E4.39

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2005

EEE PART IV: MEng and ACGI

Corrected Copy

**ENVIRONMENTAL & ECONOMIC ISSUES IN POWER SYSTEMS**

Monday, 16 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) : | B.C. Pal, C.A. Hernandez-Aramburo |

## Section A

1. A photovoltaic-based system is being assessed to provide power to a domestic application. Grid connection and batteries are required, but no other energy source is required.

   (a) Draw a block diagram of the main elements to deliver the power from the PV panel to the electrical installation. Provide a very brief explanation regarding the function of each block. [4]

   (b) Estimate the overall efficiency of the system you have proposed above. Explain the reasoning behind your estimate. [6]

   (c) Estimate the area you would require to cover with PV panels to deliver an average power of 500W over a year to the domestic installation. The average annual insolation for this particular location is 3000Wh/$m^2$ per day. The effects of tilt and orientation on the PV panels have been included in this insolation figure. A particular panel technology has not been chosen yet, but you have been advised to be conservative with respect to the achievable efficiency of the panels. [7]

   (d) Mention, and briefly explain, the difficulties that utility-size PV systems may encounter for successful adoption in the UK [3]

[4.39]

2. Explain why distributed generation schemes have been increasingly promoted worldwide. Include in your explanation the situation in Europe, USA and also developing countries. [20]

[4.39]

3 Answer the following questions with respect to the UK electricity market:

(a) Explain the need of having a system operator and its role under NETA [7]

(b) What are the main changes that BETTA will bring over NETA? [6]

(c) Explain why the pool-based market (predecessor to NETA) did not succeed in the UK [7]

## Section B

[4.39]

4. (a) What are operational consequences of loop flows in AC transmission? [2]

   (b) Discuss the usefulness of the method of bus incremental cost(BIC)in transmission pricing. [3]

   (c) How do the voltage and current profiles across the transmission length look like at surge impedance loading (SIL) ? [3]

   (d) Discuss various objectives and constraints in optimal power flows. Discuss the suitability of various mathematical tools to handle these constraints. [6]

   (e) Explain the relative advantages and disadvantages of on load tap changing transformer (OLTC) and static var compensator (SVC), as voltage control services from the perspective of transmission system operator (TSO). [6]

[4.39]

5. (a) What is meant by *loadability* of a transmission line in an interconnected system of operation? With the help of St. Clair curve (loadability curve) explain how various factors affect transmission system loadability [8]

(b) What are the basic differences between a thyristor based FACTS controller and a voltage source based FACTS controller? [5]

(c) Figure 5.1 shows a simple model of an interconnected power system. Voltages at the two ends are $V_s\angle\delta$ pu and $V_r\angle 0$ p.u. The impedance of the line is purely reactive in nature and is expressed as $X_L$ p.u. The system is transferring power $P$ with about 29% capacity margin $\left(\frac{P_{\max}-P}{P_{\max}}.100\%\right)$. If the line is series compensated with a capacitor $X_C = kX_L$. What degree of compensation $k$ is needed to improve this margin to 40% for the same power transfer? [7]

*Hint: The following relations might be useful*

$$P = P_{max}Sin(\delta)$$
$$P_{max} = \frac{V_s V_r}{X_L}$$

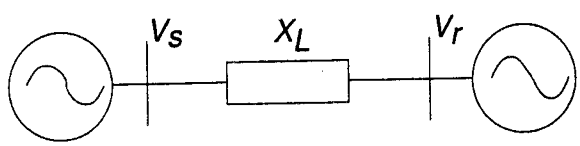


Figure 5.1: A two-area power system

[4.39]

6 (a) What is an optimal power flow (OPF) in power system operation? [3]

(b) Discuss the importance of OPF in the context of fair and competitive power market operation. [4]

(c) A power four-bus power system shown in Figure 6.1 has two load buses (bus 2 and 3) and two generator buses (bus 1 and 4). The bus voltage and angles in bus 1 to 4 are $V_i\angle\theta_i, \forall i = 1\ to\ 4$. The load bus powers are $P_2, P_3, Q_2, Q_3$, the generator output powers are $P_1$ and $P_4$ respectively. The lines have finite resistances and reactances. Each load is connected to load bus through on-load tap-changing transformers(OLTC) with tap positions $t_1$ and $t_2$. The objective $f(\mathbf{x,u,p})$ is to minimize total transmission losses in the network. List the state(**x**)and control(**u**) variables and fixed parameters(**p**). [7]

