

Power System Operation and Control (315336)

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

Q.1**a) 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)***b) Change of base formula.**

2 M

$$Z_{pu(new)} = Z_{pu(old)} \times (kV_{old} / kV_{new})^2 \times (MVA_{new} / MVA_{old})$$

$Z_{pu(old)}$ — per unit impedance on the rated (old) base; kV_{old} , MVA_{old} — old base voltage and MVA (rating); kV_{new} , MVA_{new} — chosen common base voltage and MVA; $Z_{pu(new)}$ — per unit impedance on the new base.

*(Formula 1 M, terms 1 M)***c) Adverse effects of frequency variation on generating plants.**

2 M

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.

*(Any two, 1 M each)***d) Effects of reactive power imbalance.**

2 M

1. Reactive power deficit → bus voltages fall (low voltage, possible voltage collapse).
2. Surplus reactive power (light load, long lines – Ferranti effect) → overvoltage and insulation stress.
3. Increased line current, I^2R losses and poor power factor; lines and transformers get overloaded.

4. Reduced power transfer capability and stability margin; generators forced to work over-excited or under-excited.

(Any four, $\frac{1}{2}$ M each)

e) Power system stability and instability.

2 M

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.

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.

(Each 1 M)

f) Examples of small and large disturbances.

2 M

Small disturbances: gradual increase or decrease of load; switching of a small load; normal action of AVR / governor.

Large disturbances: three-phase short-circuit fault; sudden tripping of a large generator or a heavily loaded line; sudden switching of a very large load.

(Two examples each, $\frac{1}{2}$ M each)

g) Types of load dispatch centres.

2 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)

($\frac{1}{2}$ M each)

Q.2

a) Requirements of stable power system operation.

4 M

1. **Real power balance:** generation must equal load + losses at every instant, so that frequency stays at 50 Hz (IEGC band 49.90–50.05 Hz).
2. **Reactive power balance:** reactive power generation must match demand so that bus voltages remain within permissible limits (about $\pm 5\%$).
3. **Synchronism:** all generators must run in synchronism; rotor angles must remain within the stability limit after disturbances.
4. **No overloading:** lines, transformers and generators must operate within thermal and stability limits.
5. **Adequate reserves:** spinning reserve and reactive reserve must be available for sudden loss of generation or load increase.
6. **Reliable protection and control** (governors, AVRs, relays, load dispatch centres) to clear faults quickly and keep supply continuous and economic.

(Any four, 1 M each)

b) Need of constant supply voltage for consumers.

4 M

Consumer equipment is designed to give rated performance only at rated voltage (230/415 V). Variation of voltage beyond about $\pm 6\%$ affects them as follows:

1. **Lighting:** low voltage reduces light output (incandescent lumen output falls sharply, tube lights may fail to start); high voltage shortens lamp life.
2. **Induction motors:** starting and running torque $\propto V^2$; at low voltage motors draw more current, overheat, may stall; at high voltage magnetising current and core loss increase.
3. **Heating appliances:** output $\propto V^2$ — heaters, ovens take longer at low voltage.
4. **Electronic equipment** (TV, computers, controls) malfunctions or gets damaged; refrigerator / AC compressors may fail to start.

Hence the utility must keep the supply voltage nearly constant (by AVR, OLTC, capacitors) for satisfactory operation and long life of consumer equipment.

(Any four points, 1 M each)

c) AVR with block diagram.

4 M

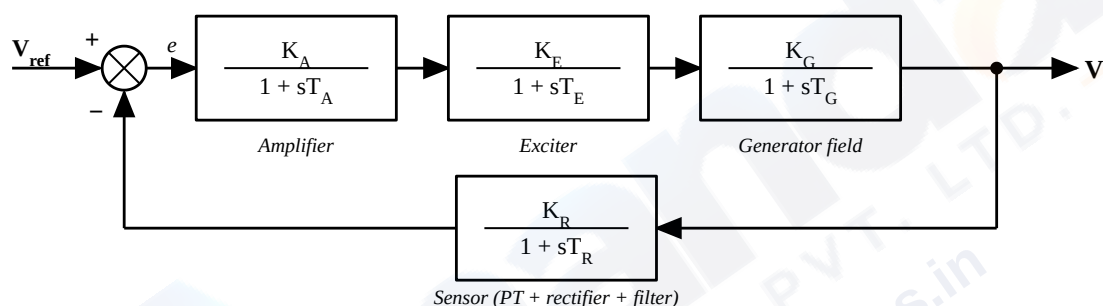


Fig.: Block diagram of automatic voltage regulator (AVR) loop

1. **Sensor** (PT + rectifier + filter) measures terminal voltage V_t and gives a DC signal.
2. **Comparator** finds the error $e = V_{ref} - V_{sensed}$.
3. **Amplifier** amplifies the error and drives the **exciter**, which changes the generator field current.
4. When V_t falls (more lagging load), e increases $\rightarrow$ field current increases $\rightarrow$ EMF and V_t rise back; the reverse happens when V_t rises. AVR thus controls voltage and reactive power output.

