E4.39
C5.24

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2006

EEE PART IV: MEng and ACGI

Corrected Copy

ENVIRONMENTAL & ECONOMIC ISSUES IN POWER SYSTEMS

Tuesday, 2 May 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Please use separate answer books for Sections A and B.

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

Examiners responsible	First Marker(s) :	C.A. Hernandez-Aramburo, B.C. Pal
	Second Marker(s) :	G. Strbac, G. Strbac

Part A

1. The following questions relate to the use of nuclear power for electricity generation in the UK.

a) Comment briefly on the following issues:

i) The contribution of nuclear power to the current electricity generation mix

ii) The savings on CO_2 emissions by the existing nuclear plants over equivalent gas-fired plants

iii) How the existing nuclear contribution will be phased out (planned plant closure)

[4]

b) Describe in some detail three important advantages of nuclear power

[6]

c) Describe in some detail three important disadvantages of nuclear power

[6]

d) Comment on the possibility of replacing the current nuclear install with clean coal technologies and renewable energy sources.

[4]

2. The initial design of a small energy system based on a wind turbine is required. This system will be installed in the Scottish island of Tiree, where the air density is estimated at 1.29 kg/m^3 and the annual average wind-speed is 7.4 m/s. The system should deliver 5000 kWh annually at the point of consumption, and very low maintenance is a strong design specification.

a) Select an appropriate topology for your proposed design and justify your selection.

[6]

b) Mention two other topologies that you have discarded and explain very briefly why they were discarded.

[4]

c) Estimate the radius of a horizontal-axis wind-turbine for the topology you are proposing. Use your engineering judgement to estimate the value of any parameter that you are not given in this problem.

[10]

3. Explain the following concepts in relation to the UK Electricity market

a) Explain why the bulk of the financial operations are shifted in time ahead of the actual delivery of electricity.

[6]

b) What is the *Balancing Mechanism*?

[8]

c) What is the *Imbalance Settlement*?

[6]

Part B

4. (a) (i) Explain the limitations of AC network in the context of power transmission.

[4]

(ii) Justify how FACTS technology can address those limitations explained in (i)

[6]

(b) Discuss the basic differences between switching voltage converter based and thyristor based FACTS devices? Justify your arguments in relation to static var compensator (SVC) and static compensator (STATCOM)

[10]

5. (a) Discuss the technical and commercial benefits of optimal power flow (OPF)

[6]

(b) Figure 5.1 describes a 3-bus power system model. The load at bus 3 is $(2+j1.0)$ p.u. The generation at bus 1 is fixed at 1.0 p.u. All the bus voltage angles are expressed with respect to that of bus 1. The line parameters are shown in the diagram. The objective is the minimisation of generation at bus 2 which, in the context of this problem, is also equivalent to minimising total power loss in the system. For this objective

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

[5]

(ii) Obtain the $Ybus$ matrix.

[3]

(iii) Formulate the objective function f(**x**,**u**,**p**), constraint vector function **g(x,u,p)** with the variables and parameters identified in part (a) 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 $Y_{km} = G_{km} + jB_{km}$.

[6]

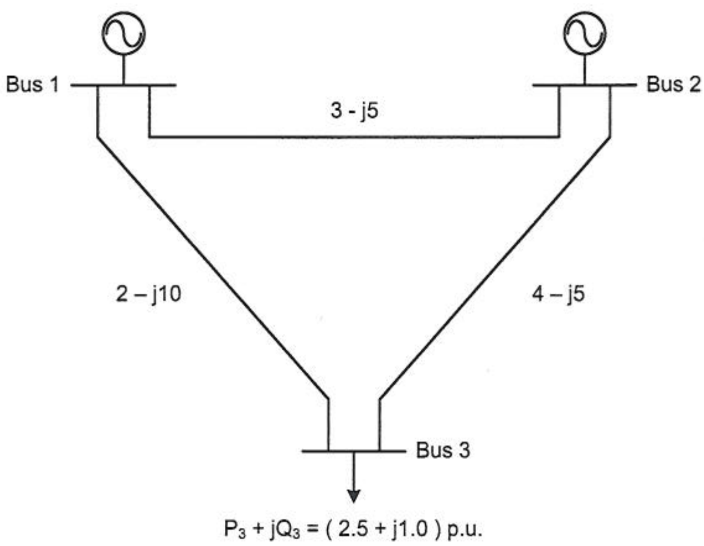


Figure 5.1: A three-bus power system model

6. Explain any four of the following.

[5x4=20]

