

Power System Operation and Control (315336)

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

Q.1

a) Per unit value; base impedance.

2 M

Per unit value: The per unit (pu) value of any quantity is the ratio of its actual value to a chosen base value of the same quantity (same unit).

$$\text{Per unit value} = \text{Actual value} / \text{Base value} \quad (\text{dimensionless})$$

$$\text{Base impedance } Z_{\text{base}} = (\text{kV}_{\text{base}})^2 / \text{MVA}_{\text{base}} \Omega \quad (\text{or } V_{\text{base}}/I_{\text{base}})$$

(Definition 1 M, expression 1 M)

b) Impedance diagram and reactance diagram.

2 M

Impedance diagram: It is the per-phase equivalent circuit of a balanced 3-phase power system obtained from the single line diagram, in which every component is replaced by its equivalent impedance — generator as an EMF source behind its impedance, transformer by its series impedance (and magnetising branch), line by its nominal- π circuit ($R + jX$ with shunt $C/2$ at each end) and loads by impedances, all referred to the neutral (reference) bus.

Reactance diagram: It is the per-phase equivalent circuit of a power system in which only the reactances of generators, transformers, lines and motors are shown; resistances, shunt branches (magnetising branch of transformers, line charging capacitance) and static loads are neglected. It is used mainly for short-circuit (fault) calculations.

(Each definition 1 M)

c) Effects of low frequency on consumers.

2 M

1. Speed of induction and synchronous motors changes ($N \propto f$) — affects product quality in textile, paper and process industries.
2. Output of fans, pumps and compressors changes ($\text{power} \propto \text{speed}^3$).
3. Electric clocks, timers and synchronous drives give wrong timing.

(Any two, 1 M each)

d) FACTS controllers.

2 M

1. STATCOM — static synchronous compensator (shunt)
2. SSSC — static synchronous series compensator (series)
3. UPFC — unified power flow controller (series–shunt)
4. IPFC — interline power flow controller (series–series)
5. SVC and TCSC (first generation, thyristor controlled)

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

e) Steady state stability and stability limit.

2 M

Steady state stability: the ability of the system to remain in synchronism when subjected to small and gradual disturbances, such as slow change of load. The maximum power transferable under this condition is the steady state stability limit.

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)

f) Components of ALFC loop.

2 M

1. Speed governor (fly-ball / electronic speed sensor)
2. Hydraulic amplifier (pilot valve and main piston)
3. Speed changer
4. Turbine (steam / hydro)
5. Generator – load (power system)
6. Frequency sensor and integral controller (secondary loop)

(Any four, ½ M each)

g) Environmental factors in load forecasting.

2 M

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.

(Any two, 1 M each)

Q.2

a) Structure of power system (single line diagram).

4 M

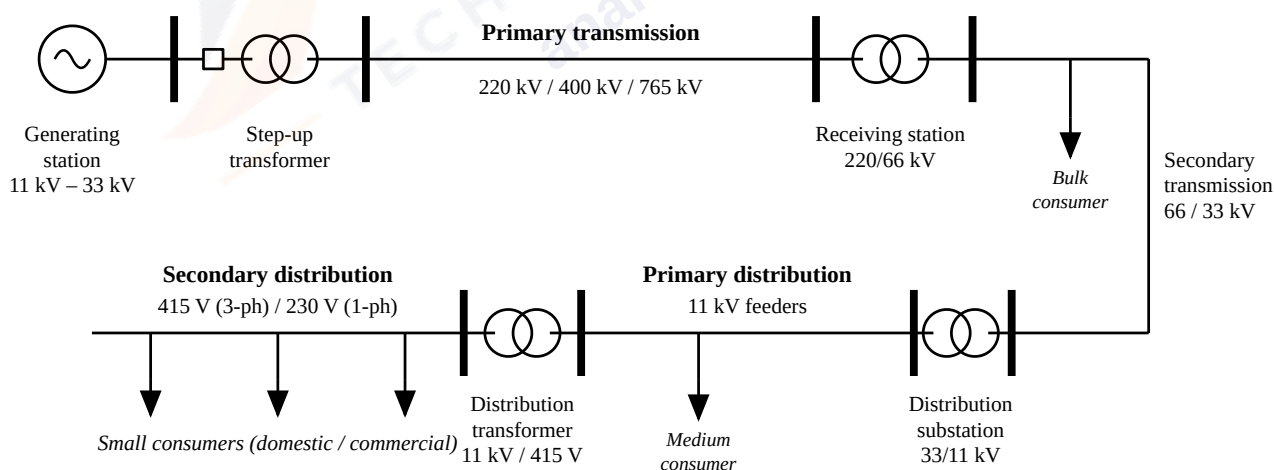


Fig.: Structure of a typical power system (single line representation)

