EE 114 TSC (CONCEPTS AND DOUBTS)

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ELECTRICAL MACHINES

Faraday's Law and Motional EMF, Forces acting on a member, DC Generators and Motors, Induction Motors

MOTIONAL EMF AND FORCES

- Flux linked with the core can change not only due to electrical excitation, but also due to structural deformations.
- Force acting on a moving member can be calculated using:
  - Lorentz force formulae (BIL)
  - Maxwell Stress Tensor
  - Virtual Work Principle
- Induced EMF due to motional effect is like an action reaction pair that complements the electromagnetic force produced. This is the basic principle of all electrical machines.

DC GENERATORS (DC MACHINES IN GENERATING MODE)

- Different classes of generators:
  - Permanent Magnet Generators
  - Series Generators
  - Shunt Generators
  - Separately Excited Generator.

- Basic principle and governing equations:
  - $V_{ind} = K\psi\omega$
  - $T_{reac} = K\psi i_a$
  - $V_{terminal} = V_{ind} - Ri_a$
  - $\psi = L_f i_f$ in general and a constant for PM excited machines
  - In case of series generator, $V_{terminal} = V_{ind} - (R + R_f)i$ and $i_f = i = i_a$
  - In case of shunt generator, $i_{load} = i - i_f$ and $i_f = \frac{V_{terminal}}{R_f}$

DC MOTORS (DC MACHINES IN MOTORING MODE)

- Different classes of motors:
  - Permanent Magnet Motors
  - Series Motors
  - Shunt Motors
  - Separately Excited Generator.
- Basic principle and governing equations:
  - $V_{ind} = K\psi\omega$
  - $T_{em} = K\psi i$
  - $V_{terminal} = V_{ind} + Ri$
  - $\psi = L_f i_f$ in general and a constant for PM excited machines
  - In case of series motor, $V_{terminal} = V_{ind} + (R + R_f)i$ and $i_f = i = i_a$.
  - In case of shunt motor, $i_{terminal} = i + i_f$ and $i_f = \frac{V_{terminal}}{R_f}$
  - IMPORTANT: DC Series Motor cannot be used as a generator and vice-versa!

DC MACHINE NAMEPLATE RATINGS

- Unless stated otherwise, voltage and current ratings for armature and field windings to be taken the same!
- Rated operating point data consists of:
  - Voltage and current ratings of armature and field windings as applicable
  - Winding resistances if necessary
  - Rated load torque/power and the speed at which it is developed.
- In case of DC Machines, the voltage and current ratings are absolute maximum values that cannot be exceeded under any circumstance!
- Given the nameplate ratings, the first line of attack is to estimate all unknowns of the DC Machine
- And then, use that information to get the desired values for a different operating point.

INDUCTION MACHINES – BASIC OPERATING PRINCIPLE AND CONCEPTS

- Total Magnetic field in the IM rotates at a speed equal to $N_s = \frac{120 f_s}{P}$ where P is the no. of poles and f_s is the AC supply frequency in Hz.
- Multipole Machine – Repetition of field pattern at smaller intervals within a mechanical cycle – multiple electrical cycles covered in a mechanical cycle.
- As rotor rotates at N_r, due to slip or relative speed, currents of frequency $f_r = \frac{P(N_s - N_r)}{120} = s f_s$ are induced in the rotor windings. This will induce a rotating magnetic field that rotates at sN_s w.r.t. the rotor that is already rotating at N_r.

POINTS TO REMEMBER WHILE DEALING WITH INDUCTION MACHINES

- Slip should be under 5% or it should not be too large.
- Mode of operation: Constant Voltage, Constant Frequency operation. Unless specified otherwise, rated supply voltage and frequency to be used.
- Leakage and magnetizing impedances are frequency dependent so beware of that!
- Use transformation ratio (equivalent to turns ratio in transformers) to get secondary side impedances referred to the primary side.
- Equivalent circuit is a per-phase equivalent circuit so total power output is thrice that of what would be calculated per phase.

INDUCTION MACHINE TESTS: NO LOAD, BLOCKED ROTOR AND DC TESTS

- No-Load Test:
  - Rated supply voltage (1 p.u. voltage) is applied at the machine terminals.
  - Series impedance (leakage inductance and winding resistance) is usually ignored.
  - Magnetizing inductance and core loss resistance is calculated
  - Very little current flows in the rotor windings due to mechanical losses
  - Rotor rotates at near synchronous speed. Therefore, the machine has no load or loading torque associated with it.

- Blocked Rotor Test:
  - Rotor is held fixed so large current can flow.
  - A small voltage is applied at the machine terminals such that it injects the rated current (1 p.u. current)
  - Shunt impedance is neglected and series impedance is calculated.
  - Calculated series impedance is equally split into primary and secondary components

- DC Test:
  - Estimates winding resistance. No time varying flux is produced so no core losses. Only winding resistances get a DC excitation.