(d) The equality constraints in achieving the objective in part 6.c is **g(x,u,p) = 0**. Find the optimal direction of the movement of the objective $f(\mathbf{x,u,p})$ with respect to control vector **u**. You may assume bus 1 as reference bus. [6]

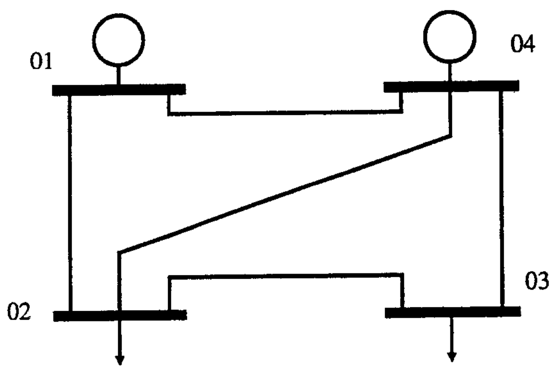


Figure 6.1: A four-bus power system

IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE
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Department of Electrical and Electronic Engineering

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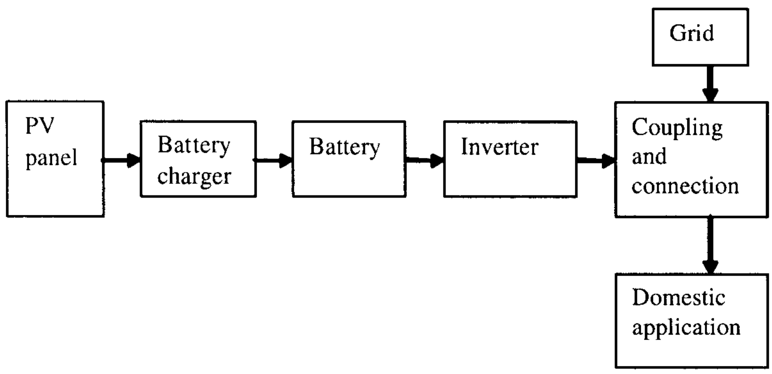
# MODEL ANSWERS

## E 4.39 Environmental and economic issues in power systems

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

## Problem 1. Numerical example

1. A PV system block diagram for domestic application In brief:




The PV panel converts light to DC power; the charger manages the amout of energy into the battery; the battery stores energy; the inverter converts DC to AC; and finally, the connection point manages the coupling between the three elements: the grid, the PV system and the domestic application. [4]

**NB.** This question has not an unique answer because there are many system topologies that may fulfil the requirements of the question.

2. Efficiency
The total efficiency of the system can be estimated as the product of the individual efficiencies:

$$\begin{aligned}\text{TotalEfficiency} &= \eta_{\text{PV}} \times \eta_{\text{Charger}} \times \eta_{\text{batt}} \times \eta_{\text{Inverter}} \\ &= 0.15 \times 0.93 \times 0.82 \times 0.93 = 0.1064 \approx 11\%\end{aligned}$$

[6]

**N.B.** The marks in this question are mainly awarded for being able to estimate reallistic efficiency figures. Efficiencies may vary; however, their typical values were discussed during the relevant lectures ($\pm 5\%$ are acceptable).

3. Area
At the **output** of the PV system:
Annual energy per year= 500W*24hr/day*365days =4380000Wh
Daily average energy=Annual energy/365days=12000Wh/day
(The multiplication and division by 365 is not necessary, but it is left

here for clarity to express that the amount of energy corresponds to an annual average)

At the **input** of the PV system:
Daily average energy = (12000 Wh/day)/(efficiency)=
= (12000 Wh/day)/(0.1064)= 112 780 Wh/day

The (given) average annual insolation is $3000Wh/(m^2\,day)$, therefore:

$$Area = \frac{112780\,Wh/day}{3000\,Wh/(m^2 * day)} = 37.5933m^2 \approx 38m^2$$

[7]

4. In broad terms, the answer should cover the following aspects:

    (a) high cost (which is not exclusive to the UK)

    (b) a very bad seasonal correlation between insolation and power demand

    (c) lack of economic incentives for utility-size systems.

