Power System Operation and Control (315336)

MSBTE K-Scheme · Model Question Paper — Set B · Model Answers

Q.1

a) Per unit impedance and base impedance. 2 M

Per unit impedance: the ratio of actual impedance (Ω) to the base impedance (Ω): $Z_{pu} = Z_{actual}/Z_{base}$.

Base impedance: the impedance which, carrying base current, gives a voltage drop equal to base voltage: $Z_{base} = V_{base}/I_{base} = (kV_{base})^2/MVA_{base}$ Ω.

(Each 1 M)

b) Main components of a power system. 2 M

1. **Generating stations** — alternators driven by prime movers (thermal, hydro, nuclear, gas, solar/wind).
2. **Step-up transformers / substations** — raise generated voltage (11–33 kV) to transmission voltage.
3. **Transmission system** — primary (220/400/765 kV) and secondary/sub-transmission (66/33 kV) lines.
4. **Substations** — receiving and distribution substations with transformers, switchgear and protection.
5. **Distribution system** — primary (11 kV feeders) and secondary (415/230 V) distribution to consumers.
6. **Loads (consumers)** — domestic, commercial, industrial and agricultural.

(Any four, ½ M each)

c) Effects of low voltage on consumer equipment. 2 M

1. Induction motors draw more current, overheat and may stall; starting torque falls ($T \propto V^2$).
2. Lighting output falls; tube lights may fail to start.
3. Heating appliances take longer ($P \propto V^2$); electronic equipment malfunctions.

(Any two, 1 M each)

d) Functions of ALFC. 2 M

1. To keep the system frequency constant (at 50 Hz) by matching real power generation with the changing load.
2. To divide the load among generators in proportion to their ratings (and economically).
3. In interconnected systems, to keep tie-line power exchange at scheduled values.

(Any two, 1 M each)

e) Transient and dynamic stability. 2 M

Transient stability: the ability of the system to remain in synchronism after a large and sudden disturbance, such as a short-circuit fault, sudden loss of a generator or line, or sudden large load change (studied for the first swing, about 1 s).

Dynamic stability: the ability of the system to remain stable under small disturbances over a longer period (several seconds to minutes) when the effect of control systems — AVR, governors, power system stabilisers — is included; oscillations must die out.

(Each 1 M)

f) Small vs large disturbance. 2 M

Sr.	Point	Small disturbance	Large disturbance
1	Magnitude	Small, gradual change	Large, sudden change
2	Examples	Gradual load change, small load switching, AVR/governor action	Short-circuit faults, tripping of a large generator / line, sudden heavy load

(Any two points, 1 M each)

g) Significance of load forecasting. 2 M

1. Helps in scheduling generation and unit commitment so that supply matches demand.
2. Needed for planning new generation, transmission and distribution capacity.
3. Enables economic operation, fuel planning and maintenance scheduling; avoids load shedding.

(Any two, 1 M each)

Q.2

a) Impedance diagram and reactance diagram. 4 M

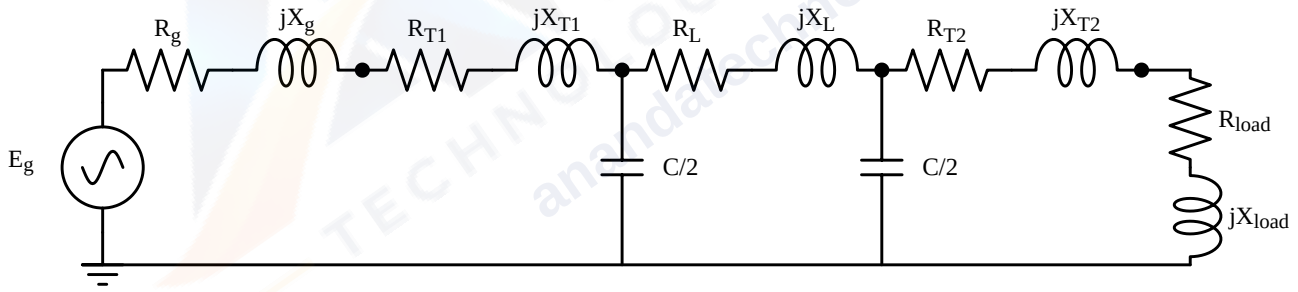


Fig.: Impedance diagram (per phase) of the system G – T1 – line – T2 – load

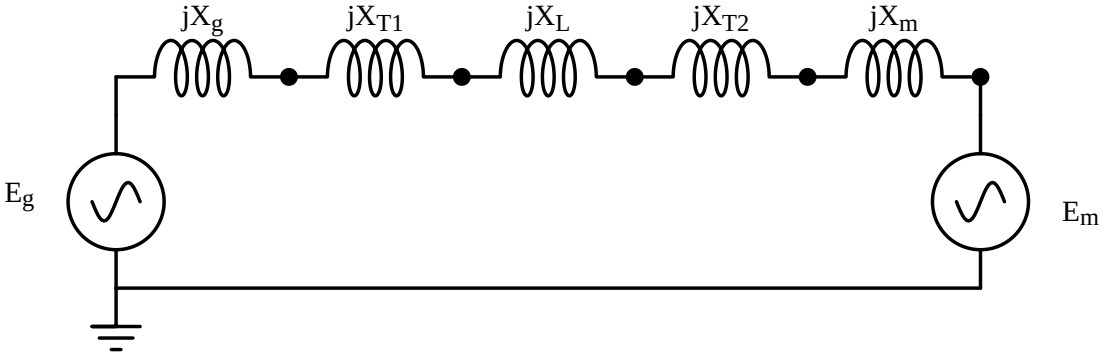


Fig.: Reactance diagram (R, shunt capacitance, magnetising branch and static loads neglected)

Assumptions for reactance diagram:

1. Neutral (reference) bus is the return path; the system is balanced, so one phase is drawn.
2. Resistances are neglected because R << X for generators, transformers and EHV lines.
3. Magnetising branch of transformers is neglected (magnetising current is very small).
4. Line charging capacitance (shunt C) of short and medium lines is neglected.
5. Static loads are neglected (load current is small compared to fault current); motors are kept as sources behind reactance.

