# Power Systems

Short notes for B.Tech EE · EEE · GATE EE

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## 1. Power System Basics

- Structure: **Generation → Transmission → Sub-transmission → Distribution → Consumer**.
- Generation at about 11–25 kV, stepped up for transmission (e.g. 132, 220, 400, 765 kV), stepped down for distribution (33, 11 kV, 415/230 V).
- Higher transmission voltage → less current → less I^2 R loss and less conductor material.

### ➤ Load curve terms

| Term | Meaning |
|---|---|
| Connected load | Sum of ratings of all equipment |
| Maximum demand | Highest load in a given period |
| Demand factor | Max demand / connected load (≤ 1) |
| Load factor | Average load / max demand |
| Diversity factor | Sum of individual max demands / max demand of the group (≥ 1) |
| Plant capacity factor | Average load / plant capacity |
| Plant use factor | Energy generated / (capacity in use x hours in operation) |

**EXAMPLE** A plant has max demand 50 MW and gives 262.8 GWh in a year. Average load = 262800 MWh / 8760 h = 30 MW. Load factor = 30/50 = 0.6.

- **Base load plants**: run all the time (thermal coal, nuclear). **Peak load plants**: started quickly (hydro, gas turbine, pumped storage).

## 2. Transmission Line Parameters

- Four parameters: series **R** and **L**, shunt **C** and **G** (G usually neglected).

- **Skin effect**: AC current crowds near the surface, so effective R rises. More at higher frequency and bigger conductors. Absent in DC.
- **Proximity effect**: current distribution changes due to nearby conductors.

**FORMULA** Inductance per phase L = 2 x 10^-7 ln(D / r') H/m, where r' = 0.7788 r (GMR of a solid round conductor).

**FORMULA** Capacitance to neutral C = 2π ε0 / ln(D / r) F/m. (Note: actual radius r is used for C, not r'.)

- For unsymmetrical spacing use **GMD** = (Dab Dbc Dca)^(1/3). **Transposition** makes the three phases have equal L and C.
- **Bundled conductors**: lower L, higher C, higher SIL, less corona and less radio interference.

**FORMULA** Surge impedance Zc = sqrt(L / C) (about 400 Ω for overhead lines, about 40–60 Ω for cables). Surge impedance loading SIL = V^2 / Zc (V = line voltage).

- At SIL, the line's reactive power generated by C equals that consumed by L; voltage stays flat along the line.
- Velocity of a travelling wave on an overhead line ≈ speed of light, 3 x 10^8 m/s.

## Corona

- Ionisation of air around conductors when the field strength exceeds the breakdown strength of air.
- Effects: power loss, hissing sound, violet glow, ozone, radio interference. Good effect: reduces the steepness of surges.
- Reduce it by: larger conductor diameter, bundled conductors, larger spacing.
- More corona in bad weather (rain, fog) and at low air density.

# 3. Performance of Transmission Lines

| Line | Length (approx.) | Model |
|---|---|---|
| Short | Up to 80 km | Series Z only, C neglected |
| Medium | 80 to about 250 km | Nominal π or nominal T |
| Long | Above about 250 km | Distributed parameters (exact) |

## ➤ ABCD constants

- $V_s = A V_r + B I_r$, $I_s = C V_r + D I_r$. For any passive two-port: $AD - BC = 1$. For a symmetrical network $A = D$.

| Model | A = D | B | C |
|---|---|---|---|
| Short line | 1 | Z | 0 |
| Nominal π | $1 + YZ/2$ | Z | $Y(1 + YZ/4)$ |
| Nominal T | $1 + YZ/2$ | $Z(1 + YZ/4)$ | Y |
| Long line | $\cosh(\gamma l)$ | $Z_c \sinh(\gamma l)$ | $\sinh(\gamma l) / Z_c$ |

**FORMULA** % Regulation = $(V_{r,no\text{-}load} - V_{r,full\text{-}load}) / V_{r,full\text{-}load} \times 100$, with $V_{r,no\text{-}load} = V_s / |A|$.