1. **Generation:** power is generated at 11–33 kV in thermal, hydro, nuclear and renewable stations.

2. **Primary transmission:** voltage is stepped up to 220/400/765 kV and power is transmitted over long distances to receiving stations.
3. **Secondary transmission:** at receiving stations voltage is reduced to 66/33 kV and fed to distribution substations; bulk consumers are supplied directly.
4. **Primary distribution:** distribution substations step down to 11 kV feeders; medium consumers take supply at 11 kV.
5. **Secondary distribution:** distribution transformers step down to 415 V (3-phase) / 230 V (1-phase) for small consumers.

(Diagram 2 M, explanation 2 M)

b) 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:* $H = 5$ s, $f_0 = 50$ Hz, sudden deficit of 0.04 pu $\rightarrow d(\Delta f)/dt = (50/10) \times (-0.04) = -0.20$ 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 2 M, relation 2 M)

c) Block diagram of AGC.

4 M

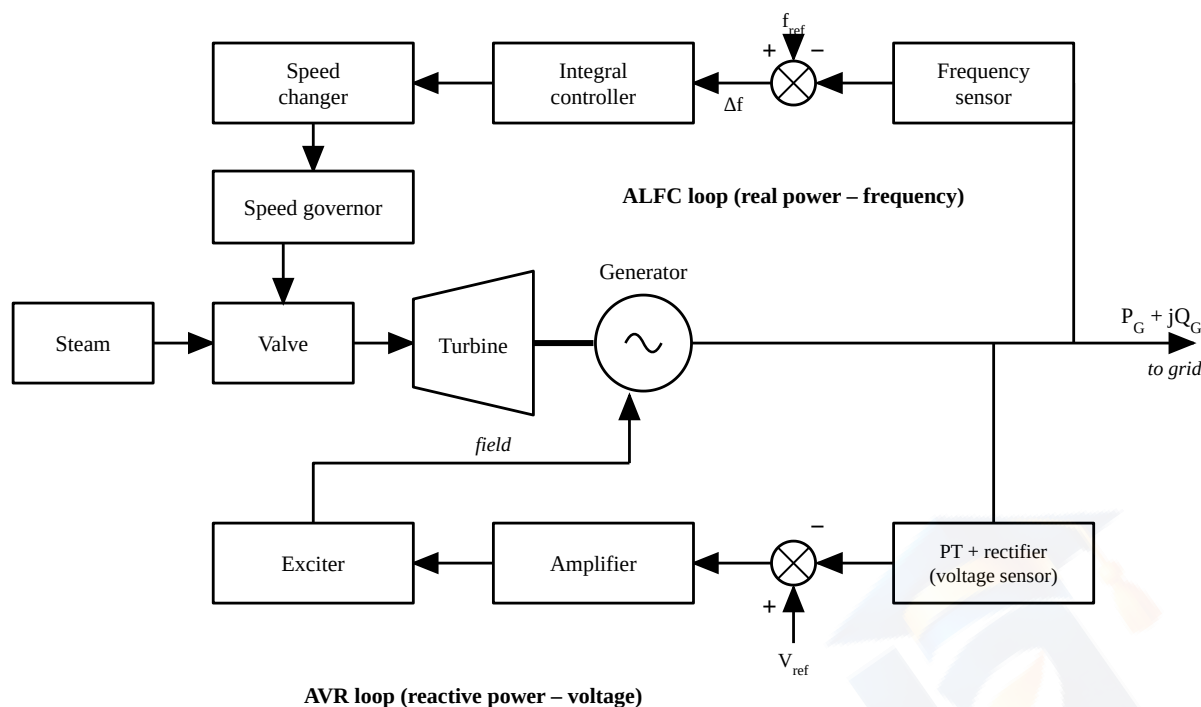


Fig.: Automatic generation control (AGC) — ALFC loop and AVR loop of a generating unit