(Diagram 2 M, explanation 2 M)

d) Adverse effects of instability.

4 M

1. Generators lose synchronism and are tripped by out-of-step protection — sudden loss of generation.
2. Large oscillations of power, current and voltage; heavy current surges stress windings and shafts of machines.
3. Cascade tripping of lines and units, splitting of the grid into islands, leading to partial or total blackout (e.g. the Indian grid disturbances of 30–31 July 2012).
4. Frequency and voltage go out of limits — load shedding; interruption of supply to consumers and industries.

5. Long restoration time, loss of revenue and damage to equipment.

(Any four, 1 M each)

Q.3

a) Relation between real power balance and frequency.

4 M

In a power system the mechanical input power to all generators must balance the electrical load plus losses. Any mismatch is taken from (or stored in) the **kinetic energy of the rotating masses** of generators and motors, which changes the speed and hence the frequency ($f = PN/120$).

- $P_G = P_D + \text{losses} \rightarrow$ frequency constant (50 Hz).
- $P_G > P_D + \text{losses} \rightarrow$ excess energy stored as kinetic energy $\rightarrow$ rotors accelerate $\rightarrow$ **frequency rises**.
- $P_G < P_D + \text{losses} \rightarrow$ deficit is supplied from kinetic energy $\rightarrow$ rotors decelerate $\rightarrow$ **frequency falls**.

Derivation: Kinetic energy stored, $W = \frac{1}{2} J\omega^2$. Inertia constant $H = W_0/S$ (MJ/MVA), so $W_0 = H \cdot S$ at rated frequency f_0 . Since $W \propto f^2$, $W = H \cdot S (f/f_0)^2$.

Power mismatch $\Delta P = P_G - P_D = dW/dt = H \cdot S \cdot (2f/f_0^2) \cdot df/dt \approx (2H \cdot S/f_0) \cdot d(\Delta f)/dt$ (since $f \approx f_0$).

Including the frequency sensitivity of load ($D = \partial P_D/\partial f$, MW/Hz):

$$\Delta P_G - \Delta P_D = (2H \cdot S / f_0) \cdot d(\Delta f)/dt + D \cdot \Delta f$$

Thus the rate of change of frequency is proportional to the real power imbalance. In per unit, $d(\Delta f)/dt = (f_0/2H) \cdot \Delta P_{pu}$. *Example:* $H = 4$ s, $f_0 = 50$ Hz, sudden deficit of 0.06 pu $\rightarrow d(\Delta f)/dt = (50/8) \times (-0.06) = -0.38$ Hz/s (initially, before governors act).

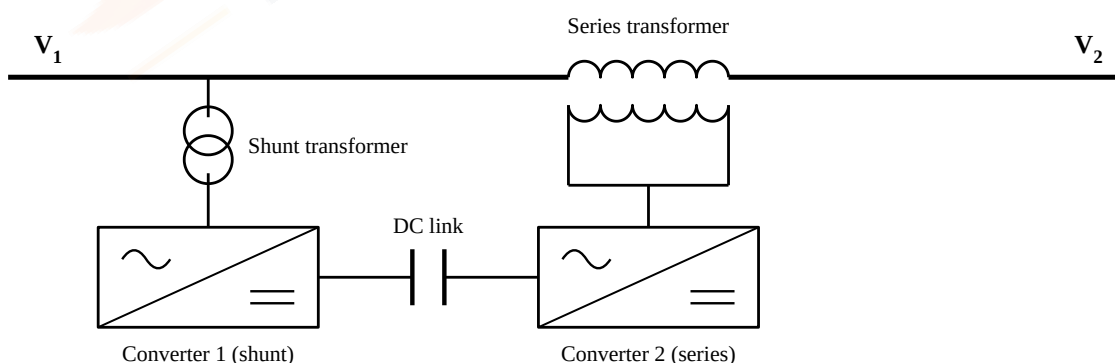
Hence **frequency is the index of real power balance**; it is controlled by controlling the real power output of generators through governors and ALFC (P–f control).

(Explanation 1 M, derivation 3 M)

b) UPFC and IPFC.

4 M

UPFC:



Real power can flow between the two converters through the DC link; each converter can also supply / absorb reactive power independently.

Fig.: UPFC — shunt converter and series converter sharing a common DC link

- UPFC combines a shunt converter (like STATCOM) and a series converter (like SSSC) connected through a **common DC link**.
- The series converter injects a voltage of controllable magnitude and phase angle in series with the line; the shunt converter supplies the real power needed by the series converter and also controls bus voltage.
- It can control voltage, line impedance and phase angle simultaneously — i.e. real and reactive power flow independently. It is the most versatile FACTS controller.