(Impedance diagram 1½ M, reactance diagram 1½ M, assumptions 1 M)

b) Impact of frequency variation. 4 M

On consumers:

1. Speed of induction and synchronous motors changes (N ∝ f) — affects product quality in textile, paper and process industries.
2. Output of fans, pumps and compressors changes (power ∝ speed³).
3. Electric clocks, timers and synchronous drives give wrong timing.

On supply agencies (generating plants):

1. Low frequency causes vibration and fatigue of long LP turbine blades (resonance), damaging steam turbines.
2. Power-station auxiliaries (boiler feed pumps, ID/FD fans, CW pumps) run slower, so unit output falls further — may lead to collapse.
3. Over-fluxing (high V/f) of generators and transformers at low frequency → core heating.

(Consumers 2 M, supply agencies 2 M)

c) Block diagram of ALFC. 4 M

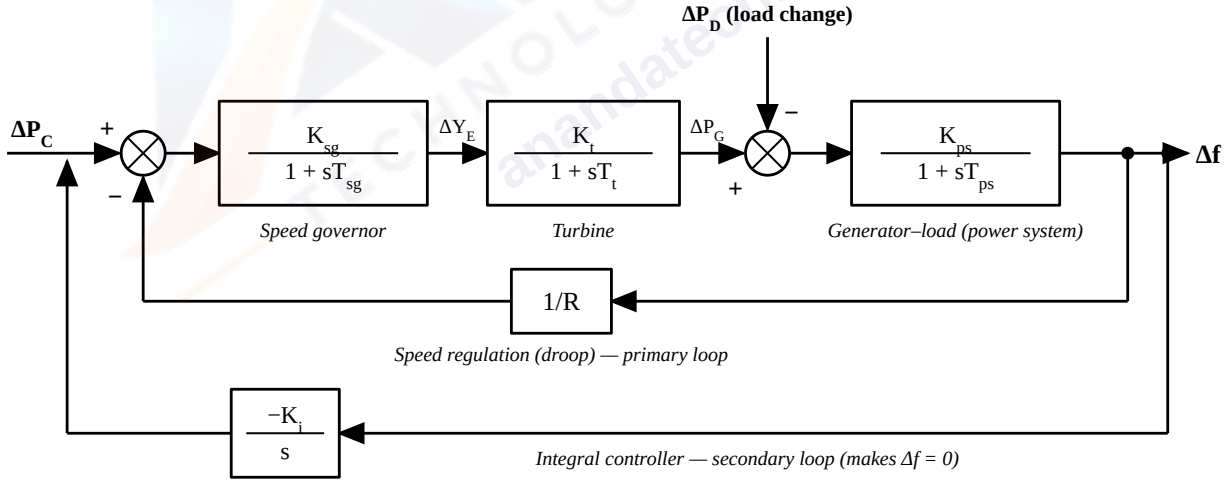


Fig.: Block diagram of ALFC (single area) with integral (secondary) control

1. **Speed governor:** senses change in speed (frequency) and, through the hydraulic amplifier, moves the steam/water control valve. Gain K_{sg}, time constant T_{sg} (≈ 0.1–0.4 s).
2. **Turbine:** converts change in valve position ΔY_E into change in mechanical power ΔP_G (time constant T_t ≈ 0.2–2 s).

3. **Generator–load (power system):** the difference $\Delta P_G - \Delta P_D$ changes kinetic energy and hence frequency; $K_{ps} = 1/D$, $T_{ps} = 2H/(f_0 D)$.
4. **Primary loop (1/R):** speed regulation (droop) R gives proportional control — when load increases, generation increases but frequency settles at a lower value (steady state error).
5. **Secondary loop (integral controller $-K_i/s$):** integrates Δf and moves the speed changer (ΔP_C) until Δf becomes zero — frequency is restored to 50 Hz.

(Diagram 2 M, explanation 2 M)