A FEW POINTERS

- Use suitable assumptions based on the data given to you.
- Core and Mechanical Losses may vary with the operating speed/slip but if the slip variation isn't too large, they may be assumed constant if no other data is given.
- Stator and Rotor copper losses are highly dependent on the slip
- Voltages applied on the terminals are line-line RMS or DC but neutrals are not accessible (unless stated otherwise).

TRANSFORMERS

Operating Principle and Equivalent Circuit, No Load and Short Circuit Tests, Nameplate Ratings, Impedance Conversions, Non-linearities, Autotransformer and Per-Unit Conversion

TRANSFORMER: OPERATING PRINCIPLE AND EQUIVALENT CIRCUIT

- Operating principle:
  - Primary voltage (a sinusoid) injects current into the Primary winding
  - Current sets up flux in the core which induces reactionary EMF in both primary and secondary windings.
  - Reactionary EMF in primary attempts to match the applied primary EMF. Secondary induced EMF drives the load connected.
  - Load will cause a current to flow in the secondary which will produce another action-reaction pair.
  - This continues till MMF of the primary side nearly balances the MMF of the secondary side.

- Equivalent Circuit:
  - Due to MMF getting nearly-balanced, some primary current is lost in magnetizing the core and also in the core loss – Magnetising/shunt branch.
  - Leakage inductances and winding resistance are the series components of the impedance.

NAMEPLATE RATINGS AND IMPEDANCE CONVERSIONS/TRANSFORMATIONS

- Transformer Power Rating: This is the maximum power that can be delivered (not extracted) from the transformer. It happens when the rated load is connected to the transformer at the rated supply voltage.
- Transformer Voltage Rating: The nominal voltage ratio to be expected under rated condition. From this we get $\frac{V_p}{V_s} = \frac{N_p}{N_s} = a$ where a is the turns ratio.
- Impedance transformation. If a transformer is of $a{:}1$ turns ratio, any impedance connected to the secondary side, when referred to the primary side gets transformed by a factor of a^2. That is $Z_s \to Z_s' = a^2 Z_s$
- Dot convention: The location of the dot determines the polarity of the induced EMF. If current enters the winding from one dot, it should leave the other winding from the other dot.

PER UNIT CONVERSIONS

- Unless specified otherwise take:
  - The Power Base S_b as the transformer power rating.
  - Voltage Base V_b as the nominal rated voltage of each isolated segment
  - Current Base $I_b = \frac{S_b}{V_b}$.
  - Impedance Base $Z_b = \frac{V_b}{I_b}$.
- At every isolated segment, normalise or divide the actual impedance by the base impedance of the segment.
- Utility: Ease of analysis and calculations. As a mathematical construct, we can fully eliminate the transformer and replace it with an equivalent circuit under a single base, provided non-linearities don't exist.

TRANSFORMER TESTS: NO LOAD AND SHORT CIRCUIT

Unless stated otherwise, the following convention to be followed:

- No-Load Test:
  - HV winding is kept open.
  - Rated supply voltage (1 p.u. voltage) is applies at the LV winding
  - Series impedance (leakage inductance and winding resistance is ignored)
  - Magnetizing inductance and core loss resistance is calculated
- Short-Circuit Test:
  - LV winding is short-circuited.
  - A small voltage is applied at the HV winding such that it injects the rated current (1 p.u. current)
  - Shunt impedance is neglected and series impedance is calculated.
  - Calculated series impedance is equally split into primary and secondary components

AUTOTRANSFORMERS AND NON-LINEARITIES IN TRANSFORMERS

- Autotransformer: both windings share an electrical linkage but similar equations as that of a regular transformer apply.
- A regular transformer may be converted into an autotransformer. This results in:
  - An increase in the power gain but at the expense of
  - Loss of electrical isolation
- In case of a mutual inductance, dot convention will play a similar role so one has to solve two simultaneous linear equations.
- Transformers and inductances are linear as long as the core doesn't enter the non-linear regime of operation (peaky currents can be expected when the core saturates)

MAGNETIC CIRCUIT ANALYSIS

Analysis of Magnetic Circuits under linear, non-linear conditions and understanding of some magnetic materials

MAGNETIC CIRCUITS: INTRODUCTION

- A quicker approach to solving Maxwell's equations.
- Maxwell's equations solved with some useful assumptions related to material properties.
- Rule of thumb: flux always tries to find the path of least reluctance.
- Maxwell's equations and their electrical circuit equivalents:
  - $\nabla \cdot \boldsymbol{B} = 0 \leftrightarrow \oiint \boldsymbol{B} \cdot d\boldsymbol{S} = 0 \leftrightarrow \sum_k \psi_k = 0$
  - $\nabla \times \boldsymbol{H} = \boldsymbol{J}_{free} \leftrightarrow \oint \boldsymbol{H} \cdot d\boldsymbol{l} = I_{cut} \leftrightarrow \sum_k \mathcal{F}_k = 0$
- MMF sources $(\mathcal{F})$:
  - Free currents/winding currents: $\mathcal{F} = Ni$.
  - Permanent Magnets $\mathcal{F} = H_{PM} l_{PM}$
- Flux source (ψ): Saturated Iron Bar

