | Mark allocation in right margin

2 (b) (Bookwork)

Peak load usually requires that the power is delivered for brief intervals during the day. So, power stations must be put into service very quickly ie. their prime movers should be started up in a few minutes. Since nuclear stations may take several days, ~~they~~ cannot be used to supply short-term peak power. 4

(c) (numerical example)

(i) Base load = 6 GW is running all year long

It represents 58% of the annual energy 4

$$\rightarrow \text{annual energy} = \frac{6 \cdot 10^9 \cdot 365 \cdot 24}{0.58} = 90.6 \text{ TWh}$$

(ii) $$\text{peak load} = \frac{90.6 \cdot 10^{12}}{365 \cdot 24 \cdot 10^9} = 10.34 \text{ GW}$$ 4

(Note that the actual peak load = 15 GW.)

/20

E4.39

3. (a) **(Bookwork)**

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.

England and Wales Electricity Pool

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.

Main features: 4

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

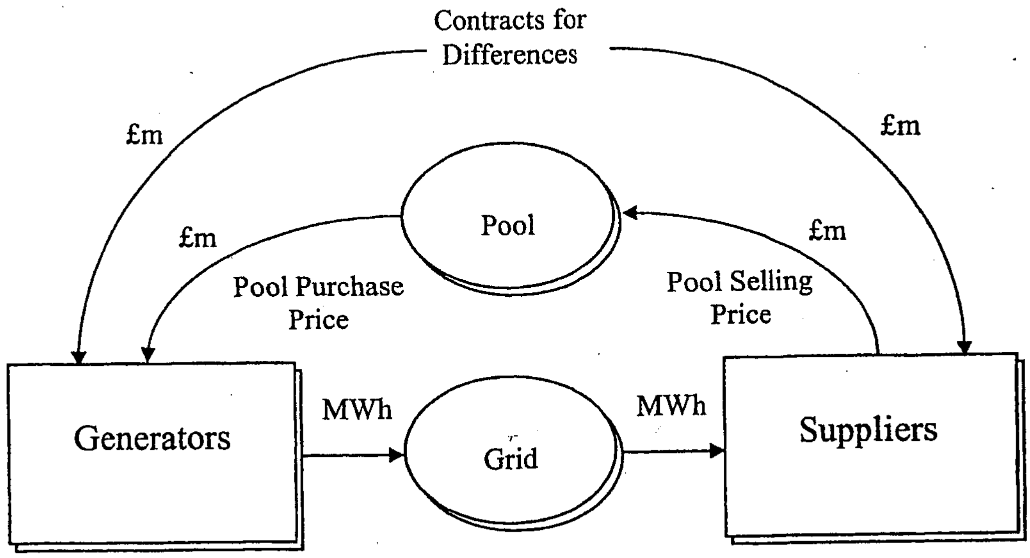
Day-ahead centralized scheduling: an "optimal" gener. schedule is determined centrally for the day-ahead on the basis of bids and the load forecast

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

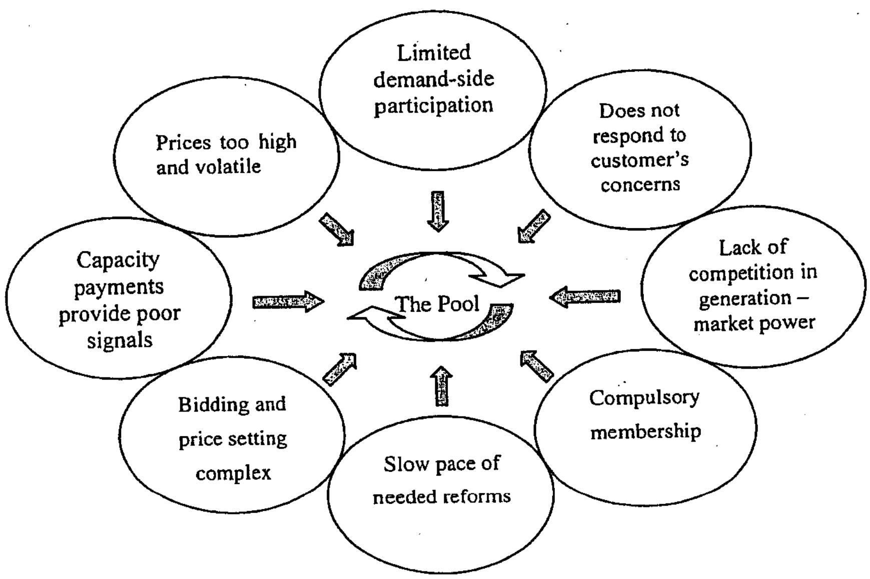
In theory, not bad system but only if there is enough competition (ie only in that case the generators' optimal bidding strategy is to bid their marginal cost.)

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**).