d) Electro-hydraulic governor; RGMO and FGMO. 4 M

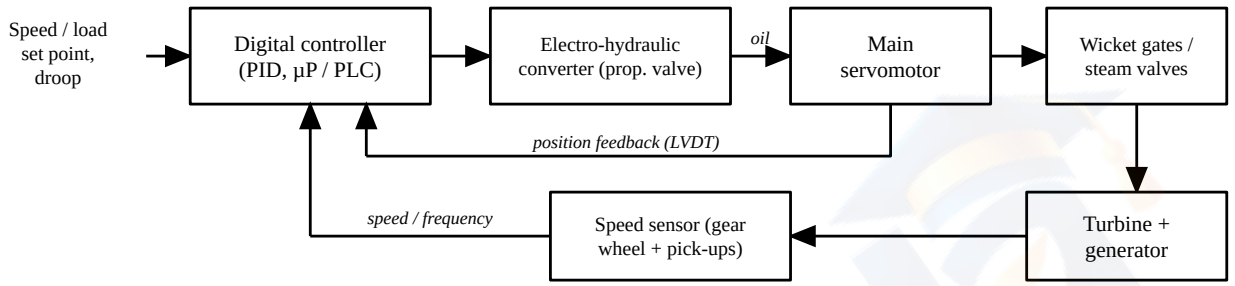


Fig.: Electro-hydraulic (digital) governor — block diagram

- In the electro-hydraulic (digital) governor the mechanical fly-ball is replaced by **electronic speed sensing** (toothed wheel with magnetic pick-ups or a permanent magnet generator).
- A **digital controller** (microprocessor / PLC with PID control) compares actual speed and power with the set points and droop setting, and gives an electrical output.
- The **electro-hydraulic converter** (proportional / servo valve) converts this signal into oil flow that moves the main servomotor, which opens or closes the wicket gates (hydro) or steam valves (thermal).
- Servomotor position is fed back (LVDT) for accurate positioning.
- **Advantages:** fast and accurate response, adjustable droop and dead band, remote control from SCADA/LDC, self-diagnostics, easy implementation of RGMO/FGMO and less maintenance.
- **FGMO — Free Governing Mode of Operation:** the governor is free to respond to every change of grid frequency as per its droop setting — output increases when frequency falls and decreases when frequency rises. It helps primary frequency control but causes frequent valve movement (hunting) and stress on boiler/turbine.
- **RGMO — Restricted Governing Mode of Operation:** introduced in India under the Grid Code; the governor response is restricted — small frequency fluctuations within a dead band are ignored, and the change in output is limited (about 5 % of MCR) so that units support the grid during frequency dips without continuous hunting (introduction only).

(Diagram and working 2 M, RGMO/FGMO 2 M)

Q.3

a) Advantages of per unit system. 4 M

1. **Transformer is eliminated:** the per unit impedance of a transformer is the same whether referred to the primary or the secondary side, so the ideal transformer disappears from the equivalent circuit.
2. **Narrow range of values:** per unit impedances of machines and transformers of the same type lie in a narrow range (e.g. transformer 0.05–0.15 pu) even though ratings differ widely; manufacturers give data in pu/percent and wrong data is easily detected.
3. **Simple calculations:** numbers are small and of similar magnitude; voltages are close to 1.0 pu, so results are easy to judge.
4. **√3 factor is avoided:** per unit values of line and phase quantities are the same, so 3-phase calculations are done like single-phase ones.
5. **Same per unit impedance for 1-phase and 3-phase** representation; no confusion between line-to-line and phase values.

(Any four, 1 M each)

b) SSSC. 4 M

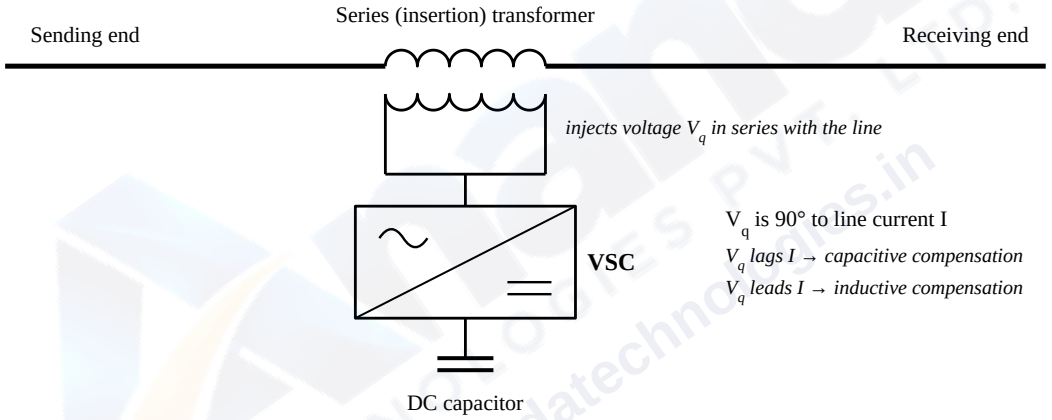


Fig.: SSSC (static synchronous series compensator) — series connected

- SSSC is a **series-connected** FACTS device: a VSC with DC capacitor injects a voltage V_q in series with the line through a series (insertion) transformer.
- V_q is kept 90° to the line current, so it behaves like a variable series capacitor (V_q lagging I) or series reactor (V_q leading I).
- It changes the effective line reactance and thereby controls power flow, increases power transfer and damps oscillations.
- Unlike a fixed series capacitor it does not cause sub-synchronous resonance.

(Diagram 2 M, explanation 2 M)