IPFC:

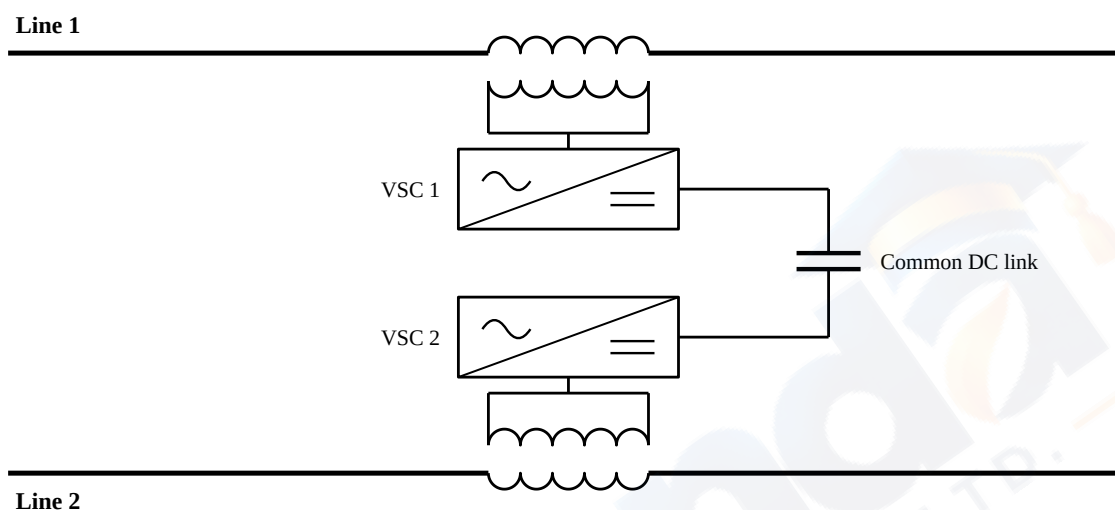


Fig.: IPFC — series converters of two lines joined by a common DC link

- IPFC (interline power flow controller) consists of two or more SSSCs installed in different lines and connected to a **common DC link**.
- Each converter gives series reactive compensation to its own line, and real power can be transferred between lines through the DC link.
- It balances real and reactive power flow among lines, relieves overloaded lines and reduces losses (introduction level).

(UPFC 2 M, IPFC 2 M)

c) Methods of improving transient stability.

4 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.

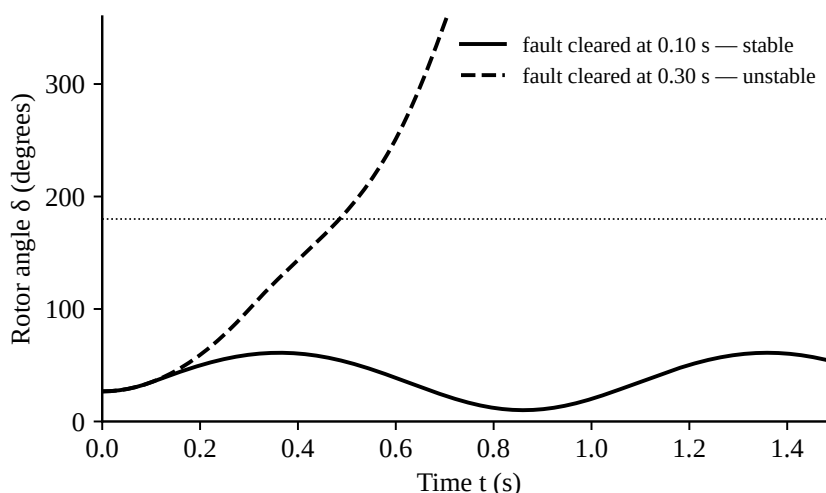


Fig.: Swing curves computed from the swing equation ($H = 5$ s, $P_m = 0.9$ pu, $P_{max} = 2.0 / 0 / 1.6$ pu before / during / after fault)

The computed swing curves show why fast clearing improves transient stability: the same fault cleared in 0.10 s gives a stable swing, while clearing in 0.30 s lets δ increase without limit (loss of synchronism).

(Any four methods, 1 M each)

d) Need of load forecasting.

4 M

1. **Generation scheduling and unit commitment** — deciding which units to run each hour.
2. **Economic operation** — merit-order despatch, power purchase and sale on exchanges.
3. **Planning of new capacity** — generating stations, transmission and distribution networks (long-term forecast).
4. **Fuel and water planning** — coal stock, hydro reservoir use.
5. **Maintenance scheduling** of generators and lines during low-load periods.
6. **Spinning reserve and security** — avoiding load shedding and keeping frequency/voltage within limits.