(a) Transfer capacity of lines

(b) Role of unified power flow controller (UPFC) in power transmission

(c) Netwon's method in OPF solution

(d) Security constraint OPF

(e) Role of bus incremental cost (BIC) as a power transmission pricing tool

(f) Various limits associated with OPF formulation

20/4/06

IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE
UNIVERSITY OF LONDON

Department of Electrical and Electronic Engineering

Examinations 2006

MODEL ANSWERS

E 4.39 Environmental and economic issues in power systems

Authors: Dr C. A. Hernandez and Dr B. Pal

Special instructions for invigilators

This section may be omitted.

Special instructions for students

Throughout this paper the word circuit is used to mean a cycle in a directed graph. The value of the fine structure constant may be assumed to be 137.

If both sections here are omitted (the normal case) the whole page may be deleted.

Model answers (PART- A)

1. **The following questions relate to the use of nuclear power for electricity generation in the UK.**

This is a bookwork-type question where the students need to recall the major issues discussed in the course lectures regarding this technology.

a) Comment briefly on the following issues:

i) The contribution of nuclear power to the current electricity generation mix

ii) The savings on CO_2 emissions by the existing nuclear plants over equivalent gas-fired plants

iii) How the existing nuclear contribution will be phased out (planned plant closure)

[4]

i) The current contribution of nuclear power to the electricity generation mix is very substantial, accounting for 19.3% (according to 2004 figures).

ii) It currently saves between and 8 and 10 millions of CO_2 emissions over gas-fired generation, which represents a 5% of the total emissions of the UK in 2004.

iii) The smallest (and oldest) plants are planned to be shut down by 2011, and only 8 nuclear reactors will remain in operation. Between 2011 and 2015, three of the remaining power plants will be closed down, leaving the UK with a third of its current nuclear generation capability. The remaining 3 plants will be shut down by 2015.

b) Describe in some detail three important advantages of nuclear power

[6]

These are some of the issues discussed during lectures:

1. No dependency on fossil fuels.
2. Do not generate carbon dioxide.
3. Can help to secure energy supplies and bridge the energy gap (UK but also world wide)
4. retaining the valuable skills and expertise necessary for further developments (fusion, Gen IV reactors) and other correlated areas such as defence and health sectors

c) Describe in some detail three important disadvantages of nuclear power

[6]

1. Nuclear waste remains dangerous for thousands of years (this is a safety issue and an ethical problem as well)
2. Risk is high (probability of an accident is small but the consequences are huge)
3. Risk of proliferation of non-peaceful nuclear activities
4. Fuel transportation represents a big risk
5. Nuclear power plants and their fuel are war prime targets
6. Fairly short-life (<60 years even for new reactor designs)

d) Comment on the possibility of replacing the current nuclear install solely with clean coal technologies and renewable energy sources.

[4]

The student should base his/her answer on the following lines:

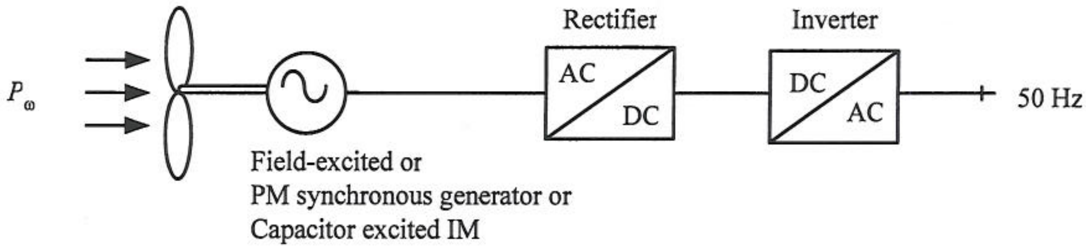
- Clean coal technologies are not mature enough to serve as a direct replacement for the nuclear power plants that will be shut down in the short term.
- Clean coal technologies are still an expensive choice. The price for clean coal technologies (gasification in particular) is estimated at £32/MWh, which represents a significant cost increment from traditional pulverised coal technology at £25/MWh, this new cost is not competitive with the cost of nuclear energy (£23/MWh).
- If renewable power is to be a replacement for nuclear power, its deployment rate needs to be accelerated. This could prove to be an expensive action.