[3]

## Problem 2. Bookwork

A full-mark answer should cover all these points:

- The de-regulation of the electricity market in many countries has encouraged participation in the generation sector, even at small scale.
- Environmental awareness [worldwide]
- Concerns over the dependence on (depleting) fossil fuels [industrialised countries]
- Departure from nuclear power [US and many countries in Europe]
- Improvement of the reliability of the grid [especially in the US]
- Reach areas where a national grid would be prohibitively expensive to lay or reinforce [poorer countries or isolated regions]
- Reach areas which have limited access to fossil fuels [some poorer countries]

[20]

## Problem 3. Bookwork

1. The System Operator manages the transmission system and preserves the integrity of the operation of the system. Some managerial tasks on both the technical and financial layers include: maintenance of the physical network, buying reactive power, reserve energy and fast reserve energy. Selecting bids during the balancing mechanism to meet the energy demand. A system operator is needed because of the inherent complexities of delivering electrical power (guaranteeing stability, technical constraints and security levels); which makes the electricity market different to any other commodity market. [7]

2. The two major changes BETTA will bring over NETA are: (1) including Scotland into the electricity market without the ownership of its transmission system and (2) Re-define the role of the S.O. to manage a transmission system without ownership. [6]

3. In principle, the pool-based system was not a bad system but it found serious problems:

   (a) It was very biased towards the generators side: generators could withhold capacity leading to an increase in price. In other words generators were able to manipulate the market.

   (b) Any drop in fuel costs was not passed to consumers. During the 1990s, the capital costs of new plants fell by nearly 40%, the efficiency of CCGT increased by more than 10%, spot gas prices fell by 50%; and yet, electricity pool prices actually increased by 10%.

   (c) Prices for electricity were set one day ahead from the actual delivery. This lead to an unwanted interaction with the gas market, which was operating closer to real time. Thus, gas generators could influence on the price of the day-ahead electricity; and shift their prices to more favourable conditions within the day of electricity delivery. This interaction was difficult to forsee because, at the Pool's inception, the gas-based energy generation was merely 0.6%; in 2000, the penetration of this form of generation had reached 38.9%

   (d) Bids issued by the generators were not simple quantity-price bids, but complex bids intended to reflect both the cost of the electricity and the technical constrains associated with delivering it.

   (e) Retailers had little impact on the price set by the pool; increasing the bias of the pool market structure towards the generators side

   [7]

# 4 Problem 4.

(a) **(Bookwork)**

$1 \longrightarrow B$

$2 \longrightarrow C$

$3 \longrightarrow J$

$4 \longrightarrow I$

$5 \longrightarrow H$

$6 \longrightarrow K$

$7 \longrightarrow G$

$8 \longrightarrow M$

$9 \longrightarrow E$

$10 \longrightarrow F$

**[10x2=20 marks]**

# 5 Problem 5.

(a) (**Bookwork**) The loadability 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. **[2 marks]**
The loadability of a transmission line can easily be explained with the help of St. Clair curve. This is very useful to planner and system