(Any four, 1 M each)

Q.4

a) Reactive power compensation; equipment.

4 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.

Compensating equipment:

1. Shunt capacitor banks (supply lagging VAR at heavy load)
2. Shunt reactors (absorb VAR at light load on long EHV lines)
3. Synchronous condenser (over/under-excited synchronous motor on no load)

4. Series capacitors (and TCSC)
5. Static VAR compensator — SVC (TCR, TSC)
6. STATCOM, SSSC, UPFC (FACTS devices)

(Concept 2 M, any four equipment 2 M)

b) ALFC block diagram with integral control.

4 M

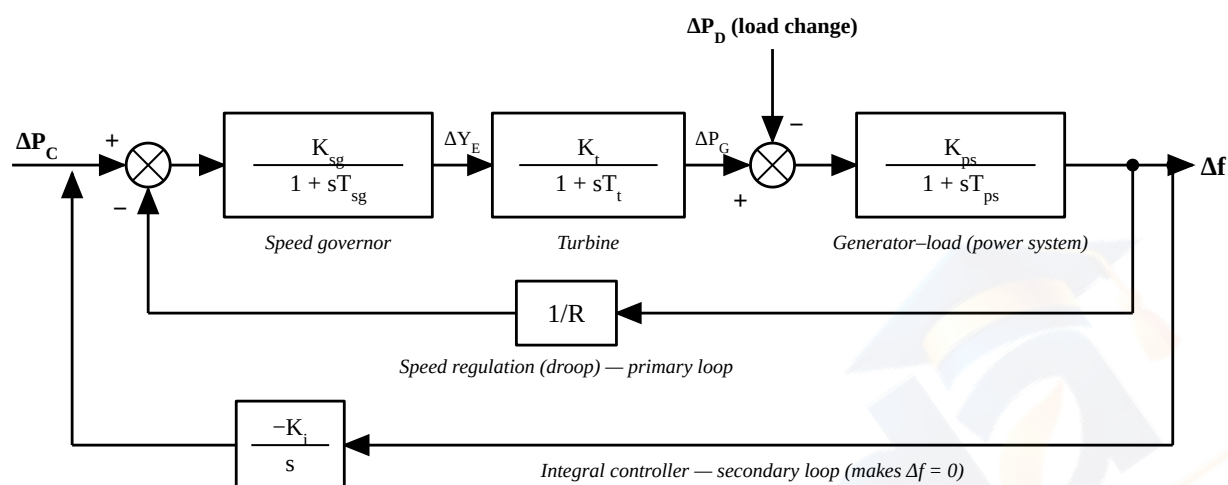


Fig.: Block diagram of ALFC (single area) with integral (secondary) control

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 $T_t \approx 0.2$ – 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.

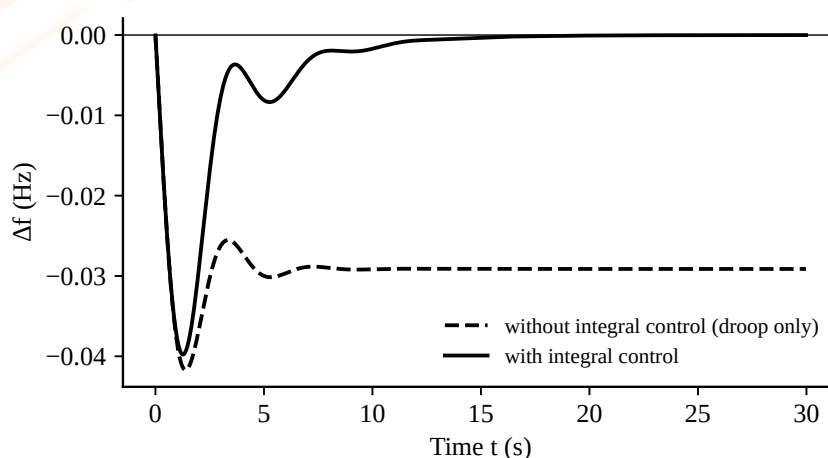


Fig.: Computed frequency response to a 0.01 pu load increase ($K_{ps} = 100$, $T_{ps} = 20$ s, $T_{sg} = 0.2$ s, $T_t = 0.5$ s, $R = 3$ Hz/pu)

With only the droop loop the frequency settles at $\Delta f = -0.01/(1/R + 1/K_{ps}) = -0.0291 \text{ Hz}$; with integral control it returns to **0.0000 $\approx$ 0 Hz** (values computed by simulating the block diagram).

(Diagram 2 M, explanation 2 M)

c) Dynamic stability and methods to improve it.