2. The initial design of a small energy system based on a wind turbine is required. This system will be installed in the Scottish island of Tiree, where the air density is estimated at 1.29 kg/m^3 and the annual average wind-speed is 7.4 m/s. The system should deliver 5000 kWh annually at the point of consumption and very low maintenance is a strong design specification.

a) Select an appropriate topology for your proposed solution and justify your selection.

[6]

The required power at the point of consumption is P=5MWh/(365x24)=571W. This is a reasonable small system that can be implemented with a direct drive, as shown in the figure below. Fairly low maintenance is a characteristic of this topology.



b) Mention two other topologies that you have discarded and explain very briefly why they were discarded.

[4]

- Topologies based on gearboxes were discarded on the basis of a high maintenance requirement.
- Topologies based on DFIGs were discarded because they require more maintenance (on the slip rings) than direct drive topologies, and they do not offer a significant cost saving (if any) for the required size (~570W).

c) **Estimate the radius of a horizontal-axis wind-turbine for the topology you are proposing. Use your engineering judgement to estimate the value of any parameter that you are not given in this problem.**

[10]

(This is a question involving a numerical exercise new for the students)

$$P_{delivered} = \frac{E_{delivered,annually}}{\left(365 \frac{days}{year}\right)\left(\frac{24h}{day}\right)} = \frac{5\times10^6\ Wh}{365\times 24\ h} = 570.78\ W$$

$$P_{extracted} = \frac{P_{delivered}}{\eta_{gen}\times\eta_{AC/DC}\times\eta_{DC/AC}} = \frac{570.78\ W}{\underbrace{(0.9)(0.97)(0.95)}_{Estimated}} = 688.22\ W$$

From:

$$P_{extracted} = C_p \frac{1}{2}\rho A V^3$$

$$A = \frac{2P_{extracted}}{\underbrace{C_p}_{estimated}\rho V^3}$$

$$r = \sqrt{\frac{2P_{extracted}}{C_p \rho V^3 \pi}} = \sqrt{\frac{(2)(688.22)}{\underbrace{(0.35)}_{Estimated}(1.29\ kg/m^3)(7.4\ m/s)^3\pi}}$$

$$\underline{r = 1.547\ m}$$

3. **Explain following concepts in relation to the UK Electricity market**

This is a bookwork-type question.

a) Explain why the bulk of the financial operations are shifted in time ahead of the actual delivery of electricity.

[6]

The delivery of electricity requires a considerable amount of engineering expertise in power systems. For the grid to operate reliably, stably and with a reasonable margin of security, some "ancillary services" must be in place. Among these services are reactive power compensation, frequency response, reserve power, fast reserve power and black start. Analysing the role of each of these services is out of the scope of this course; it is only important to emphasise that there are a number of crucial technical issues behind the operation of a large power system.

The technical requirements for electricity delivery and the fact that electricity is not being stored at an AC utility level, a true spot market (instant pricing and delivery) cannot be implemented. For this reason financial transactions must be scheduled some time in advance of the physical delivery. Electricity can be traded up to one year in advance or few hours previous to the actual delivery.

b) What is the Balancing Mechanism?

[8]

The balancing mechanism takes places after the gate closure and during the physical delivery of electricity. This mechanism has three main objectives:

i. to conciliate the (hopefully small) differences between supply and demand
ii. to address the physical requirements for optimising generation and demand
iii. to allow the system operator to buy the ancillary services in order to preserve the integrity of the network.

The balancing action to bring into agreement supply and demand takes the form of "bids" and "offers" to the system operator. Generators willing to supply more energy than their FPNs, or suppliers willing to consume less energy than their FPNs, will submit offers to NG. Conversely, those generators that would like to produce less energy, or suppliers consuming more energy, will submit bids. Only about 2 per cent of electricity is bought and sold by NG in the balancing mechanism.

c) What is the Imbalance Settlement?

[6]

Generators are out of balance if they cannot provide all the electricity they have been contracted to provide (according to the FPNs), or if they have generated too much. Suppliers are out of balance if they have consumed more electricity than they have contracted for, or if they have consumed too little. This unbalance in the participants means that NG incurs in additional costs because it has to buy or sell electricity at short notice to keep the system in balance. The participants that are out of balance face certain charges (prices) based on the additional costs the system operator has incurred. This process, known as *imbalance settlement*, takes place after the closure of the balancing mechanism (after ΔT0).