- 1. ALFC loop (P–f control):** frequency sensor $\rightarrow$ comparator with f_{ref} $\rightarrow$ integral controller $\rightarrow$ speed changer $\rightarrow$ speed governor $\rightarrow$ steam valve $\rightarrow$ turbine. It controls real power output and keeps frequency constant.
- 2. AVR loop (Q–V control):** PT and rectifier (voltage sensor) $\rightarrow$ comparator with V_{ref} $\rightarrow$ amplifier $\rightarrow$ exciter $\rightarrow$ generator field. It controls reactive power and keeps terminal voltage constant.
- 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.
- 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.

(Diagram 2 M, explanation 2 M)

d) Small disturbance vs large disturbance.

4 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
3	Stability concerned	Steady state and dynamic stability	Transient stability
4	Analysis	Equations can be linearised	Non-linear swing equation must be solved

(Any four points, 1 M each)

Q.3

a) Per unit impedance; change of base numerical.

4 M

Per unit impedance = actual impedance (Ω) / base impedance (Ω), where $Z_{\text{base}} = \text{kV}_{\text{base}}^2 / \text{MVA}_{\text{base}}$.

Given: $X_{\text{old}} = 0.2$ pu on 25 MVA, 11 kV. New base: 100 MVA, 12 kV.

$$Z_{\text{pu}(\text{new})} = Z_{\text{pu}(\text{old})} \times (\text{kV}_{\text{old}} / \text{kV}_{\text{new}})^2 \times (\text{MVA}_{\text{new}} / \text{MVA}_{\text{old}})$$

$$X_{\text{pu}(\text{new})} = 0.2 \times (11/12)^2 \times (100/25) = 0.2 \times 0.8403 \times 4 = \mathbf{0.6722 \text{ pu}}$$

Check through ohms: $X = 0.2 \times (11^2/25) = 0.9680 \Omega$; new $Z_{\text{base}} = 12^2/100 = 1.4400 \Omega$; $X_{\text{pu}} = 0.9680/1.4400 = 0.6722$ pu ✓

(Definition 1 M, formula 1 M, calculation 2 M)

b) Shunt vs series compensation.

4 M

Sr.	Point	Shunt compensation	Series compensation
1	Connection	Capacitor/reactor connected in parallel with load at the bus	Capacitor connected in series with the line
2	Main effect	Supplies reactive power, improves power factor and bus voltage	Reduces net line reactance ($X_L - X_C$)
3	Power transfer & stability	Small improvement	Large increase in power transfer and stability limit
4	Reactive output	$Q = V^2/X_C$ — falls when voltage falls	$Q = I^2X_C$ — rises automatically with load
5	Rating / insulation	Insulated for full bus voltage	Carries full line current; needs over-voltage protection (MOV)
6	Typical use	Distribution and sub-transmission substations; reactors on EHV lines at light load	Long EHV transmission lines

(Any four points, 1 M each)

c) 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.

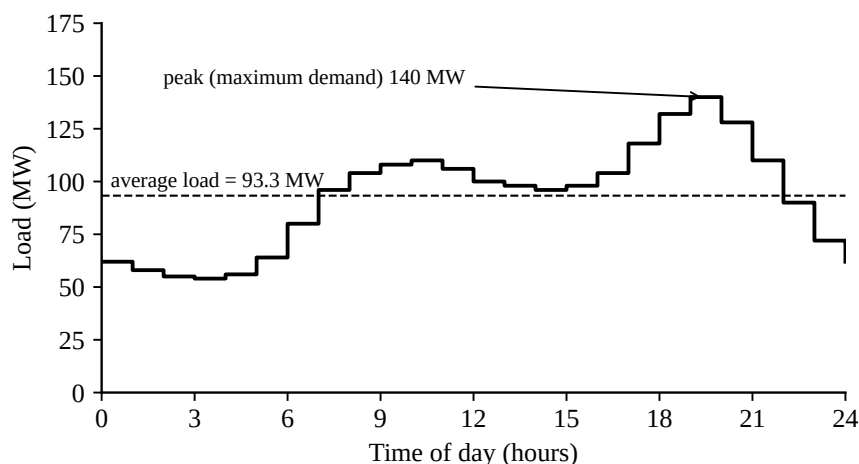


Fig.: Typical daily load curve of a utility (illustrative data) — forecasting predicts such curves

The forecast daily load curve shows the morning and evening peaks (here peak 140 MW at 19–20 h, average 93.3 MW); generation is scheduled to follow it.