4 M

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.

Methods to improve dynamic stability:

1. **Power system stabiliser (PSS)** added to the AVR to provide damping torque.
2. Proper tuning of AVR and governor parameters; use of damper windings on rotors.
3. FACTS devices (STATCOM, TCSC, UPFC) with power oscillation damping control; HVDC modulation.

(Definition 1 M, methods 3 M)

d) 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.
4. **Cloud cover and daylight hours:** cloudy or dark days increase lighting load; also reduce rooftop solar output (net load rises).

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.
4. **Population growth and urbanisation:** increase the long-term load.

(Environmental 2 M, social 2 M)

e) Need and importance of LDC.

4 M

1. Load changes continuously; generation must be matched with load at every instant from a central point.
2. Large interconnected grids with many generating stations need coordinated, secure and economic operation.
3. To maintain frequency and voltage within grid-code limits and avoid overloading of lines.
4. To schedule generation economically (merit order) and handle inter-state / inter-regional exchanges.
5. To act quickly during faults and emergencies and restore supply after blackouts.

(Any four, 1 M each)

Q.5

a) Per unit reactance diagram (line as base).

6 M

Step 1 — Base values: $MVA_{base} = 50 \text{ MVA}$, $kV_{base} = 220 \text{ kV}$ in the transmission line circuit (zone 2).

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)	50	11
Zone 2 (transmission line)	50	220
Zone 3 (motor side)	50	33

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	40 MVA, 11 kV, 12 %	$0.12 \times (11/11)^2 \times (50/40)$	j0.1500
T1	50 MVA, 11/220 kV, 10 %	0.1 (rating = base)	j0.1000
Line	j120 Ω	$Z_{base} = 220^2/50 = 968.0000 \Omega$; $X = 120/968.0000$	j0.1240
T2	40 MVA, 220/33 kV, 8 %	$0.08 \times (50/40)$	j0.1000
M	30 MVA, 33 kV, 16 %	$0.16 \times (33/33)^2 \times (50/30)$	j0.2667

Step 4 — Per unit reactance diagram:

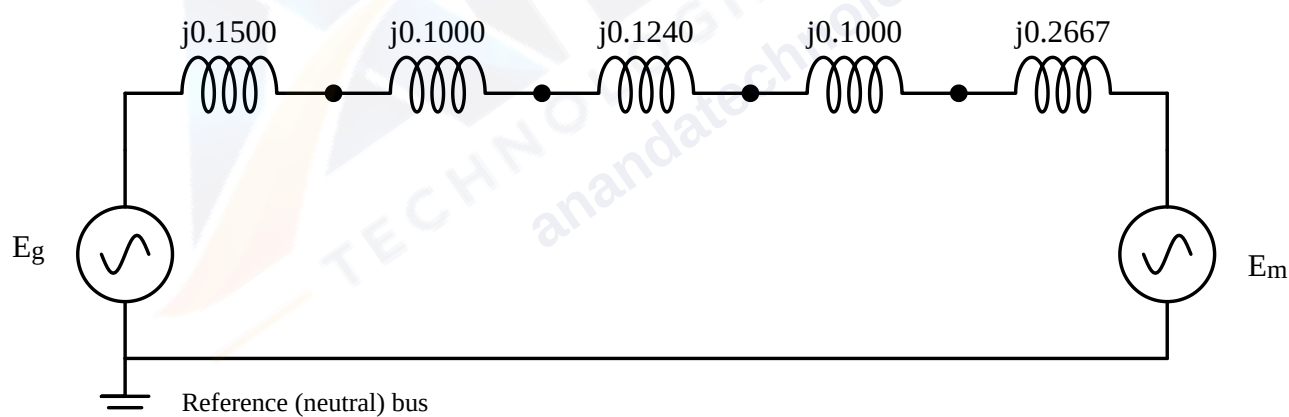


Fig.: Per unit reactance diagram (50 MVA base)

(Base values 1 M, zone base kV 1 M, per unit values 3 M, diagram 1 M)

b) Shunt and series compensation.

6 M

A) Shunt compensation

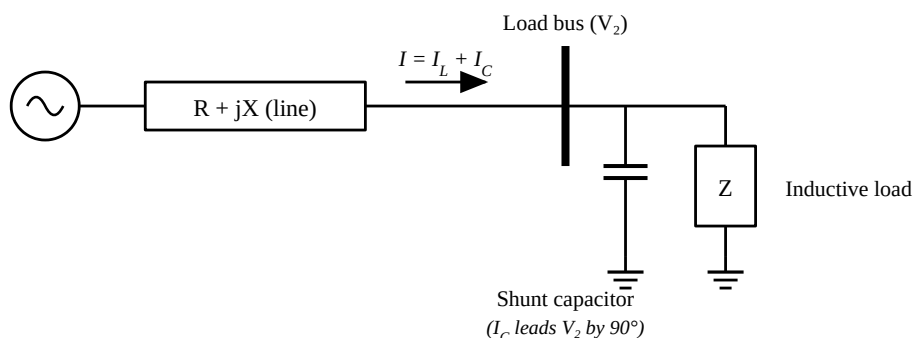


Fig.: Shunt compensation — capacitor bank connected at the receiving end (load bus)

- 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 ($\phi_2 < \phi_1$).
- 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).