Figure 1 shows the energy imbalance of two generators at the end of ΔT0. The generator on the left sold a surplus of energy during the balancing process and is charged for it according to the system selling price (SSP). The generator on the right was in deficit of generation during the balancing process according to its own notification, and therefore it is charged according to the System Buy Price (SBP). Both the SSP and SBP are determined after ΔT0. A similar situation occurs for a supplier that consumes less (or more) energy than the contracted volume.

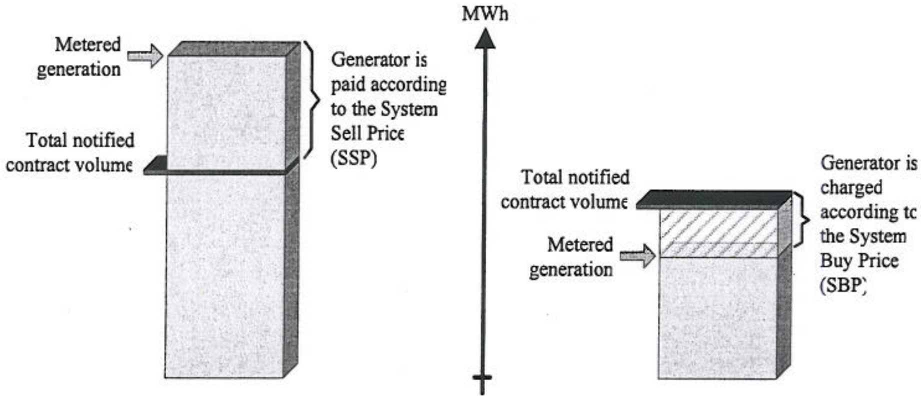


Figure 1. Two generators in imbalance

Under NETA, the settlement process is carried out by a non-profit making organisation called ELEXON under the Balancing and Settlements Code (BSC). Settlement is not to price and pay bulk purchases of electricity, but to deal with differences between contractual position and metered consumption or generation.

PART B: Dr Pal

Problem 4.

(a) (i) **(Bookwork)**

The power flows in AC network are dictated by the line impedance, voltage magnitude and phase angle. In the absence of any control over these parameters and variables, the full power transfer capacity remains unutilized. Because of the meshed nature of the system, sometimes loop flows take place. Such situation gives rise to additional copper loss and also poor voltage regulations. The transmission efficiency thus drops. In longer lines, the power transfer is limited by stability consideration. Even though the voltage regulation problem is addressed through mechanically switched shunt capacitor and reactors, the variation in operating conditions does not allow theses device to control voltage effectively.

[4 marks]

(ii) **(Bookwork)**

The FACTS devices make the transmission network more controllable. Essentially through voltage magnitude, phase angle and line impedance control, the power transfer characteristics of AC lines can be modified to suit the desired objective. The student is expected to illustrate this through power angle sketch. They should also show the effects of angle, magnitude and impedance on the real and reactive power transfer. Unlike in fixed shunt reactor/capacitor the controls associated with FACTS are very fast. Depending on the topology, power flow can be controlled through voltage magnitude, phase angle and line reactance control as appropriate.

[6 marks]

(b) **(Bookwork)**

Thyristor based controllers such as TCSC and SVC can introduce variable series capacitance and shunt capacitance respectively within the control range. The reactive power compensation is dependent on line current and bus voltage respectively for TCSC and SVC. At high current and low voltage network conditions, they are not very useful; rather they are taken out of service. The convertor based facts controllers operates on the principle of synchronous voltage source and hence their actions are virtually independent of the network operating condition. They can be used during contingency conditions also with proper control. Forced commutated switches such as GTO and IGBT etc. are used in voltage sourced converter. The SVC, TCSC and TCPAR uses simple thyristor where the turning on instant of the switches are controlled but not the turning off. In the second category both turn on and turn off instants are controlled. The facts controllers that employ forced commutated voltage source switching converters to rapidly realise controllable synchronous ac voltage or current sources. This approach provides superior performance when compared to thyristor based controllers. Ideally, voltage sourced converters are variable voltage and variable angle three phase synchronous machines with no inertia. These sources can exchange (generate) or absorb reactive power. When coupled with energy storage options, it can even exchange (supply/absorb) real power with the ac system.

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 where SVC is connected is regulated by defining proper slope defined within the maximum current (inductive and capacitive)limits by control circuit in SVC. 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 of its control range, the 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 **[10 marks]**

Problem 5.

(a) (**Bookwork**)
The OPF is an important tool that benefits the system planner, opeartor, bidders in the power market. Few of these benefits are listed below.

