Electrical Machines and Power Systems

Curated undergraduate study track (not accredited, no external exam). Original explanations and practice only, following the reviewed course handout.

From flux to grid

- Magnetic circuits and machines first, then the networks that connect them, then the electronics that control the energy.
- Every worked number closes a power balance; every network number closes in **per-unit**.

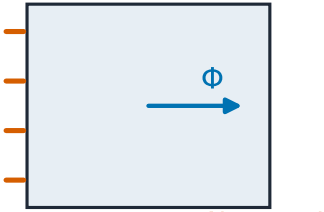
Magnetic circuits and transformers: two tests, two losses

1. **Core** 200 turns at 0.5 A on Rm = 99 472 At/Wb: **flux** 1.005 mWb, B = 1.005 T - the range check is part of the answer.
2. **Tests** 10 kVA transformer: OC test 240 W (core), SC test 300 W (full-load copper) - full load efficiency 94.9%.
3. **Half** At half load core stays 240 W but copper falls to a quarter (75 W): 94.1% - flat because the loss families move differently.

The magnetic circuit and its mirror

(1) the magnetic circuit

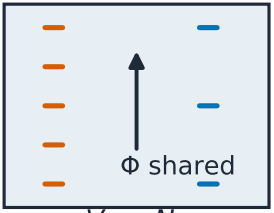
$F = NI$ drives $\Phi = F/R_m$



$R_m = l/(\mu A)$

(2) the transformer

V_1, N_1 turns V_2, N_2 turns



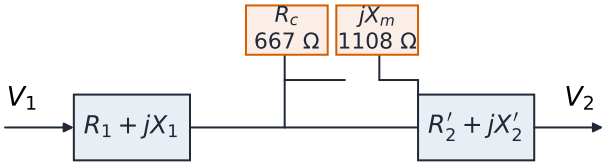
$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

F = NI drives the **flux** against Rm = l/(μA); a transformer shares one loop.

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Two tests, two branches

open-circuit test fills these in



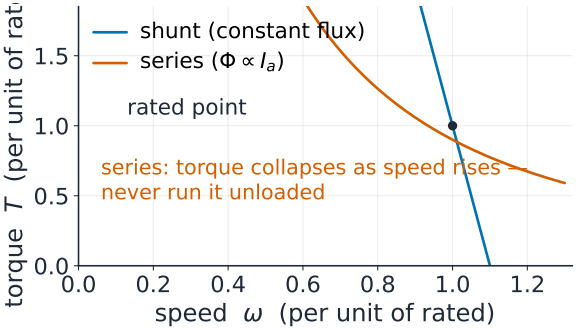
short-circuit test: $R_{eq} = 12\ \Omega$, $Z_{eq} = 16\ \Omega$, $X_{eq} = 10.6\ \Omega$ (HV side)

> The open circuit fills in the shunt magnetising pair; the short circuit fills in the series pair - 94.9% at full load.

DC machines: the back-EMF ledger

1. **Operating** $E = 210$ V at 157.1 rad/s gives $k\Phi = 1.337$ V-s; at 50 A, $T = 66.85$ N-m.
2. **Ledger** $T \cdot \omega = 66.85 \times 157.1 = 10\,500$ W and $E \cdot I_a = 210 \times 50 = 10\,500$ W - the same wattage through mechanics and electricity.
3. **Series** A **series motor**'s **flux** rises with current, so torque grows faster than linearly - $k\Phi$ must be taken at the operating point, not assumed.

Shunt holds speed, series makes torque

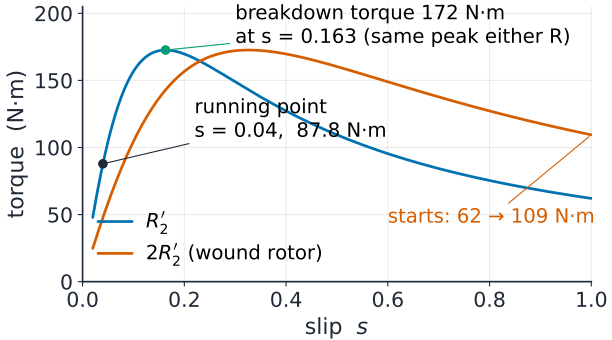


The shunt curve is flat; the series curve collapses as speed rises - never run it unloaded.

Induction machines: slip runs everything

1. **Speeds** 4-pole 50 Hz: $n_s = 1500$ rpm; at 1440 rpm **slip** is $60/1500 = 0.04$ and the rotor frequency is 2 Hz.
2. **Element** At $s = 0.04$ the slip-transformed resistance R_2/s is $25\times$ its locked-rotor value - a running motor is a different circuit from a starting one.
3. **Loss** Rotor **copper loss** is exactly s x air-gap power: 4% here - which is why big induction machines cluster near 1% slip.

One curve, two addresses

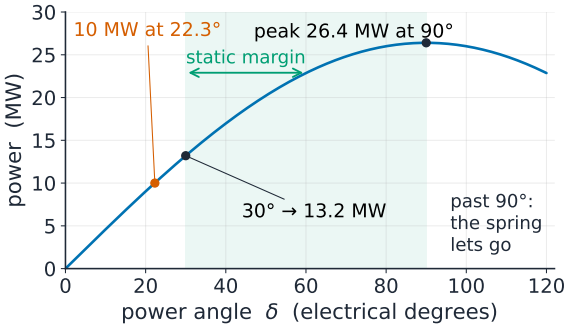


Rotor resistance moves the breakdown peak toward start (62 to 109 N-m) and leaves the 172 N-m peak untouched.