- **Ferranti effect**: at light load or no load, receiving-end voltage becomes **more** than sending-end voltage on long lines, due to line charging current. Controlled with shunt reactors.
- Power transfer: $P = (V_s V_r / X) \sin \delta$. Max at $\delta = 90°$ (steady-state limit).

# 4. Insulators and Cables

- Overhead line insulators: pin type (up to 33 kV), suspension (disc) type (higher voltages), strain type (at dead ends, sharp turns).
- In a suspension string, voltage is **not equally shared** because of shunt capacitance to the tower. The disc nearest the conductor takes the most voltage.

**FORMULA** String efficiency = voltage across whole string / (n x voltage across disc nearest the conductor) x 100.

**EXAMPLE** 3-disc string, m = shunt C / self C = 0.1. V2 = V1(1 + m) = 1.1 V1. V3 = V1(1 + 3m + m^2) = 1.31 V1. Total = 3.41 V1. String efficiency = 3.41 / (3 x 1.31) = 86.8%.

- Improve string efficiency with: longer cross-arms (smaller m), capacitance grading, **guard ring** (static shielding).

### ➤ Underground cables

- Insulation resistance R = (ρ / 2πl) ln(R/r). Capacitance C = 2π ε0 εr l / ln(R/r).
- Max stress at the conductor surface. Most economical size when ln(R/r) = 1, i.e. R/r = e = 2.718.
- **Grading of cables** (capacitance grading, intersheath grading) makes stress more uniform.

## 5. Per-Unit System and Symmetrical Faults

- Per-unit value = actual value / base value. Choose base MVA (same everywhere) and base kV (changes with transformer ratio).

**FORMULA** Base Z = (base kV)^2 / base MVA. Change of base: Z_new = Z_old x (MVA_new / MVA_old) x (kV_old / kV_new)^2.

- Advantages: transformer per-unit impedance is the same on both sides, values fall in a narrow range, easy to spot errors.

**EXAMPLE** Generator X = 0.2 pu on 50 MVA, 11 kV. On 100 MVA, 11 kV base: X = 0.2 x 100/50 = 0.4 pu.

### ➤ Symmetrical (3-phase) fault

- Generator reactances after a fault: **subtransient X"** (first few cycles), **transient X'**, **synchronous Xd**. X" < X' < Xd.
- Fault MVA = base MVA / X_pu (total pu reactance up to the fault point).

**EXAMPLE** 20 MVA, 11 kV generator, X = 0.2 pu, 3-phase fault at its terminals. Fault MVA = 20/0.2 = 100 MVA. Fault current = 100 x 10^6 / (√3 x 11000) = 5249 A.

- **Current limiting reactors** (generator, feeder, bus-bar) reduce fault MVA so breakers of smaller rating can be used.

# 6. Symmetrical Components and Unsymmetrical Faults

- Any unbalanced set of 3 phasors = **positive** + **negative** + **zero** sequence sets (Fortescue).
- Operator a = 1∠120°. a^3 = 1, 1 + a + a^2 = 0.

**FORMULA** Ia0 = (Ia + Ib + Ic)/3, Ia1 = (Ia + a Ib + a^2 Ic)/3, Ia2 = (Ia + a^2 Ib + a Ic)/3.

- Zero-sequence current flows only if there is a path to ground (grounded star). In delta it circulates inside and does not reach the line.

| Fault | Sequence network connection | Fault current |
|---|---|---|
| L-G | All three in series | If = 3E / (Z1 + Z2 + Z0 + 3Zf) |
| L-L | Positive and negative in parallel | If = √3 E / (Z1 + Z2 + Zf) |
| L-L-G | Negative and (zero + 3Zf) in parallel, in series with positive | Ia1 = E / (Z1 + Z2 parallel (Z0 + 3Zf)) |
| L-L-L | Positive only | If = E / Z1 |

**REMEMBER** L-G fault is the most common type. The 3-phase fault is usually the most severe and is used for breaker rating.