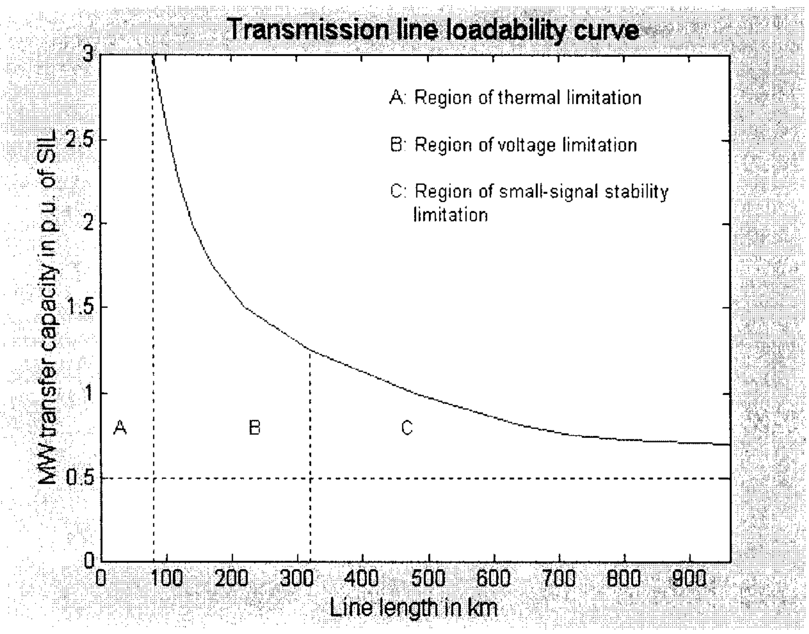



Figure 5.1: The St Clair Curve

operators. These curves are drawn on the basis single conductor line with 60 Hz operating frequency. For 50 Hz, a correction factor of 1.2 is to be multiplied. For bundle conductors the actual loadability would be little higher than the value produced by the curve as the surge impedance loading tends to increase because of increased surge impedance. Various factors that affect the line loadability are thermal, voltage regulation, and stability. For short lines of length less than 50 miles thermal characteristic is the limitation. This is restricted by sag and minimum ground clearance due to expansion of the conductors at high current and also irreversible change in mechanical strength at annealing temperature. Approximately a line of 50 miles can be loaded to 3 times the surge impedance loading of the lines. The thermal loading is not fixed and is dependent on atmospheric condition such ambient temperature, wind velocity, condition of the conductors and recent loading history. Accordingly the transfer capability varies and there can be short-term (of the order of few minutes) overload capacity and normal load capacity. For lines of length between 50 to 200 miles, the reactive power generation and absorption capacity of the line dictates the amount of loading. Reactive power management of the line is the important issue and maintaining an acceptable voltage profile is important. At higher loading with no shunt compensation voltage at the receiving end tends to be unacceptably low. The problem can only be overcome with controlled compensation. For long distance transmission (length beyond 200 miles), the relative angular separation introduced by the equivalent machines at both end is higher. The distributed inductance and shunt capacitance of the line introduces 11-12 degree phase shift per 100 miles of transmission length. This means longer the line length, higher is the angular shift introduced between sending and receiving end voltage and hence lesser is the relative angular separation available for power transfer. It is not possible to load line even close to its SIL values for line longer than 300 miles. Compensation is necessary to enhance loadability of the line. **[6 marks]**

(b) **Bookwork** FACTS controllers employs two technologies for switching: naturally commutated thyristors and forced commutated swtiches such as GTO and IGBT etc. 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. This is used in voltage sourced converter where the magnitude of the voltage/current can be controlled through switching independent of system variables such as bus voltage and current as seen in STATCOM,SSSC and UPFC. In SVC and TCSC for example the amount of reactive power injection and absorption becomes function of bus voltgae and line current. The facts controllers that employs 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 and when coupled with energy storage options, can even exchange (supply/absorb) real power with the ac system. **[5 marks]**

(c) (**computed example**) With reference to Figure 5.1 the power flow between two areas is given by

$$P = P_{max} Sin(\delta) \tag{5.1}$$

where $P_{max} = \frac{V_s V_r}{X_L}$
With series capacitor in place the power angle relation would be

$$P = P'_{max} Sin(\delta) \tag{5.2}$$

where $P'_{max} = \frac{V_s V_r}{X_L - X_C}$
since $X_C = kX_L$, $P'_{max}$ can be expressed as $\frac{V_s V_r}{(1-k)X_L} = \frac{P_{max}}{1-k}$
The capacity margin $CM = \frac{P_{max}-P}{P_{max}}$.
From the definition of capacity margin, one can write the following expression

$$\frac{P}{P_{max}} = 1 - CM \tag{5.3}$$

Let the capacity margin for the compensated case be $CM'$ to satisfy

$$\frac{P}{P_{max}} = 1 - CM' \tag{5.4}$$

Lets take the ratio of (5.3) and (5.4) $\frac{1-CM'}{1-CM}$ which is

$$\frac{P_{max}}{P'_{max}} = 1 - k. \tag{5.5}$$

Substituting the values of $CM = 0.29$ and $CM' = 0.40$ in the above ratio, one gets $k = 0.155$
The degree of compensation needs to be 15.5% to improve the capacity margin to 40% for the same level of power transfer. **[7 marks]**