(Any four points, 1 M each)

d) Types of LDCs in India with locations.

4 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):

LDC	Jurisdiction	Location
NLDC	National	New Delhi
NRLDC	Northern region	New Delhi
WRLDC	Western region	Mumbai
SRLDC	Southern region	Bengaluru
ERLDC	Eastern region	Kolkata
NERLDC	North-eastern region	Shillong
SLDC	Each state (e.g. Maharashtra)	State capital / chosen place (Maharashtra SLDC: Kalwa, Navi Mumbai)
Area / Sub-LDC	Part of a state	Zonal locations

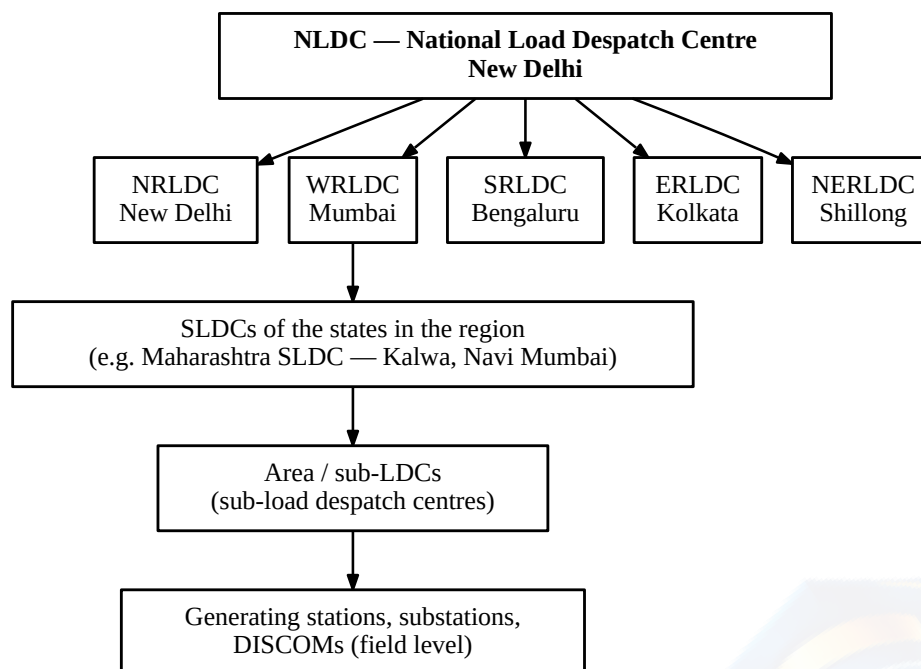


Fig.: Hierarchy of load dispatch centres in India (Grid-India)

(Types 2 M, locations 2 M)

Q.4

a) Schematic diagram of AVC.