(i) The calculation of optimal generation pattern to achieve minimum cost of total generation whilst meeting the transmission system limitations.

(ii) When security constraints are incorporated, using short-term load forecast, a 'preventive dispatch' schedule can be generated from the output of the OPF.

(iii) In an emergency, when some component of the system is overloaded or a bus is experiencing a voltage violation, the OPF can provide a corrective dispatch that tells the operator to make appropriate adjustment to come out of that situation.

(iv) The OPF can be used periodically to find optimum setting for generator bus voltages, transformer taps, switched capacitors and static var compensators. This is known as reactive power optimisation.

(v) This is used routinely in planning studies to determine the maximum stress that a planned system can stand.

(vi) For economic analysis *Bus Incremental Cost* (BIC) which is the output of OPF can be used for transmission pricing, cost of wheeling and spot pricing etc. This is very useful information for transmission pricing in today's open power market environment.

[6 marks]

(b) (**Bookwork and computed example combined**)

(i) Fixed parameters($\mathbf{p}$): θ_1, P_1, 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 marks]

(ii) (**New computed example**)
First the Y_{bus} matrix has to be constructed. This can be done through inspection of Figure 5.1 in question paper.

$$Y_{bus} = \begin{bmatrix} +5-j15 & -3+j5 & -2+j10 \\ -3+j5 & +7-j10 & -4+j5 \\ -2+j10 & -4+j5 & +6-j15 \end{bmatrix} \tag{0.1}$$

This can be resolved into $G_{bus} + jB_{bus}$

[3 marks]

The objective function $f(\mathbf{x},\mathbf{u},\mathbf{p})$ is the real power output of bus 2:

$$P_2 = V_2V_1[G_{21}cos(\theta_2 - \theta_1) + B_{21}sin(\theta_2 - \theta_1)] \\ + V_2V_3[G_{23}cos(\theta_2 - \theta_3) + B_{23}sin(\theta_2 - \theta_3)] + V_2^2G_{22} \tag{0.2}$$

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

$$P_1 = V_1V_2[G_{12}cos(\theta_1 - \theta_2) + B_{12}sin(\theta_1 - \theta_2)] \\ + V_1V_3[G_{13}cos(\theta_1 - \theta_3) + B_{13}sin(\theta_1 - \theta_3)] + V_1^2G_{11} \tag{0.3}$$

$$P_3 = V_3V_1[G_{31}cos(\theta_3 - \theta_1) + B_{31}sin(\theta_3 - \theta_1)] \\ + V_3V_2[G_{32}cos(\theta_3 - \theta_2) + B_{32}sin(\theta_3 - \theta_2)] + V_3^2G_{33} \tag{0.4}$$

$$Q_3 = V_3V_1[G_{31}sin(\theta_3 - \theta_1) - B_{31}cos(\theta_3 - \theta_1)] \\ + V_3V_2[G_{32}sin(\theta_3 - \theta_2) - B_{32}cos(\theta_3 - \theta_2)] - V_3^2B_{33} \tag{0.5}$$

[6 marks]

Problem 6.

(a) **Capacity of lines**(*Bookwork*) The capacity of a transmission line in an interconnected system of operation is defined as the amount of MW that can be transferred without violating operational constraints such as thermal, voltage and stability limits. Usually thermal capacity varies over atmospheric conditions. For shorter lines the thermal capacity are the limiting factors. However for longer lines voltage regulation and stability related issues decides the capacity. Transmission system operators use this as constraint and any mechanism to address this constraint out lead to congestion charge to parties (generation company) who are responsible for it. Some players buy the capacity in the forward market and trade it in the balancing market.

[5 marks]

(b) **Role of unified power flow controller in power transmission**(*Bookwork*) Unified power flow controller (UPFC) is a most versatile member of FACTS based on forced converter technology. It is a hybrid device that has series and shunt converter. Consequenctly functionality of series converter (power flow and impedance control) and shunt converter (bus voltage control) can be realised. Two degrees of freedom associated with each converter allow four objectives to be achieved. The required control can be designed to achieve one of the four functions (line impedance, phase angle, shunt voltage and voltage regulation) or combination of some or all of them. This makes this device so versatile. The students are expected to draw the basic diagram of the device and possibly operating characteristic in PQ plane.