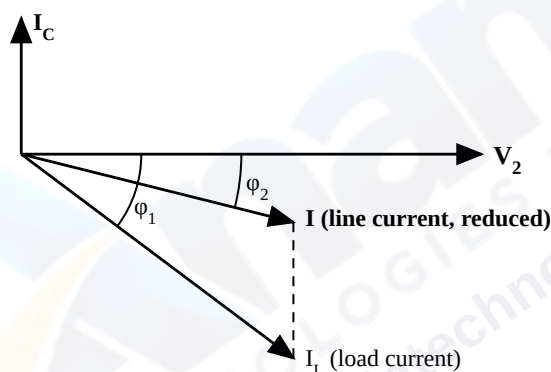
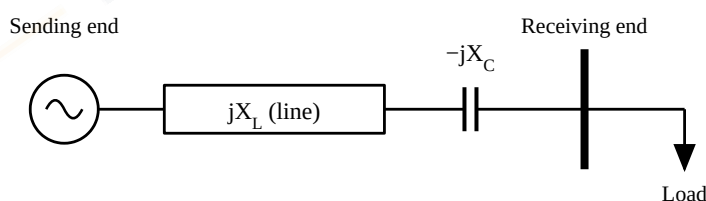


Fig.: Phasor diagram — I_C cancels part of the lagging reactive current of the load

B) Series compensation



$$\text{Net series reactance} = X_L - X_C$$

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

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 $P = V_1 V_2 \sin \delta / (X_L - X_C)$ increases, voltage drop ($\approx I X$) reduces, and steady state and transient stability improve.
- Reactive power produced by the series capacitor ($I^2 X_C$) increases automatically with load — it is self-regulating.
- Needs protection (MOV / bypass breaker) against fault over-voltage; risk of sub-synchronous resonance.

Comparison:

Sr.	Point	Shunt compensation	Series compensation
1	Connection	Parallel with load / bus	In series with line
2	Main purpose	Supply reactive power, improve PF and voltage	Reduce line reactance, increase power transfer
3	Effect on stability	Small	Large improvement
4	Rating	Full bus voltage	Carries full line current, small voltage

(Shunt 3 M, series 3 M)

c) AGC block diagram, components and working.