4 M

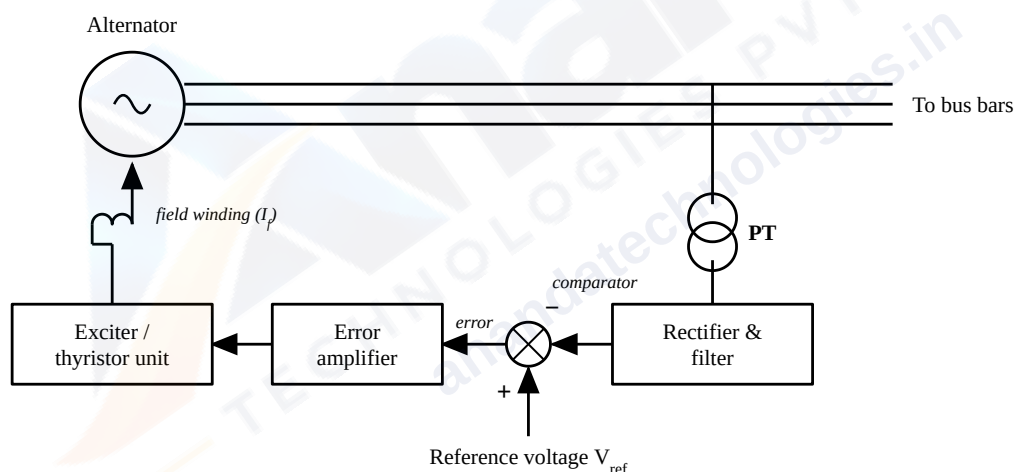


Fig.: Schematic diagram of automatic voltage control (AVC) of an alternator

- Potential transformer (PT):** senses the alternator terminal voltage and steps it down.
- Rectifier and filter:** converts the sensed AC voltage into a smooth DC signal proportional to terminal voltage.
- Comparator:** compares this signal with the reference voltage V_{ref} (set value) and produces an error signal.
- Error amplifier:** amplifies the error signal.
- 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, explanation 2 M)

b) 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)

c) Impact of voltage variation.

4 M

On consumers:

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.

On supply agencies (generating plants / utilities):

1. Low voltage increases current for the same power $\rightarrow$ higher I^2R losses and heating in generators, lines and transformers.
2. Power transfer capability and stability margin of lines reduce; risk of voltage instability / collapse.
3. High voltage causes over-fluxing of transformers, insulation stress, corona loss and failure of equipment.
4. Generator has to operate at higher excitation (low V) or under-excited (high V) — limits of the capability curve; station auxiliaries motors overheat; revenue falls because consumers draw less energy at low voltage.

(Consumers 2 M, supply agencies 2 M)

d) Working principle of STATCOM.

4 M

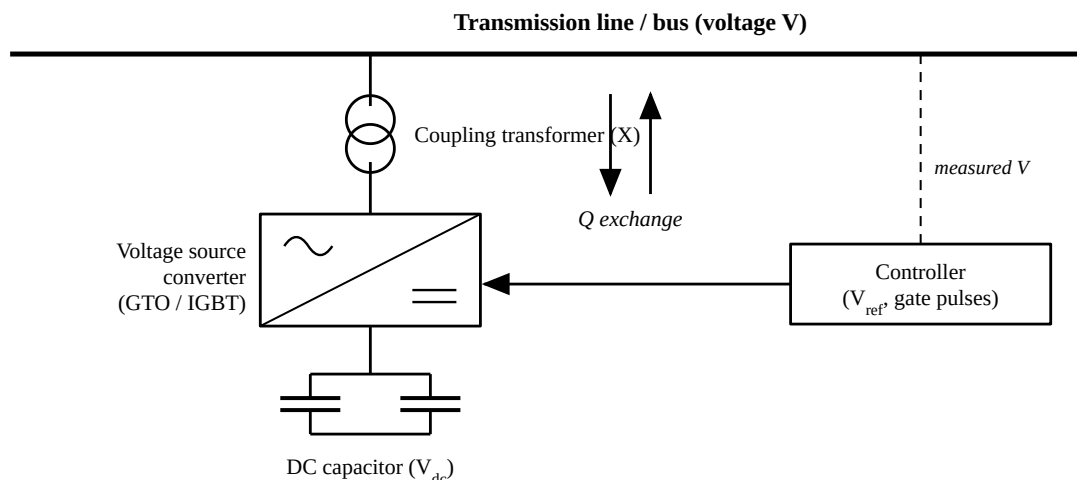


Fig.: STATCOM (static synchronous compensator) — shunt connected

- **Construction:** A voltage source converter (VSC) using GTOs/IGBTs, a DC capacitor which provides the DC voltage, a coupling transformer (reactance X) connecting the converter to the bus, and a controller.
- The VSC produces a 3-phase AC voltage V_C in phase with the bus voltage V ; its magnitude is controlled by the converter switching (PWM).
- If $V_C > V$: current leads V — STATCOM **supplies reactive power** (acts like a capacitor).
- If $V_C < V$: current lags V — STATCOM **absorbs reactive power** (acts like a reactor). If $V_C = V$, no exchange.
- Reactive power exchanged $Q = V(V_C - V)/X$; a small phase shift lets it draw real power to charge the DC capacitor.