c) Schematic diagram of AVC. 4 M

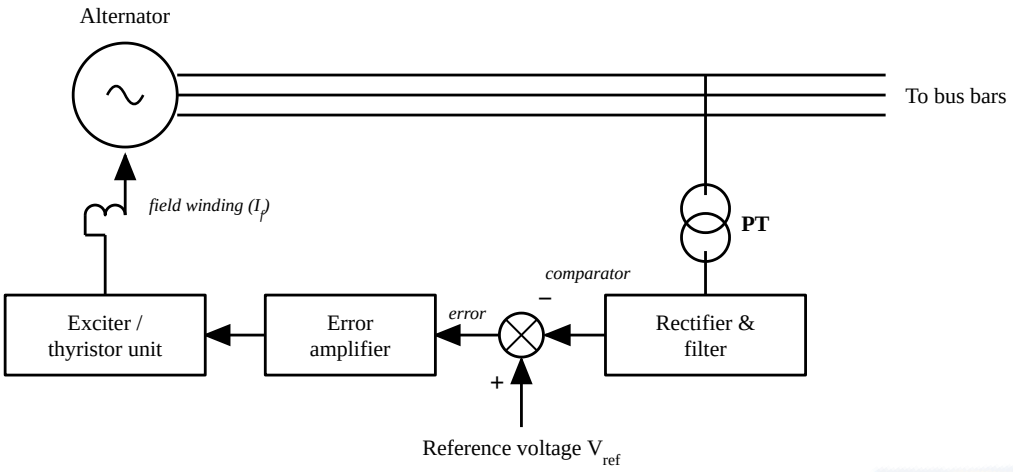


Fig.: Schematic diagram of automatic voltage control (AVC) of an alternator

1. **Potential transformer (PT):** senses the alternator terminal voltage and steps it down.
2. **Rectifier and filter:** converts the sensed AC voltage into a smooth DC signal proportional to terminal voltage.
3. **Comparator:** compares this signal with the reference voltage V_{ref} (set value) and produces an error signal.
4. **Error amplifier:** amplifies the error signal.
5. **Exciter / thyristor unit:** changes the field current of the alternator according to the amplified error.
6. **Working:** if terminal voltage falls (load increases or lagging PF), the error increases, excitation (field current) increases and the generated EMF and terminal voltage rise back to the set value; if voltage rises the reverse happens. AVC also controls the reactive power output of the alternator and shares reactive load among parallel machines.

(Diagram 2 M, working 2 M)

d) Stability terms. 4 M

Instability: the condition in which the system cannot return to equilibrium after a disturbance — rotor angles go on increasing, machines lose synchronism (fall out of step) and voltages/flows oscillate heavily.

Power system stability: the ability of a power system to remain in a state of operating equilibrium (all synchronous machines in synchronism) under normal conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.

Overall stability: stability of the complete interconnected system — all generators and areas of the whole system remain in synchronism with one another (as opposed to local stability of one machine or small part of the system).

Stability limit: the maximum power that can be transferred through a point of the system (or from a machine) without loss of synchronism.

(Each definition 1 M)

Q.4

a) Per unit reactance diagram (transformer as base). 4 M

Step 1 — Base values: MVA_{base} = 15 MVA, kV_{base} = 11 kV on the LV side of T1 (zone 1) — rating of T1.

Step 2 — Base kV of each zone (base kV changes in the ratio of transformer turns):

Zone	Base MVA	Base kV
Zone 1 (generator side)	15	11
Zone 2 (transmission line)	15	66
Zone 3 (motor side)	15	11

Step 3 — Per unit reactances on the common base using $X_{pu(new)} = X_{pu(old)} \times (kV_{old}/kV_{new})^2 \times (MVA_{new}/MVA_{old})$, and $X_{pu} = X_{\Omega}/Z_{base}$ for the line:

Element	Given rating	Per-unit reactance on common base	X (pu)
G	10 MVA, 11 kV, 12 %	$0.12 \times (11/11)^2 \times (15/10)$	j0.1800
T1	15 MVA, 11/66 kV, 9 %	0.09 (rating = base)	j0.0900
Line	j25 Ω	$Z_{base} = 66^2/15 = 290.4000\ \Omega$; X = 25/290.4000	j0.0861
T2	15 MVA, 66/11 kV, 9 %	0.09 (rating = base)	j0.0900
M	8 MVA, 11 kV, 15 %	$0.15 \times (11/11)^2 \times (15/8)$	j0.2812

Step 4 — Per unit reactance diagram:

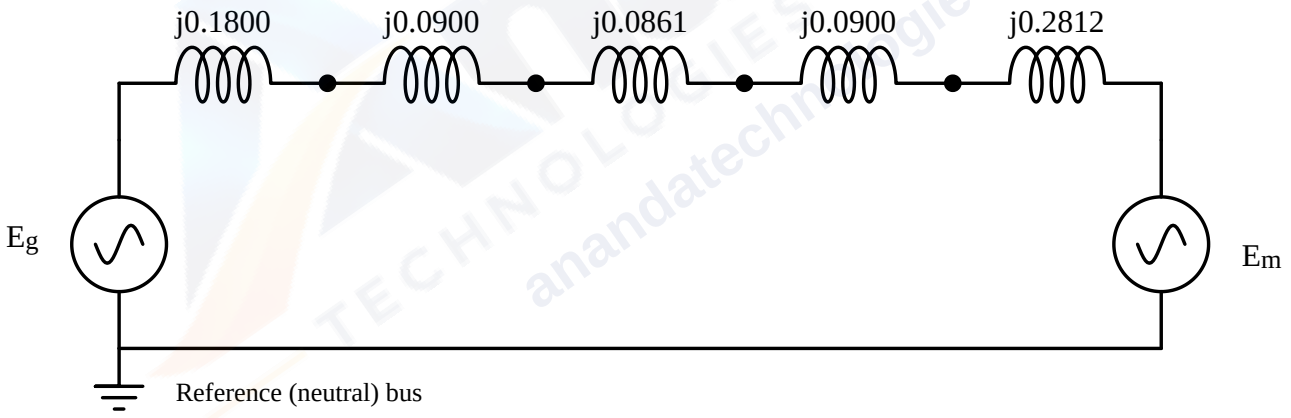


Fig.: Per unit reactance diagram (15 MVA base)

(Base kV of zones 1 M, per unit values 2 M, diagram 1 M)

b) Real power flow and frequency — load sharing by governor droop. 4 M

When load increases, the generators supply the extra power from stored kinetic energy, so speed and frequency fall. The governors sense the fall and open the valves; each generator picks up load according to its **speed regulation (droop)** R. Frequency settles at a lower value — real power balance decides frequency.

Power response of a unit: $\Delta P_i = -(P_{rated,i} / (R_i\ f_0))\ \Delta f = -\beta_i \Delta f$ (MW).