3.(a) (cont)



The pool



Problems with the pool

E4.39

3.(a) (cont)

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.

Reformed England and Wales Electricity Market (NETA) (2001)

Pool operation ⇒ market power and high prices
Pool couldn't reinvent itself to provide more transparency and lower prices; also, how to allow for interactions with gas markets.

New electricity trading arrangements (NETA) have been planned (market based, more akin to those in commodity markets). In longer-term, should be harmonized with gas market.

- Decentralized energy market, access market and ancillary services market
- Free bilateral trade of energy through short-term PX (to give the participants the opportunity to fine tune their contract position) 4
- (Voluntary) Balancing mechanism
  System operator (SO) accepts offers and bids from all participants to balance the system in real-time
- SO (NGC) responsible for energy (demand = supply) and system balancing (freq and voltage within limits)
  Combination of AS contracts, rescheduling of plant by accepting bids and offers; NGC own equipment
- Energy and access imbalance settlement

⇒

- Lower prices (at least 10% at the wholesale level over the medium term)
- Single price (no capacity payment)
- Increased transparency in operation and pricing
- Increase on flexibility and controllability of system operation
- More direct demand-side participation
- Focus on bilateral contracts and firm trades
- Greater choice of markets

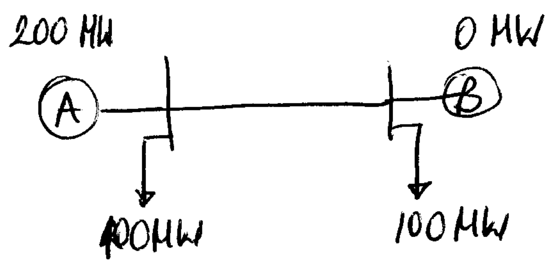
Department of Electrical and Electronic Engineering Examinations 2002 **Confidential**

Model Answers and Mark Schemes First Examiner: POPOVIC ; PAL

Paper Code: E4.39 Second Examiner: PAL ; POPOVIC

Question Number etc. in left margin | Mark allocation in right margin

3. b) (numerical example)



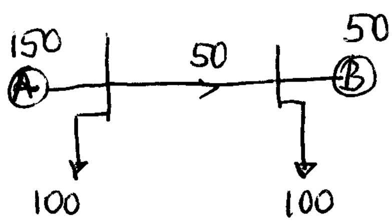
G_A : 200 MW
$IC_A = \$10/MWh$

G_B : 200 MW
$IC_B = \$20/MWh$

(i) If no transfer limit between zones (optimal costs): all 200MW of load will be supplied from G_A at \$10/MWh. cheaper 4

$\Rightarrow$ cost = \$2000/h

(ii) If there is a 50 MW transfer limit



150MW will be bought from G_A
$\Rightarrow cost_A = \$1500/h$

50 MW will be bought from G_B
$\Rightarrow cost_B = \$1000/h$ 4

Total cost = \$2500/h

So, congestion has created a market inefficiency of 25% of the optimal costs even without strategic behaviour by two generators.

(iii) Congestion has created unlimited market power for G_B. (G_B can increase its bid as much as it wants because the loads must still buy 50 MW from it). 2

G_B's market power can be limited if there is an additional generator in zone B with a higher incremental cost or if the loads had nonzero price elasticity (ie. can reduce their demands as prices increased) 2

/20

Model Answers (Dr. B. Pal)

4 Solution

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

[10x2=20]

5 solution

(a) **(Bookwork)** Static var compensators (SVC) are the forerunners of todays FACTS controllers. Developed in the early 1970s for arc furnace voltage unbalance compensation, they are being used in transmission systems in large scale for years. Simple Thyristor is at the heart of this class of device. A typically shunt connected static var compensator composed of thyristor controlled reactor (TCR) and fixed capacitor (FC) or Thyristor switched Capacitor (TSC) and TCR. The var output can be varied in a controlled way between the maximum inductive current and capacitive current rating. The voltage at the point SVC is connected is regulated through SVC by defining proper slope defined within the maximum current (inductive and capacitive)limits by control circuit. Beyond these range the SVC behaves as a passive device, i.e beyond capacitive maximum limit, it acts as a simple capacitor and beyond inductive limits it acts as a pure inductor. Outside its control range, reactive power injected to or absorbed from the system is proportional to the square of the system voltage.
Static synchronous compensator (STATCOM) is also a controllable shunt reactive power source or sink. It is relatively new concept and topology. The device utilizes voltage sourced converter (VSC) technology. For reactive power compensation, a capacitor is adequate on the DC side. STATCOM has an additional features that when equipped with energy storage source , it can exchange real power with the system. The STATCOM provides reactive power compensation which is independent of system voltage in a wide range (0.2 p.u. to 1.1 p.u.) unlike SVC. STATCOM results in

higher power transfer capacity of the system than that of SVC of comparable rating. The transient stability margin improvement capacity of STATCOM is also larger than that of SVC. [Students can alternatively answer this question through VI characteristics of both the devices **[5]**