(Diagram 2 M, working 2 M)

e) Functions of NLDC.

4 M

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.

(Any four, 1 M each)

Q.5

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).

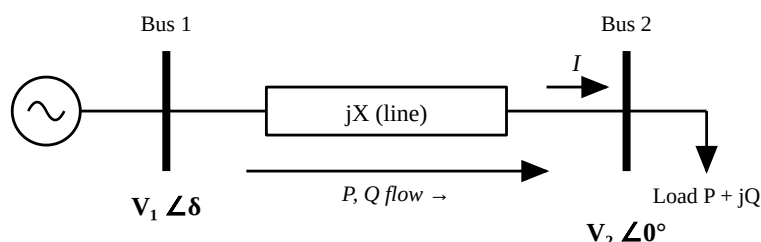


Fig.: Two-bus system — sending end and receiving end connected by a line of reactance X

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 .

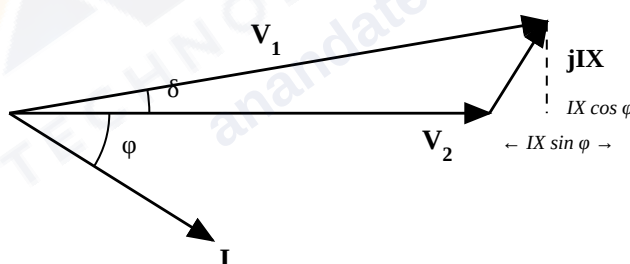


Fig.: Phasor diagram (R neglected): $V_1 = V_2 + jIX$

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, $X = 0.25$ pu, load $P = 0.8$ pu, $Q = 0.4$ pu. $V_1 = (1 + 0.25 \times 0.4/1) + j(0.25 \times 0.8/1) = 1.100 + j0.200$; $|V_1| = 1.1180$ pu, $\delta = 10.30^\circ$. Exact $\Delta V = 0.1180$ pu, approximate $XQ/V_2 = 0.1000$ pu — the drop is decided almost entirely by Q .

Answer: Sending-end voltage $|V_1| = 1.1180 \text{ pu}$.

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

b) Turbine speed governing system.

6 M

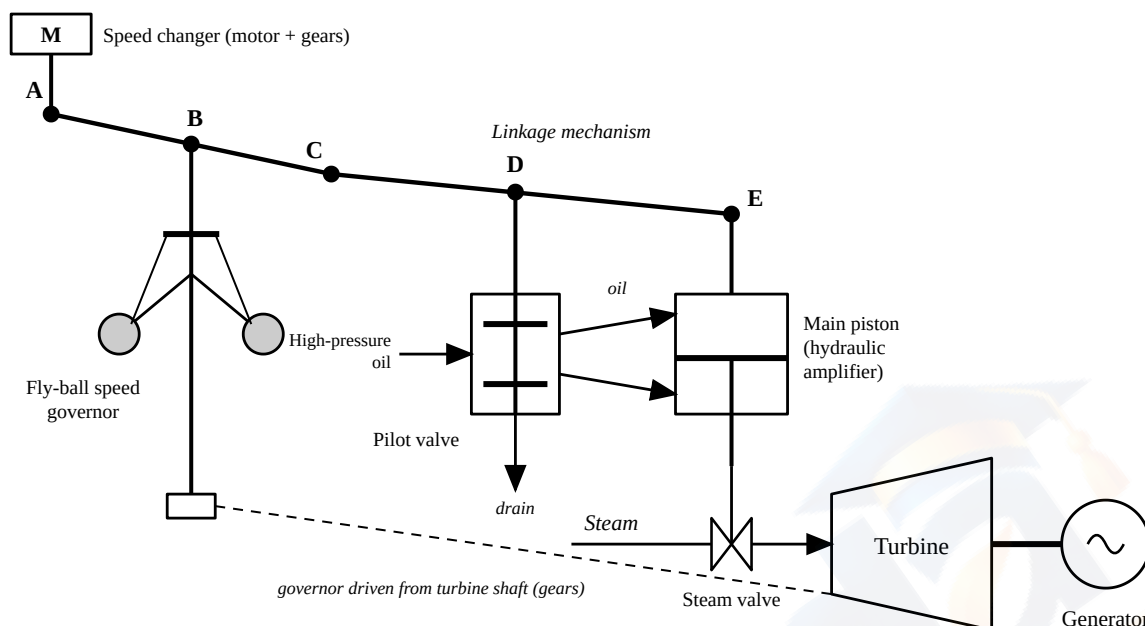


Fig.: Turbine speed governing system (schematic)

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, parts and working 3 M)

c) Methods of improving transient stability.