Generator	Rating (MW)	R	$\beta = P_r/(R\ f_0)$ (MW/Hz)
G1	200	4 %	200/(0.04×50) = 100.0
G2	300	5 %	300/(0.05×50) = 120.0

Total β = 220.0 MW/Hz. $\Delta f = -\Delta P_L/\Sigma\beta = -60/220.0 =$ **-0.2727 Hz** → new frequency = **49.727 Hz**.

Additional load: G1 = 100.0 × 0.2727 = **27.27 MW**; G2 = 120.0 × 0.2727 = **32.73 MW** (check: 60.00 MW).

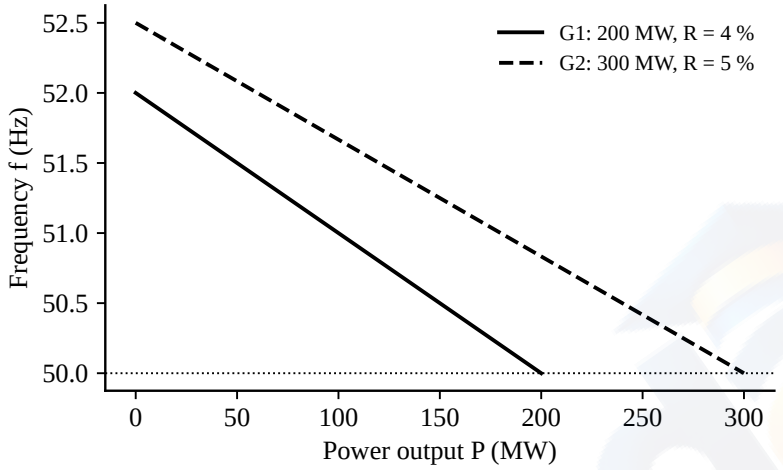


Fig.: Speed–load (droop) characteristics of the two governors (100 % load at 50 Hz)

(Explanation 1 M, calculation 3 M)

c) Environmental and social factors in load forecasting. 4 M

Environmental factors:

1. **Temperature:** high temperature in summer increases air-conditioning, cooling and irrigation-pump load; low temperature increases heating load.
2. **Humidity:** high humidity increases use of fans, coolers and ACs.
3. **Rainfall / monsoon:** rain reduces agricultural pumping and cooling load; drought increases it.

Social factors:

1. **Day of the week and holidays:** load is lower on Sundays and public holidays (offices, industries closed).
2. **Festivals and special events:** Diwali lighting, cricket matches and TV events, elections change the load curve.
3. **Working hours and lifestyle:** office/shift timings, school timings decide morning and evening peaks.

(Environmental 2 M, social 2 M)

d) Methods of improving steady state stability. 4 M

Steady state limit P_{max} = EV/X; it is raised by increasing E or V, or by reducing X:

1. Increase the excitation (EMF E) of generators and keep the system voltage V high.
2. Reduce the transfer reactance X — parallel lines, bundled conductors, low-reactance transformers.

3. Use series capacitors in long lines.
4. Use quick-response AVR / static excitation and operate at load angle well below 90°.

Example (computed): E = V = 1 pu, X = 0.8 pu → P_{max} = 1.250 pu. With 40 % series compensation, X = 0.48 pu → P_{max} = **2.083 pu**, an increase of 66.7 %.

(Any four methods, 1 M each)

e) Types of LDCs and their functions. 4 M

1. NLDC — National Load Despatch Centre (New Delhi)
2. RLDC — Regional Load Despatch Centres (five regions)
3. SLDC — State Load Despatch Centres
4. Area / Sub-LDCs (within a state)

NLDC: apex body for the national grid — inter-regional scheduling and despatch, supervision of RLDCs, inter-regional energy accounting, cross-border exchanges.

RLDC: integrated operation of the regional grid — scheduling and despatch among states of the region, real-time monitoring, supervision of inter-state transmission, regional energy accounting.

SLDC: apex body in the state — scheduling and despatch within the state, real-time monitoring, load shedding, supervision of intra-state transmission, state energy accounting.

(Types 1 M, functions 3 M)

Q.5

a) Reactive power compensation; shunt and series compensation. 6 M

Reactive power compensation means supplying (or absorbing) reactive power locally, near the point where it is needed, instead of transmitting it from distant generators. Most loads (induction motors, transformers) draw lagging reactive power; transmitting it over lines increases current, losses and voltage drop.

Objectives: maintain voltage profile within limits, improve power factor, reduce line current and losses, increase power transfer capability and improve stability.

A) Shunt compensation

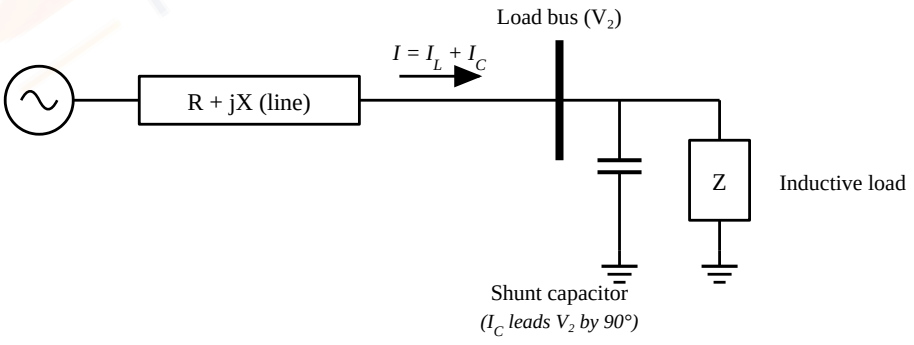
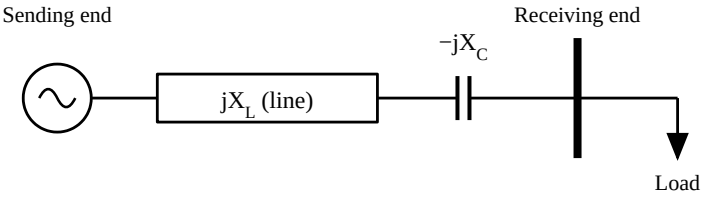


Fig.: Shunt compensation — capacitor bank connected at the receiving end (load bus)

- Capacitor banks (or synchronous condensers / SVC / STATCOM) are connected **in parallel** with the load at the receiving-end substation.