# 6 Problem 6.

(a) (**book work**) Optimal power flow is a methodology that produces network voltage and line flow that maximize/minimize some operational objectives. Essentially this is a constraint optimization with equality and inequality constraints. The objective is usually non-linear and so are the constraints. It is solved by nonlinear optimization methods. However,linear programming techniques have largely been used to solve the problem based on local linearization of objectives and constraints. **[3 marks]**
From the transmission system operator's (TSO) point of view operation of system with highest efficiency is important. This is irrespective of business model regulated monopoly or open competition in the market. The TSO will attempt to minimize loss in the system for given loads generations pattern. This could be achieved by maintaining voltage profile by way of proper reactive power control. On load tap changing control can be used. The objetcive is loss minimization and hence transmission efficiency optimization. The cost of doing this is to have more and more controllable reactive power source in the system. Constraints are bus voltage limits etc. At times some transactions in the market would lead to power flow over some routes with heavy congestion. TSO can set that as an objective to minimize congestion by imposing congestion charge on the genertaion companies causing it. In this case an OPF to minimize congestion is formulated with power flow and voltage limits constraints.
It can be seen that many business decisions of TSOs are largely influenced by OPF. This influences operating cost of generation companies and distribution companies. An optimal transmission pricing would lead to reduced price for electricity in the wholesale and retail market. **[4 marks]**

(b) (**bookwork**) The generator output and voltage magnitude are controllable. OLTC tap positions are controllable. Generator angles (except for reference angle) are unknown. The magnitude and phase angle of load bus voltages are unknown. Usually the power output of one generator is decided once loss is known hence both of $P_1$ and $P_2$ can not be taken as control variable at the same time. Load powers are usually given In view of this the variables and fixed parameters are as follows

$$\mathbf{x} : V_2, V_3, \theta_2, \theta_3, \theta_4$$
$$\mathbf{u} : V_1, V_2, t_1, t_2, P_1 \text{ or } P_4$$
$$\mathbf{p} : \theta_1, P_2, P_3, Q_2, Q_3$$

**[6 marks]**

(c) This can be solved by standard Lagrangian method. Lets form the Lagrange equation as:

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

At optimum point, the derivative of **L** with respect to **x** and **u** and $\lambda$ must equate to zero. This will give rise to following set of vector equations:

$$\frac{\partial f}{\partial \mathbf{x}} + \left[\frac{\partial \mathbf{g}}{\partial \mathbf{x}}\right]^T \lambda = 0 \tag{6.2}$$

$$\frac{\partial f}{\partial \mathbf{u}} + \left[\frac{\partial \mathbf{g}}{\partial \mathbf{u}}\right]^T \lambda = 0 \tag{6.3}$$

$$\mathbf{g}(\mathbf{x}, \mathbf{u}, \mathbf{p}) = 0 \tag{6.4}$$

$$\tag{6.5}$$

Solving for $\lambda$ and substituting in (6.3) one gets the following

$$\lambda = -\left[\left(\frac{\partial \mathbf{g}}{\partial \mathbf{x}}\right)^T\right]^{-1} \left[\frac{\partial \mathbf{f}}{\partial \mathbf{x}}\right] \tag{6.6}$$

$$\frac{\partial \mathbf{f}}{\partial \mathbf{u}} = \left[\frac{\partial \mathbf{g}}{\partial \mathbf{u}}\right]^T \left[\left(\frac{\partial \mathbf{g}}{\partial \mathbf{x}}\right)^T\right]^{-1} \left[\frac{\partial f}{\partial \mathbf{x}}\right] \tag{6.7}$$

$$\tag{6.8}$$

The expression in (6.7) provides teh direction of maximum increase in objetcive function with respect to control variables. **[7 marks]**