# 7. Load Flow Studies

- Finds voltage magnitude, angle δ at every bus, and P, Q flows in lines, under steady state.

| Bus type | Known | Unknown |
|---|---|---|
| Slack (swing) | V magnitude, δ | P, Q |
| PV (generator) | P, V magnitude | Q, δ |
| PQ (load) | P, Q | V magnitude, δ |

- **Ybus**: diagonal Yii = sum of all admittances connected to bus i. Off-diagonal Yij = -(admittance between i and j). It is **sparse** and symmetric (without phase shifters).

| Method | Convergence | Memory / time per iteration | Use |
|---|---|---|---|
| Gauss-Seidel | Linear, many iterations | Low, simple | Small systems |
| Newton-Raphson | Quadratic, few iterations | High (Jacobian) | Large systems |
| Fast decoupled | Between the two | Low (constant matrices) | Quick and repeated studies |

- Acceleration factor (about 1.6) speeds up Gauss-Seidel.

# 8. Power System Stability

- **Steady-state**: small, slow changes. **Transient**: large sudden disturbance (fault). **Dynamic**: small disturbance with controllers acting.

**FORMULA** Swing equation: $M\, d^2\delta/dt^2 = Pm - Pe$, with $M = H\, S / (\pi\, f)$ in per unit. $Pe = Pmax \sin \delta$, $Pmax = E\, V / X$.

- **H (inertia constant)** = stored kinetic energy (MJ) / machine rating (MVA).
- **Equal area criterion** (one machine vs infinite bus): stable if accelerating area A1 = decelerating area A2 is possible before δ reaches its max limit.
- **Critical clearing angle** $\delta cr = \cos^{-1}[(\pi - 2\delta 0) \sin \delta 0 - \cos \delta 0]$, for a fault where Pe = 0 during fault and pre- and post-fault curves are same.
- Improve stability: fast circuit breakers, auto-reclosing, higher system voltage, series capacitors, fast excitation, more parallel lines.

# 9. Economic Dispatch, Frequency Control and HVDC

- **Economic dispatch**: share load among units so total fuel cost is minimum.

**FORMULA** Without losses: $dC1/dP1 = dC2/dP2 = \ldots = \lambda$ (equal incremental cost), with $P1 + P2 + \ldots =$ load.

**EXAMPLE** $dC1/dP1 = 0.02\,P1 + 20$, $dC2/dP2 = 0.03\,P2 + 16$ (Rs/MWh), load 300 MW. Set equal: $0.02\,P1 + 20 = 0.03\,P2 + 16$ and $P1 + P2 = 300$. Solving: $P2 = 200$ MW, $P1 = 100$ MW, $\lambda = 22$ Rs/MWh.

- **Load frequency control (LFC)**: real power controls frequency. **Reactive power** controls voltage (AVR, capacitors, reactors).
- Speed regulation $R = \Delta f / \Delta P$ (Hz/MW or pu). Static frequency drop $\Delta f = -\Delta PD / (1/R + D)$.
- **HVDC**: no reactive power or skin effect issues, no stability limit, asynchronous link, cheaper for long distances and cables. But converter stations are costly and produce harmonics.
- HVDC links: monopolar, bipolar, homopolar, back-to-back.

| Point | HVAC | HVDC |
|---|---|---|
| Line cost | Higher (3 conductors) | Lower (2 or 1 conductor) |
| Terminal cost | Low | High (converters) |
| Stability limit | Yes | No |
| Linking different frequency grids | Not possible | Possible |

# 10. Most Asked Questions (practice)

1. Define load factor, diversity factor and demand factor. Solve a numerical.
2. Derive inductance and capacitance of a 3-phase line. Why is transposition done?
3. Find ABCD constants of nominal π and T models. Explain Ferranti effect.
4. Find string efficiency of a 3-disc string. How is it improved?
5. What is corona? State its advantages, disadvantages and methods to reduce it.
6. Explain the per-unit system. Change of base formula with example.
7. Derive the fault current for an L-G fault using symmetrical components.

8. Compare Gauss-Seidel and Newton-Raphson load flow. Form Ybus for a 3-bus system.
9. Derive the swing equation. Explain the equal area criterion.
10. Solve an economic dispatch problem using equal incremental cost.

**TIP** GATE EE power systems: per-unit, fault MVA, symmetrical components, ABCD, swing equation / equal area, Ybus and economic dispatch carry most marks. Keep all formulas on one sheet and revise them daily.