- The capacitor draws leading current I_C, which cancels part of the lagging reactive current of the load, so the line current $I = I_L + I_C$ reduces and the power factor improves ($\varphi_2 < \varphi_1$).
- Line losses and voltage drop reduce; receiving-end voltage improves; capacity of lines and transformers is released.
- At light load on long EHV lines, **shunt reactors** are switched in to absorb surplus reactive power and limit overvoltage (Ferranti effect).

B) Series compensation



Net series reactance = $X_L - X_C$

$P = V_{1V2} \sin \delta / (X_L - X_C) \rightarrow$ more power, less voltage drop

Fig.: Series compensation — capacitor (X_C) inserted in series with the line

- Capacitors are connected **in series** with the transmission line (usually at the middle or ends of long lines).
- Net series reactance becomes $X_L - X_C$; degree of compensation $k = X_C/X_L$ (typically 25–70 %).
- Power transfer $P = V_1V_2 \sin \delta/(X_L - X_C)$ increases, voltage drop ($\approx I X$) reduces, and steady state and transient stability improve.
- Reactive power produced by the series capacitor (I^2X_C) increases automatically with load — it is self-regulating.
- Needs protection (MOV / bypass breaker) against fault over-voltage; risk of sub-synchronous resonance.

(Concept 1 M, shunt 2½ M, series 2½ M)

b) Schematic diagram of AGC. 6 M

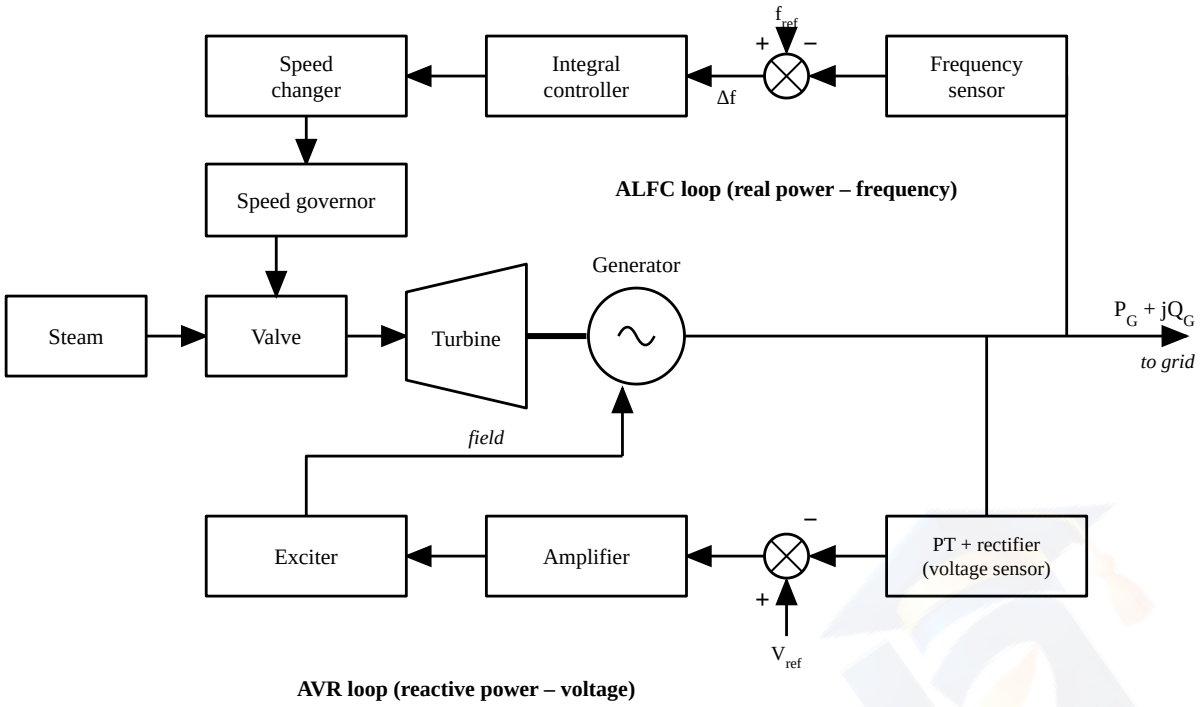


Fig.: Automatic generation control (AGC) — ALFC loop and AVR loop of a generating unit

1. **ALFC loop (P–f control):** frequency sensor → comparator with f_{ref} → integral controller → speed changer → speed governor → steam valve → turbine. It controls real power output and keeps frequency constant.
2. **AVR loop (Q–V control):** PT and rectifier (voltage sensor) → comparator with V_{ref} → amplifier → exciter → generator field. It controls reactive power and keeps terminal voltage constant.
3. The two loops are almost **decoupled** — a change in excitation mainly affects Q and V, while a change in steam input mainly affects P and f. The AVR loop is fast (time constants of a few seconds), the ALFC loop is slower.
4. In interconnected systems AGC also controls tie-line power (area control error ACE = ΔP_{tie} + BΔf) and allocates generation economically among units; commands are sent from the load dispatch centre.