(b) (**Bookwork**) The current that flows through the line is in Fig 5.1 is :

$$\overline{I} = \frac{V_s\angle\delta - V_r\angle 0}{jX_L} \tag{5.1}$$

The complex power injected is

$$P + jQ = \overline{V_s}\,\overline{I}^* \tag{5.2}$$

The substitution of $\overline{I}$ from (5.1) into (5.2) and equating the real components on both side the well known expression of real power results

$$P = \frac{V_sV_r}{X_L}sin\delta \tag{5.3}$$

[5]

(c) (**Bookwork and new computed example combined**) The series capacitor when installed in the line, the overall reactance would change to $(1-k)X_L$. In view of this the expression for power angle equation would be modified to

$$P = \frac{V_sV_r}{(1-k)X_L}sin\delta \tag{5.4}$$

Note that $k = 0$ takes (5.4) to (5.3). In otherwords, $k = 0$ is no compensation case and all other cases would be compared against this. (5.4) is sinusoidal curve. the amplitude of this curve, $\frac{V_sV_r}{(1-k)X_L}$, is influenced by k. Figure 5.1 shows the variation of line power P versus δ for different values of k. $\frac{V_sV_r}{X_L}$ is taken as 1.0 p.u. It is seen that as k is increased the amplitude of the power transfer curve is increased. In other words, for same transmission angle δ, the amount of power transfer is increased with increasing degree of compensation. This has direct bearing on the stability margin of the system. Thus the influence of series capacitor in transmission power flow control is very beneficial both from from the perspective of power flow control in the steady state and in dynamic state (stability margin).

[10]

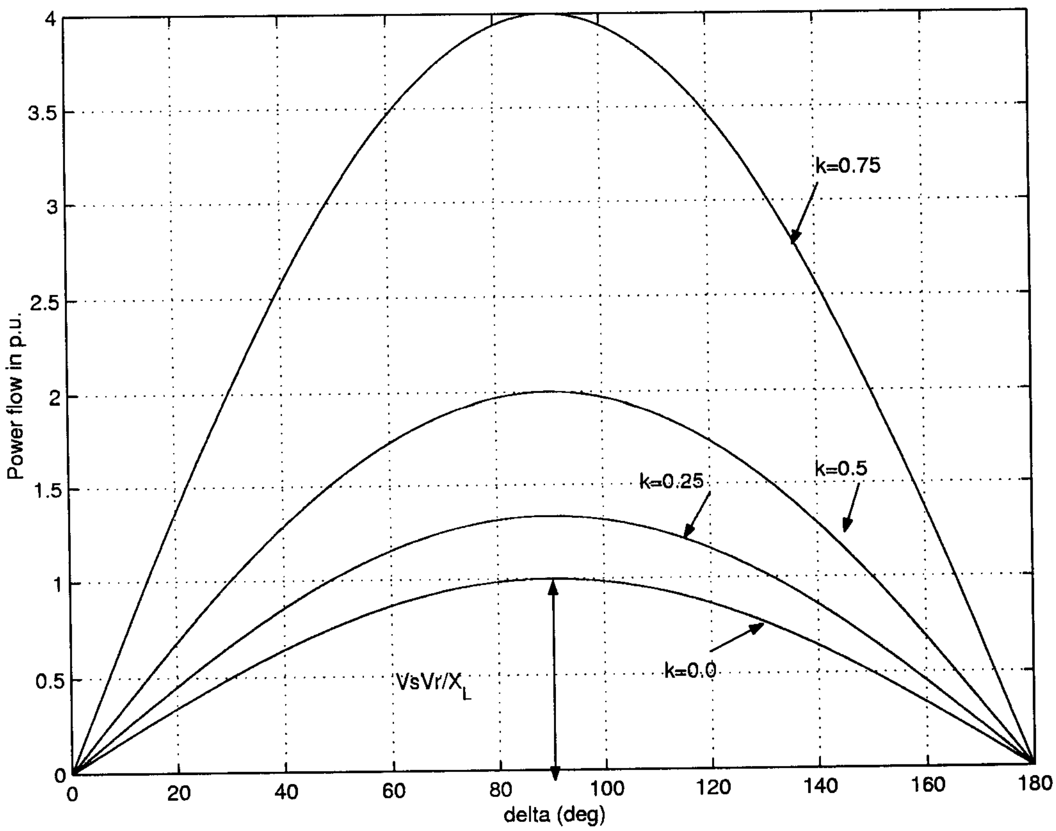


Figure 5.1

6 solution

(a) **(Bookwork)**
Fixed parameters($\mathbf{p}$): θ_1, P_2, P_3 and Q_3
State variables ($\mathbf{x}$): θ_2, V_3 and θ_3
Control variables ($\mathbf{u}$): V_1 and V_2