6 M

Transient stability is the ability of the system to remain in synchronism after a large sudden disturbance. It is improved by the following methods:

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.

(Any six methods, 1 M each)

Q.6

a) Per unit reactance diagram (two motors).

6 M

Step 1 — Base values: $MVA_{\text{base}} = 100 \text{ MVA}$, $kV_{\text{base}} = 13.8 \text{ kV}$ in the generator circuit (zone 1).

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)	100	13.8
Zone 2 (transmission line)	100	138
Zone 3 (motor side)	100	11.5

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

Element	Given rating	Per-unit reactance on common base	X (pu)
G	50 MVA, 13.8 kV, 15 %	$0.15 \times (13.8/13.8)^2 \times (100/50)$	j0.3000
T1	60 MVA, 13.2/132 kV, 10 %	$0.1 \times (13.2/13.8)^2 \times (100/60)$	j0.1525
Line	j40 Ω	$Z_{\text{base}} = 138^2/100 = 190.4400 \Omega$; $X = 40/190.4400$	j0.2100
T2	40 MVA, 132/11 kV, 8 %	$0.08 \times (132/138)^2 \times (100/40)$	j0.1830
M1	20 MVA, 10.5 kV, 20 %	$0.2 \times (10.5/11.5)^2 \times (100/20)$	j0.8336
M2	15 MVA, 10.5 kV, 18 %	$0.18 \times (10.5/11.5)^2 \times (100/15)$	j1.0004

Step 4 — Per unit reactance diagram:

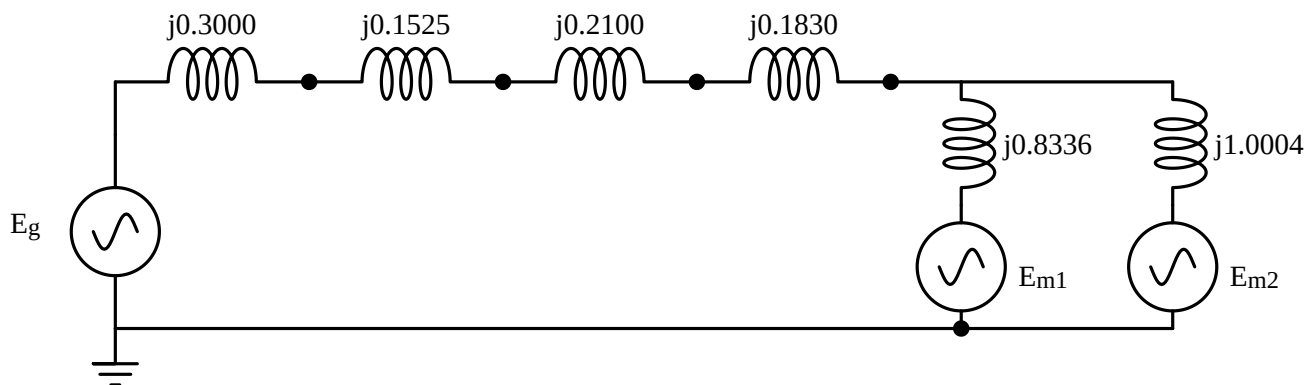


Fig.: Per unit reactance diagram (all values in pu on 100 MVA base)

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

Note: T1 is rated 13.2 kV on the LV side while base is 13.8 kV, so the voltage-ratio correction $(13.2/13.8)^2$ is applied; the motors are rated 10.5 kV while zone 3 base is 11.5 kV.

b) Steady state stability — power angle diagram and numerical.

6 M

For a generator (EMF E) connected to an infinite bus (voltage V) through total reactance X , the electrical power is

$$P_e = (E V / X) \sin \delta = P_{\max} \sin \delta$$

where δ is the load (power) angle between E and V . The graph of P_e against δ is the **power angle diagram**.