Working: when load increases, frequency falls; the frequency sensor gives Δf, the integral controller raises the speed-changer setting until $\Delta f = 0$ — the turbine output increases to match the load. At the same time, if terminal voltage falls because of increased reactive demand, the AVR loop increases excitation to restore voltage. Thus AGC keeps both frequency and voltage at their scheduled values.

(Diagram 3 M, explanation 3 M)

c) Steady state vs transient stability. 6 M

Sr.	Point	Steady state stability	Transient stability
1	Disturbance	Small and gradual	Large and sudden
2	Example	Slow increase of load	Three-phase fault, loss of line/generator

3	Limit	Steady state limit P_{max} = EV/X at $\delta = 90°$	Transient limit lower than steady state limit
4	Analysis	Power-angle curve; linear	Swing equation / equal area criterion; non-linear
5	Time period	Long (continuous operation)	Short — first swing (about 1 s)
6	Improved by	Higher E, V; lower X; quick AVR	Fast fault clearing, auto-reclosing, fast excitation, fast valving, braking resistors

(Any six points, 1 M each)

Q.6

a) Relation between reactive power balance and voltage. 6 M

If the reactive power generated in a system (generators, line charging, capacitors) is less than the reactive power demand (loads, line reactance, transformers), bus voltages fall; if it is more, voltages rise. This is shown for a two-bus system:

Consider a sending-end bus (voltage $V_1 \angle \delta$) supplying a load P + jQ at the receiving-end bus (voltage $V_2 \angle 0°$) through a line of reactance X (resistance neglected).

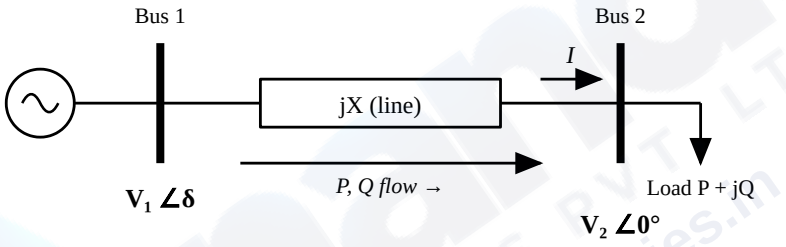


Fig.: Two-bus system — sending end and receiving end connected by a line of reactance X

Current drawn by the load: $I = (P - jQ) / V_2^* = (P - jQ)/V_2$ (V_2 taken as reference).

Sending-end voltage: $V_1 = V_2 + jXI = V_2 + jX(P - jQ)/V_2$

$$\mathbf{V_1 = (V_2 + XQ/V_2) + j(XP/V_2)}$$

The in-phase component XQ/V_2 changes the **magnitude** of voltage, while the quadrature component XP/V_2 mainly changes the **angle** δ. Since XP/V_2 is small compared with V_2,

$$\mathbf{\Delta V = |V_1| - |V_2| \approx X \cdot Q / V_2}$$

Similarly, the reactive power received is $Q = (V_1V_2 \cos\delta - V_2^2)/X \approx V_2(V_1 - V_2)/X$ for small δ.

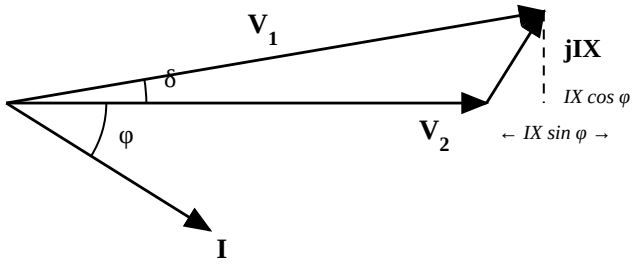


Fig.: Phasor diagram (R neglected): $V_1 = V_2 + jIX$

Conclusion: the voltage difference between two buses depends mainly on the **reactive power flow**; reactive power flows from the bus of higher voltage to the bus of lower voltage. A shortage of reactive power at a bus lowers its voltage, a surplus raises it — **voltage is the index of reactive power balance** (Q–V control by AVR, capacitors, reactors, tap changers, SVC/STATCOM).

Illustration: V_2 = 1 pu, X = 0.15 pu, load P = 0.9 pu, Q = 0.6 pu. $V_1 = (1 + 0.15\times0.6/1) + j(0.15\times0.9/1) = 1.090 + j0.135$; $|V_1| = 1.0983$ pu, $\delta = 7.06°$. Exact $\Delta V = 0.0983$ pu, approximate $XQ/V_2 = 0.0900$ pu — the drop is decided almost entirely by Q.

(Explanation 2 M, diagram 1 M, relation 3 M)