6 M

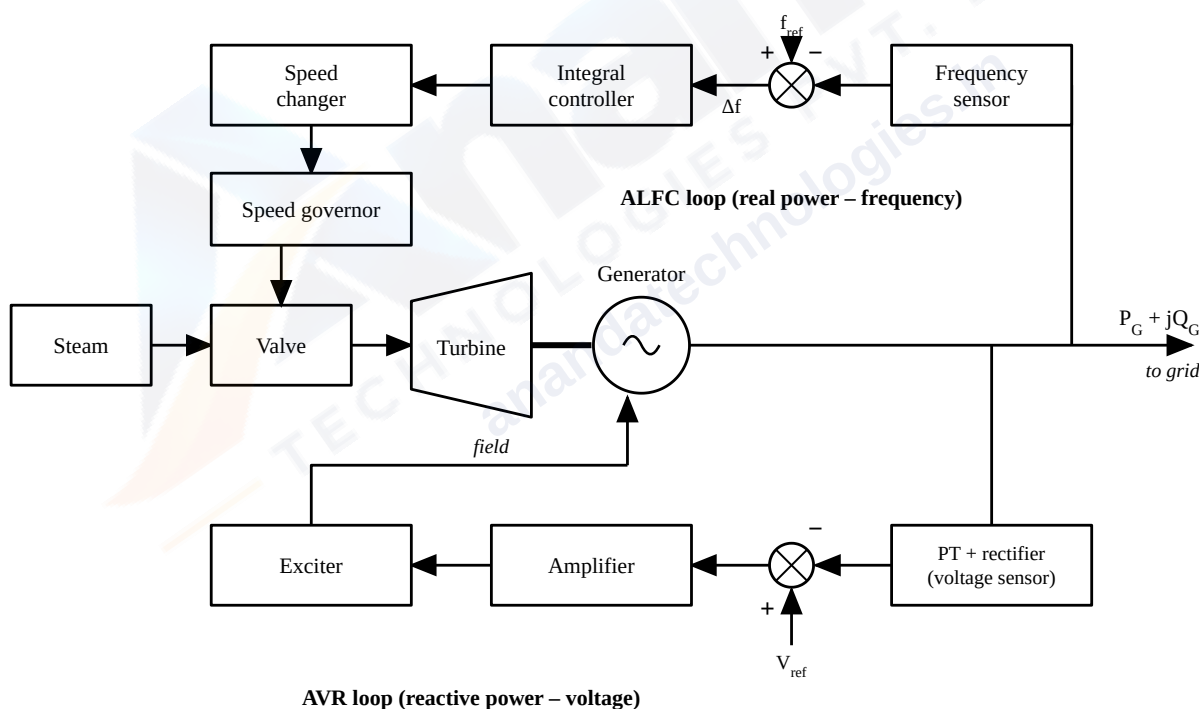


Fig.: Automatic generation control (AGC) — ALFC loop and AVR loop of a generating unit

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 $ACE = \Delta P_{tie} + B\Delta f$) and allocates generation economically among units; commands are sent from the load dispatch centre.

Components:

1. Speed governor and speed changer
2. Turbine with control valve
3. Frequency sensor and integral controller
4. Exciter, amplifier and voltage sensor (AVR loop)

(Diagram 3 M, components 1 M, working 2 M)

Q.6

a) V–Q relation in a two-bus system with numerical.

6 M

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

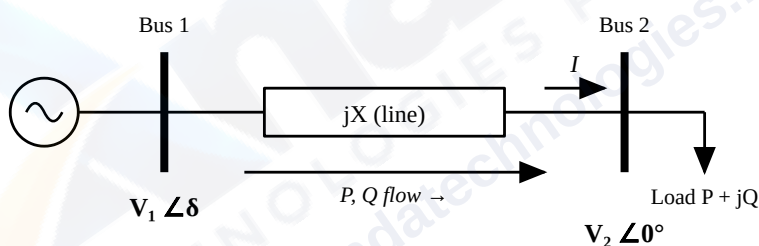


Fig.: Two-bus system — sending end and receiving end connected by a line of reactance X

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

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

$$V_1 = (V_2 + XQ/V_2) + j(XP/V_2)$$

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 ,

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

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

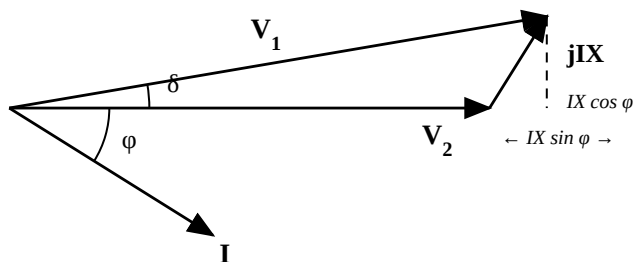


Fig.: Phasor diagram (R neglected): $V_1 = V_2 + jIX$

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, $X = 0.3$ pu, load $P = 0.6$ pu, $Q = 0.3$ pu. $V_1 = (1 + 0.3 \times 0.3/1) + j(0.3 \times 0.6/1) = 1.090 + j0.180$; $|V_1| = 1.1048$ pu, $\delta = 9.38^\circ$. Exact $\Delta V = 0.1048$ pu, approximate $XQ/V_2 = 0.0900$ pu — the drop is decided almost entirely by Q .

Answer: $|V_1| = 1.1048$ pu, load angle $\delta = 9.38^\circ$.

(Diagram 1 M, derivation 3 M, numerical 2 M)

b) Turbine speed governing system.