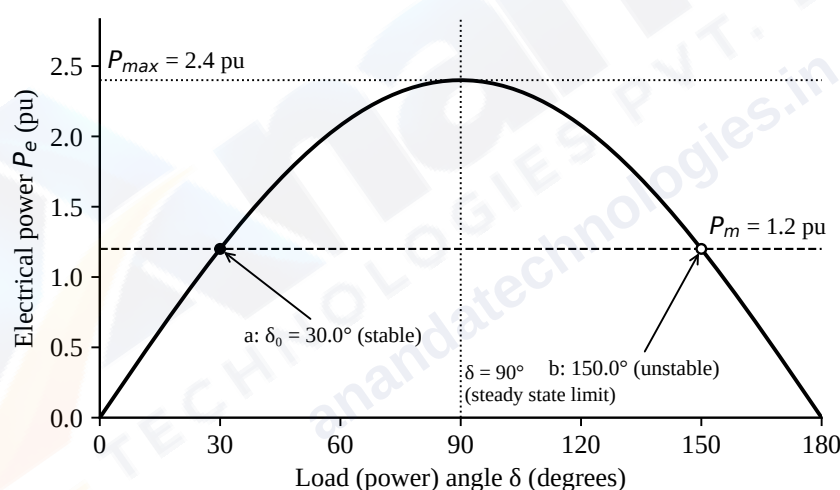


Fig.: Power angle diagram (computed) — $E = 1.2$ pu, $V = 1$ pu, $X = 0.5$ pu

1. For a mechanical input P_m the machine operates at point a (δ_0) where $P_e = P_m$.
2. If load is increased slowly, δ increases and P_e increases — the machine remains stable as long as $dP_e/d\delta = P_{\max} \cos \delta > 0$, i.e. $\delta < 90^\circ$.
3. At $\delta = 90^\circ$ the power is maximum ($P_{\max} = EV/X$) — this is the **steady state stability limit**. Any further increase makes δ increase continuously and the machine falls out of step.
4. Point b ($180^\circ - \delta_0$) is an unstable equilibrium point. In practice machines operate at $\delta \approx 30^\circ - 45^\circ$ to keep a stability margin.
5. Steady state limit is increased by raising E (excitation) or V and reducing X .

Numerical (computed): $P_{\max} = EV/X = 1.2 \times 1/0.5 = 2.40 \text{ pu}$; for $P = 1.2 \text{ pu}$, $\sin \delta_0 = 1.2/2.40 \rightarrow \delta_0 = 30.00^\circ$; steady state stability margin = $(P_{\max} - P)/P_{\max} = 50.0 \%$.

(Diagram 2 M, explanation 2 M, numerical 2 M)

c) Need of LDC and role of SCADA.

6 M

Need of load dispatch centre:

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.

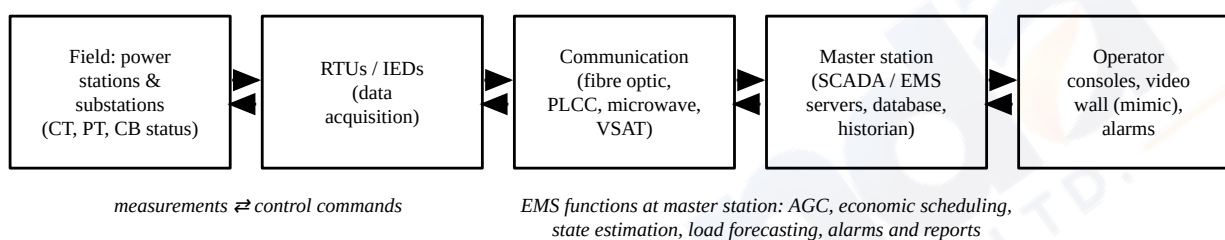


Fig.: SCADA system in a load dispatch centre

Role of SCADA in an LDC: RTUs at stations and substations collect analog data (MW, MVar, kV, Hz, tap position) and status (breaker/isolator), which reach the master station through communication links. The operator sees the whole grid on the video wall, gets alarms, and sends control commands (breaker operation, generation set points). EMS applications such as AGC, state estimation, load forecasting and scheduling run on this data.

(Need 2 M, block diagram 2 M, role 2 M)

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