[5 marks]

(c) **Newton's method in OPF solution***(Bookwork)* Usually the objective and constraints are highly nonlinear functions requiring suitable nonlinear optimization techniques for solution. Many methods that exploit the gradient information are used for OPF solution. The problem with gradient methods are the direction of gradient changes as the iterative solution steps proceed. This requires calculation at the begining of each itertaion. This is computationally expensive for system with large number of constraints. On the otherhand, the solution speed slows down and takes larger number of iterations if gradient is not updated. The Netwon method has the advantage that it converges very fast (quadratic convergence) as it takes the derivative of the gradients with respect to the decision and control variables. The complexity of equations and manipulations are larger here but the number of iterations needed for the solution are very less. It is also not required to update the Jacobean always. Overall the solution time is much reduced than that in other gradient based methods. The problem of handling the inequality constraints can be addresed as a penalty function. Some suitable quadratic functions of bus voltage magnitudes when added to objective functions, Newton's method performs easily in the presence of inequality constraints. The students can illustrate penalty function a little bit to impress upon the examiner further.

[5 marks]

(d) **Security constraint OPF**(*Bookwork*) In basic optimal power flow problem formulation and solution we generally assume power flow constraints for fixed topology and load schedule. In real world the operating point changes as generation and demand change. The network configuartion also varies for various reasons. What will be very useful in OPF to include these possibilities/contingencies and come with a solution that will be available to the operator. The OPF that incorporates these is known as security constraint OPF. The base case optimum operation conditions for a power system will often result in violation of system security. This is especially true when a large amount of interchange power is available at a favourable price. In this instance the selling power system can be modelled in the OPF with its price of production set accrodingly, and the OPF will then raise the interchange up to the point where transmission system components are limiting. Now when the contingency analysis is run, there may be many cases which result in contingency violations and the OPF, with constraints added, will have to back off the interchange power in order to meet the contingency limits. With added contingency constraints added to OPF solution, the generation will be redispatched; voltage and transformer control will be adjusted to meet these constraints.
This works out well with the inclusion of each contingency case as set off AC load flow for that contingency into OPF. Usually there will be a limited number of such credible contingency cases which will have significant impact. The contignecy screeing algorithm needs to be integrated to this procedure.

[5 marks]

(e) **Role of bus incremental cost as a power transmission pricing tool***Bookwork* Let's take the classical Lagrange equation for an optimal power flow

$$L(\mathbf{x}, \mathbf{u}, \mathbf{p}) = f(\mathbf{x}, \mathbf{u}) + \lambda^t \mathbf{g}(\mathbf{x}, \mathbf{u}, \mathbf{p}) \tag{0.6}$$

Let's assume that we have an optimal solution to this problem and then ask an interesting question: "What is the change in optimal operating

cost if we change one of the parameters $\mathbf{p}$?" More specifically: "What is the change in optimal operating cost if we change the power produced or consumed at a bus in the network?". What we want is the derivative information:
$\frac{\partial L}{\partial P_i}$ Let's evaluate this for simple load bus where demand is specified. This will produce

$$\frac{\partial L}{\partial P_i} = \lambda_i \tag{0.7}$$

We now can have a new interpretation of Lagrange multipliers: they indicate the increment in optimal cost with respect to small changes in the parameters of the network. In the case of small change in power, either consumed or produced at a bus, the Lagrange multiplier for that bus then indicates the incremental cost that will be incurred as a result of this change. This cost is known as bus incremental cost (BIC). The BIC is is a useful concept for nondispatched generator buses and for evaluating the marginal cost of wheeling. In some proposed schemes, this bus incremental cost is used to establish spot market price for energy. Some methods of OPF solution may not produce the Lagrange multiplier directly (say LP technique), in those cases it can be obtained from the solution of the following:

$$\left[\frac{\partial \mathbf{g}}{\partial \mathbf{x}}\right]^T \lambda = -\left[\frac{\partial \mathbf{f}}{\partial \mathbf{x}}\right] \tag{0.8}$$

[5 marks]

(f) **Various limits associated with OPF formulation***Bookwork* Primarily there are three categories of variables in OPF: decision variables, control variables and fixed parameters which can be used for sensitivity analysis for pricing etc. Decision variables will have the limits. For example bus voltage magnitude in EHV transmission system is typically allowed to vary within ±5%. The OPF must include them in order to respect these. Control variables have limits: typically, OLTC operating range, FACTS limits, HVDC modulation control limits, shunt and series compensator,generator reactive power limits, real power limits all come under this. In security constrained power flow, line MVA limits are very important. The students can offer explanation to operational limits associated with various important components.

[5 marks]