[5]

(b) **(New computed example)**
First the Y_{bus} matrix has to be constructed. This can be done through infection of Figure 6.1 in question paper.

$$Y_{bus} = \begin{bmatrix} +5-j10 & -3+j5 & -2+j5 \\ -3+j5 & +7-j15 & -4+j10 \\ -2+j5 & -4+j10 & +6-j15 \end{bmatrix} \tag{6.1}$$

This can be resolved into $G_{bus} + jB_{bus}$ **[3]**

The objective function $f(\mathbf{x},\mathbf{u},\mathbf{p})$ is the real power output of bus1:

$$P_1 = V_1V_2[G_{12}cos(\theta_1-\theta_2)+B_{12}sin(\theta_1-\theta_2)] \\ +V_1V_3[G_{12}cos(\theta_1-\theta_2)+B_{12}sin(\theta_1-\theta_2)]+V_1^2G_{11} \tag{6.2}$$

The constraint vector function $g(\mathbf{x},\mathbf{u},\mathbf{p})$ comes from power flow equations:

$$P_2 = V_2V_1[G_{21}cos(\theta_2-\theta_1)+B_{21}sin(\theta_2-\theta_1)] \\ +V_2V_3[G_{23}cos(\theta_2-\theta_3)+B_{23}sin(\theta_2-\theta_3)]+V_2^2G_{22} \tag{6.3}$$

$$P_3 = V_3V_1[G_{31}cos(\theta_3-\theta_1)+B_{31}sin(\theta_3-\theta_1)] \\ +V_3V_2[G_{32}cos(\theta_3-\theta_2)+B_{32}sin(\theta_3-\theta_2)]+V_3^2G_{33} \tag{6.4}$$

$$Q_3 = V_3V_1[G_{31}sin(\theta_3-\theta_1)-B_{31}cos(\theta_3-\theta_1)] \\ +V_3V_2[G_{32}sin(\theta_3-\theta_2)-B_{32}cos(\theta_3-\theta_2)]-V_3^2B_{33} \tag{6.5}$$

[5]

(c) The derivatives $\frac{\partial f}{\partial \mathbf{x}}$ are

$$\frac{\partial P_1}{\partial V_3} = V_1[G_{13}cos(\theta_1-\theta_3)+B_{13}sin(\theta_1-\theta_3)] \tag{6.6}$$

$$\frac{\partial P_1}{\partial \theta_2} = V_1V_2[G_{12}sin(\theta_1-\theta_2)-B_{12}cos(\theta_1-\theta_2)] \tag{6.7}$$

$$\frac{\partial P_1}{\partial \theta_3} = V_1V_3[G_{13}sin(\theta_1-\theta_3)-B_{13}cos(\theta_1-\theta_3)] \tag{6.8}$$

The derivatives $\frac{\partial f}{\partial \mathbf{u}}$ are

$$\frac{\partial P_1}{\partial V_1} = V_2[G_{12}cos(\theta_1-\theta_2)+B_{12}sin(\theta_1-\theta_2)] \\ +V_3[G_{13}cos(\theta_1-\theta_3)+B_{13}sin(\theta_1-\theta_3)]+2V_1G_{11} \tag{6.9}$$

$$\frac{\partial P_1}{\partial V_2} = V_1[G_{12}cos(\theta_1-\theta_2)+B_{12}sin(\theta_1-\theta_2)] \tag{6.10}$$

[4]

Given the initial conditions $V_{10} = V_{20} = V_{30} = 1.0$ p.u.and $\theta_{10} = \theta_{20} = \theta_{30} = 0.0$; the values of these derivatives in (6.6) to (6.10) with obtained values G_{bus} and B_{bus} in section (b) are computed and the results are given:

$$\left.\frac{\partial P_1}{\partial V_3}\right|_{V_{10},V_{20},V_{30},\theta_{10},\theta_{20},\theta_{30}} = 2.0$$

$$\left.\frac{\partial P_1}{\partial \theta_2}\right|_{V_{10},V_{20},V_{30},\theta_{10},\theta_{20},\theta_{30}} = 3.0$$

$$\left.\frac{\partial P_1}{\partial \theta_3}\right|_{V_{10},V_{20},V_{30},\theta_{10},\theta_{20},\theta_{30}} = 3.0$$

$$\left.\frac{\partial P_1}{\partial V_1}\right|_{V_{10},V_{20},V_{30},\theta_{10},\theta_{20},\theta_{30}} = 5.0$$

$$\left.\frac{\partial P_1}{\partial V_2}\right|_{V_{10},V_{20},V_{30},\theta_{10},\theta_{20},\theta_{30}} = -3.0$$

[3]