b) Turbine speed governing system; speed changer. 6 M

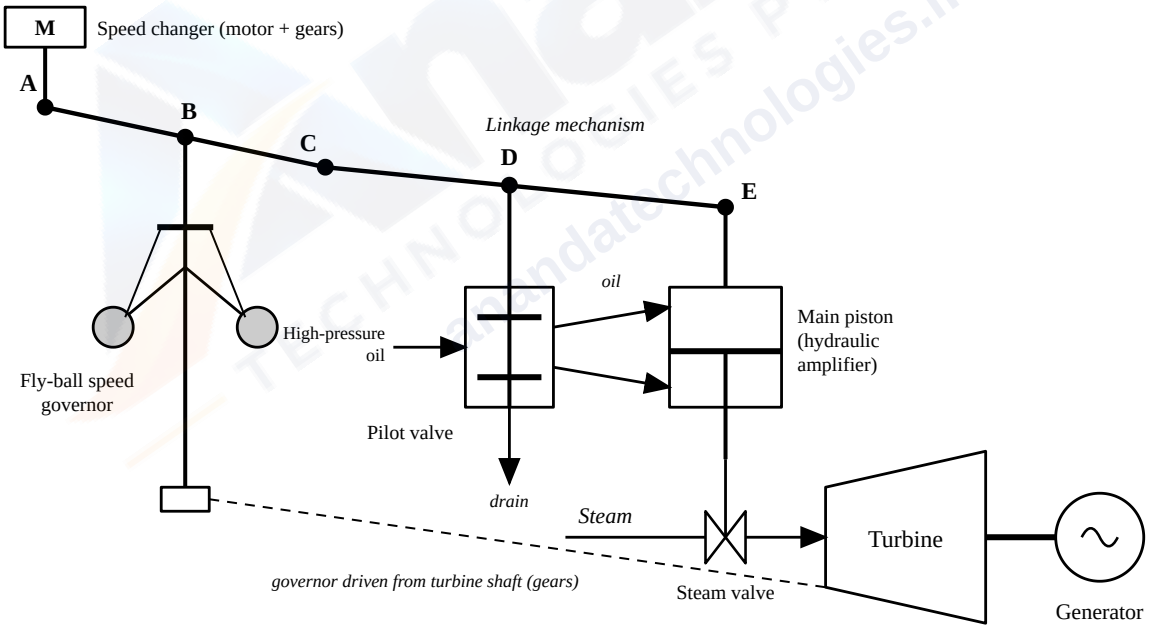


Fig.: Turbine speed governing system (schematic)

Main parts:

1. **Fly-ball speed governor:** driven from the turbine shaft; the balls move outward when speed rises and inward when speed falls, moving the sleeve (point B).

2. **Linkage mechanism (A–B–C and C–D–E):** transmits the governor motion to the pilot valve and gives feedback from the main piston (point E).
3. **Hydraulic amplifier:** pilot valve + main piston; the small force of the pilot valve controls high-pressure oil which moves the heavy main piston and the steam valve.
4. **Speed changer:** motor-driven screw at A; it shifts the governor setting to change the loading of the unit or to restore frequency.

Working:

1. When load on the generator increases, speed (frequency) falls; the fly-balls move inward and point B moves.
2. Point C moves through link A–B–C, which moves D and opens the pilot-valve ports.
3. High-pressure oil enters the main piston cylinder; the main piston moves the steam valve to admit more steam to the turbine.
4. Turbine output increases to meet the new load. Movement of the main piston moves E, which brings the pilot valve back to its closed (neutral) position — the system settles at a new steady state with a slightly lower speed (droop).
5. To bring the frequency back to 50 Hz, the speed changer (A) is operated (manually or by the integral controller of ALFC). For load decrease the action is reverse.

Function of speed changer: it gives a steady-state power output setting to the turbine — by moving point A it changes the speed–load characteristic so that the unit takes more or less load at the same frequency, or restores frequency to 50 Hz after a load change.

(Diagram 3 M, working 2 M, speed changer 1 M)

c) Methods of improving transient stability. 6 M

1. **High-speed fault clearing:** fast protective relays and circuit breakers (2–3 cycles) clear the fault before the rotor angle swings too far.
2. **High-speed auto-reclosing:** most faults are transient; the line is reclosed quickly so that power transfer is restored.
3. **Single-pole switching:** only the faulted phase is opened, so the healthy phases continue to transfer power.
4. **Reduction of transfer reactance:** parallel lines, bundled conductors, series capacitors and low-reactance transformers increase P_{max}.
5. **Fast-acting excitation systems** (high ceiling voltage, static exciters) raise EMF quickly during the fault.
6. **Fast valving of turbines:** steam input is reduced quickly during the fault to reduce rotor acceleration.
7. **Braking resistors:** switched in near the generator during the fault to absorb surplus power.
8. **Higher transmission voltage, HVDC links, FACTS devices, generator tripping / load shedding** schemes.

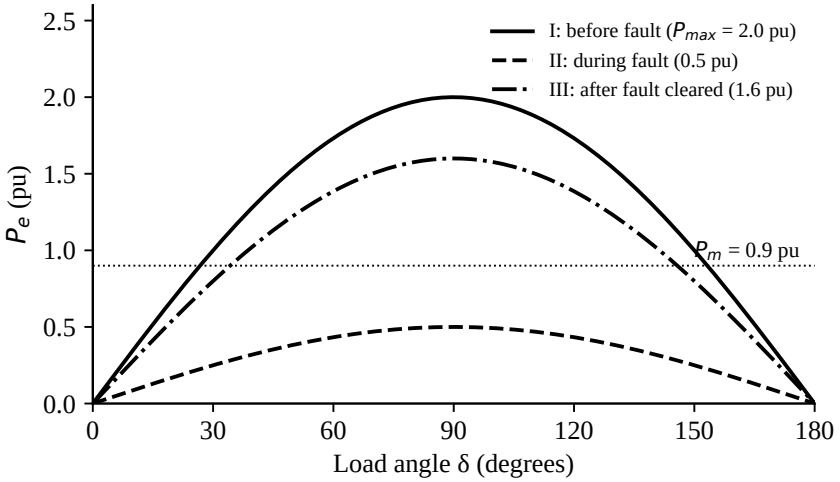


Fig.: Power angle curves before, during and after a fault — faster clearing / higher post-fault curve keeps the machine stable

(Any six methods, 1 M each)

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