Synchronous machines: locked speed, swinging angle

1. **Angle** V = 11 kV line, $X_s = 5\ \Omega$, E = 12 kV line: $P_{max} = 26.4$ MW; at $\delta = 30$ degrees, 13.2 MW.
2. **Margin** Operating at 30 degrees leaves (26.4 - 13.2)/13.2 = 100% **static margin** - the arithmetic before every dispatch.
3. **Excite** Raise E and the machine exports reactive power like a capacitor; lower it and it imports - the same machine is a reactive source you can tune.

A sine-shaped spring

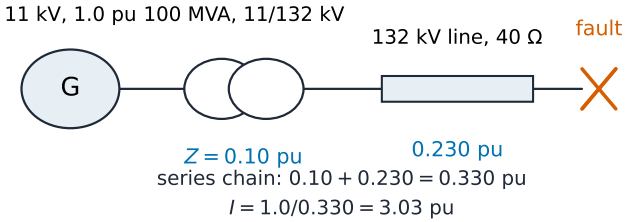


Power grows with the **power angle** to a 26.4 MW peak; at 30 degrees the machine runs at 13.2 MW with a 100% margin.

Power networks and the per-unit system: one base everywhere

1. **Base** 100 MVA at 132 kV: Z base $= 132^2/100 = 174.2\ \Omega$; a 40 Ω line is 0.230 pu.
2. **Fault** Transformer 0.10 pu + line 0.230 pu = 0.330 pu to a three-phase fault: current $1/0.330 = 3.03$ pu.
3. **Both** 3.03 pu reads 1327 A at 132 kV AND 3.03 x 5249 A at 11 kV - one number, both voltage levels.

One line, one chain

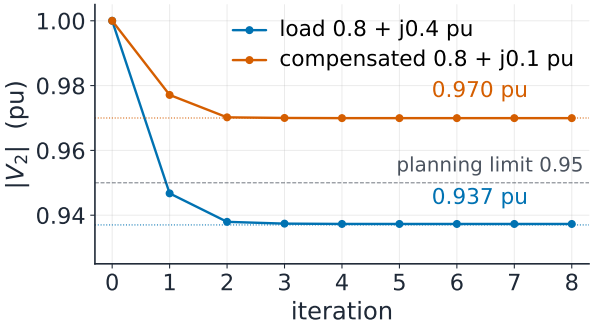


Generator behind 0.10 pu transformer and 0.230 pu line: the fault sees 0.330 pu and 3.03 pu flows at every voltage level.

Per-unit and power flow: the two-bus hand solve

1. **Solve** Z = 0.02 + j0.10 pu, load 0.8 + j0.4: V_2 converges to 0.937 at -4.4 degrees with current 0.954 pu.
2. **Split** Drop = (0.8 x 0.02 + 0.4 x 0.10)/0.937 = 0.060 pu; the reactive term Q-X is 0.040 of it - two-thirds of the drop.
3. **Balance** Sending power 0.8 + I^2R = 0.8 + 0.018 = 0.818 pu - the iteration's answer satisfies the books.

Guess, correct, repeat

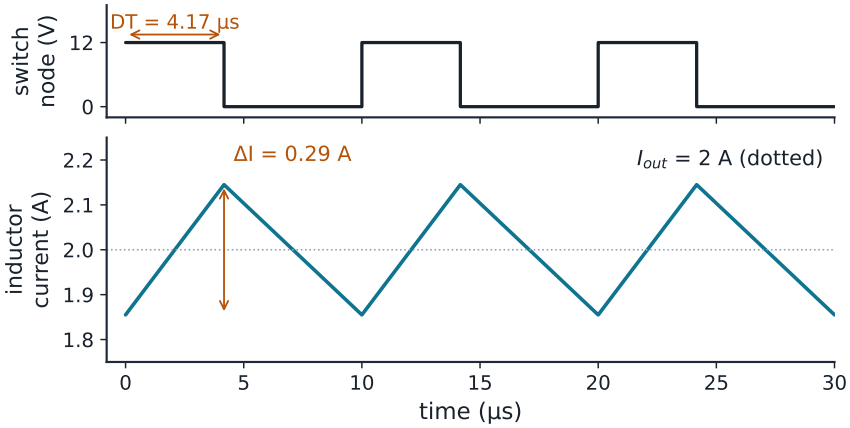


The two-bus iteration settles in a few passes: 0.937 pu as loaded, 0.970 pu after 0.3 pu of capacitors.

Power electronics introduction: duty cycle is the ratio

1. **Buck** 12 V to 5 V at 2 A, 100 kHz, 100 µH: D = 0.417, ripple 0.29 A - 15% of load, a standard value.
2. **Conduction** Half the ripple is 0.145 A against a 2 A load - current never reverses, so the continuous-conduction formulas hold.
3. **Loss** Switch 1.2 W, diode 0.8 W, control 0.3 W on 40 W out: 94.6%; a synchronous MOSFET rectifier recovers most of the diode term.

The buck in motion



At duty 0.417 the inductor ripples 0.29 A peak to peak around the 2 A load.

Check yourself

- Transformer: OC 240 W, SC 300 W - full-load efficiency? (94.9%.)
- Induction: 1500 rpm machine at 1440 - **slip** and rotor frequency? (0.04, 2 Hz.)
- **Boost**: 12 V to 24 V at 1.5 A - input current? (3 A: power conserved.)
- Synchronous: same 10 MW, **excitation** 12 kV then 10 kV - what moves? (Q: +0.23 to -4.6 MVAr.)