6 M

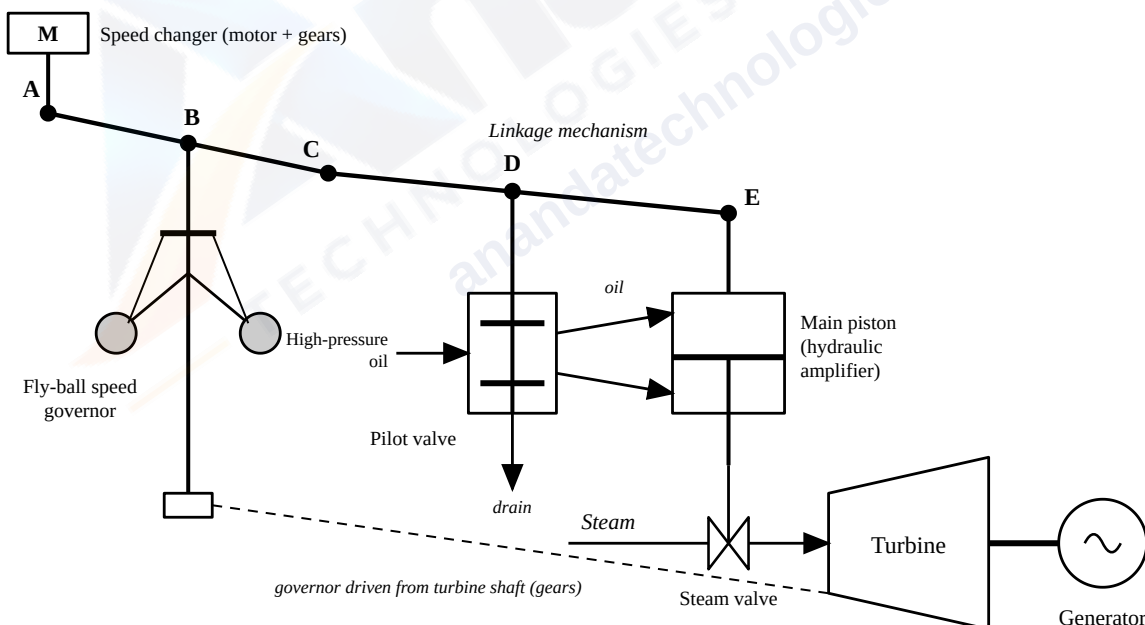


Fig.: Turbine speed governing system (schematic)

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.

(Diagram 3 M, working 3 M)

c) Types of LDCs; functions of NLDC, RLDC and SLDC.

6 M

Load despatch centres in India are arranged in a hierarchy (operated by Grid Controller of India Ltd — Grid-India, formerly POSOCO, for NLDC and RLDCs; SLDCs by the state transmission utilities):

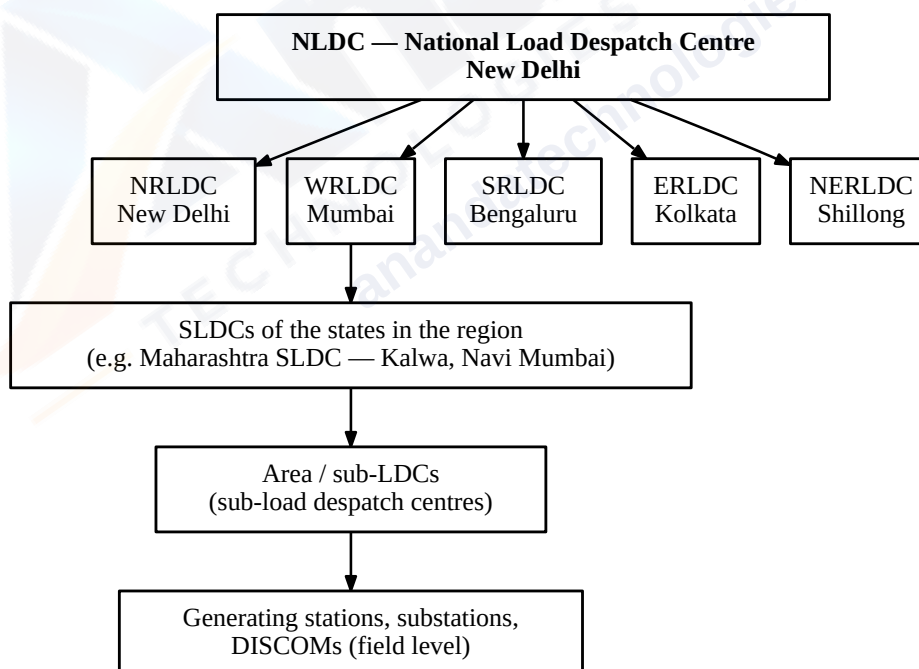


Fig.: Hierarchy of load dispatch centres in India (Grid-India)

Functions of NLDC:

1. Apex body for integrated operation of the national grid; supervision over RLDCs.

2. Scheduling and despatch of electricity over inter-regional links as per grid standards and grid code.
3. Coordination with RLDCs for optimum scheduling and despatch of electricity at national level.
4. Monitoring of operations and grid security of the national grid; restoration of synchronous operation after disturbances.
5. Energy accounting of inter-regional exchanges; operation of cross-border (trans-national) exchanges; dissemination of grid data.

Functions of RLDC:

1. Apex body for integrated operation of the regional grid.
2. Optimum scheduling and despatch of electricity within the region (inter-state).
3. Real-time monitoring of grid operation and security; supervision and control of the inter-state transmission system.
4. Energy accounting and settlement (deviation) for the region.

Functions of SLDC:

1. Apex body for integrated operation of the state power system.
2. Optimum scheduling and despatch of electricity within the state.
3. Real-time monitoring of grid, load-generation balance, load shedding when needed.
4. Supervision of intra-state transmission; energy accounting of state utilities.

(Types 1 M, NLDC 2 M, RLDC 1½ M, SLDC 1½ M)

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