MAGNETIC CIRCUITS: GENERAL STRATEGY

Procedure for solving magnetic circuit problems:

- Get the geometry from the given data or assume parameters to define the geometry of the structures in question.
- Identify MMF sources like windings and permanent magnets.
- Calculate the reluctance of each segment in the geometry.
  - In most cases simple formulae are enough.
  - In complicated cases, if symmetry exists, it is possible to calculate reluctance using $\mathcal{R} = \frac{\mathcal{F}}{\psi}$.
  - Permeability term is $\mu = \frac{B}{H} \neq \frac{\partial B}{\partial H}$.
- Solve the magnetic circuit problem using electrical circuit rules (KCL, KVL, Node Voltage, Mesh Current Analysis)
- Check any assumptions if they are made:
  - Permanent magnet MMF drop and core permeability to be updated if operating point changes.
  - If any segment of the core saturates, it works like a flux source!

EXAMPLE PROBLEM OF RELUCTANCE CALCULATION

A coil of 2N turns is wound around a thin iron rod of radius r such that N turns lie on either side of a small air gap of length t. The other ends of the rod are linked with a hollow spherical shell of radius R. Find the current to be injected into the coil such that it is able to set up a flux ψ in the rod.

- Assume infinite permeability of the core:
- Assume a finite permeability μ of the core.

Neglect saturation and any other non-linearities

MAGNETIC CIRCUITS: NON-LINEARITIES

- For simple structures: using Maxwell's Equations directly with symmetry
  - Calculate H for a given i, and use the material B-H curve to calculate B and flux.
  - Given a flux requirement, calculate B and use the B-H curve to get H and integrate over the loop to get i.
- Iterative procedure for complicated structures:
  - Assume a certain flux in the segment and calculate the permeability of the segment.
  - Model the reluctance of the segment appropriately and solve the magnetic circuit problem.
  - Calculate the flux in the core and update the flux value used in step 1
  - Repeat this process till you see a convergence.
- Saturation of a core segment: Flux source

MAGNETIC CIRCUITS: PERMANENT MAGNETS

- Permanent Magnet: Highly non-linear material.
- Retentivity: Amount of residual flux density in the PM when no MMF is applied on it.
- Coercivity: A measure of the MMF required to demagnetize the PM.
- Rule of thumb: when PM supplies flux to the core, it works in the demagnetizing regime (it supplies flux at the expense of moving towards coercive MMF)
- Solving circuits with PM is an iterative procedure as the MMF itself depends on flux. But it is possible to get a one-step solution for simpler models.

HYSTERESIS AND EDDY CURRENTS

- Hysteresis effect: Due to B-H curve, energy is dissipated in one cycle of traversing the entire loop
- Hysteresis loss is generally proportional to the frequency of the applied source.
- Also proportional to the area of the B-H curve.
- Eddy currents are induced currents in the magnetic material.
- Directly proportional to the square of the applied frequency and inversely proportional to the resistivity of the material

FARADAY'S LAW, TIME FOR THE NEXT LEVEL!

- Faraday's law: the magnetic world's reaction into the electrical world that forces or injects current into the magnetic circuit
- $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \leftrightarrow \; V_{ind} = -\frac{\partial \lambda}{\partial t}.$
- Flux linkage with a coil $\lambda = N\psi$.
- -ve sign in magnetic fields POV disappears when we move to the electrical circuits POV hence:
- $V_{forcing} = Ri + \frac{\partial \lambda}{\partial t}$
- These equations are the basic building blocks of all electrical machinery like motors, generators, relays, transformers, etc.

REVIEW: SINGLE AND THREE PHASE CIRCUITS

Phasor Basics, Power in Single and Three Phase Circuits, Phasor Diagrams, Solving Balanced and Unbalanced Circuits, $\mathrm{Y} - \Delta$ conversions.

PHASORS … THE BEGINNING!

- A vector rotating with a constant angular frequency ω.
- Phasor convention:
  - Time domain signal is of a single angular frequency ω.
  - Magnitude in phasor representation – RMS and not peak value.
  - Phase in phasor representation - $\varphi = 0$ corresponds to a signal of the form $\cos(\omega t)$
- Time domain to phasor domain conversion:
  - Convert time domain signal to a form that looks like $A\cos(\omega t +$

PHASOR DIAGRAMS

Steps:

- Identify a reference phasor in the circuit
- Calculate other quantities of interest using the impedance relations.
- Add the voltage drops that occur in series vectorially and the currents that jointly enter/leave the node.

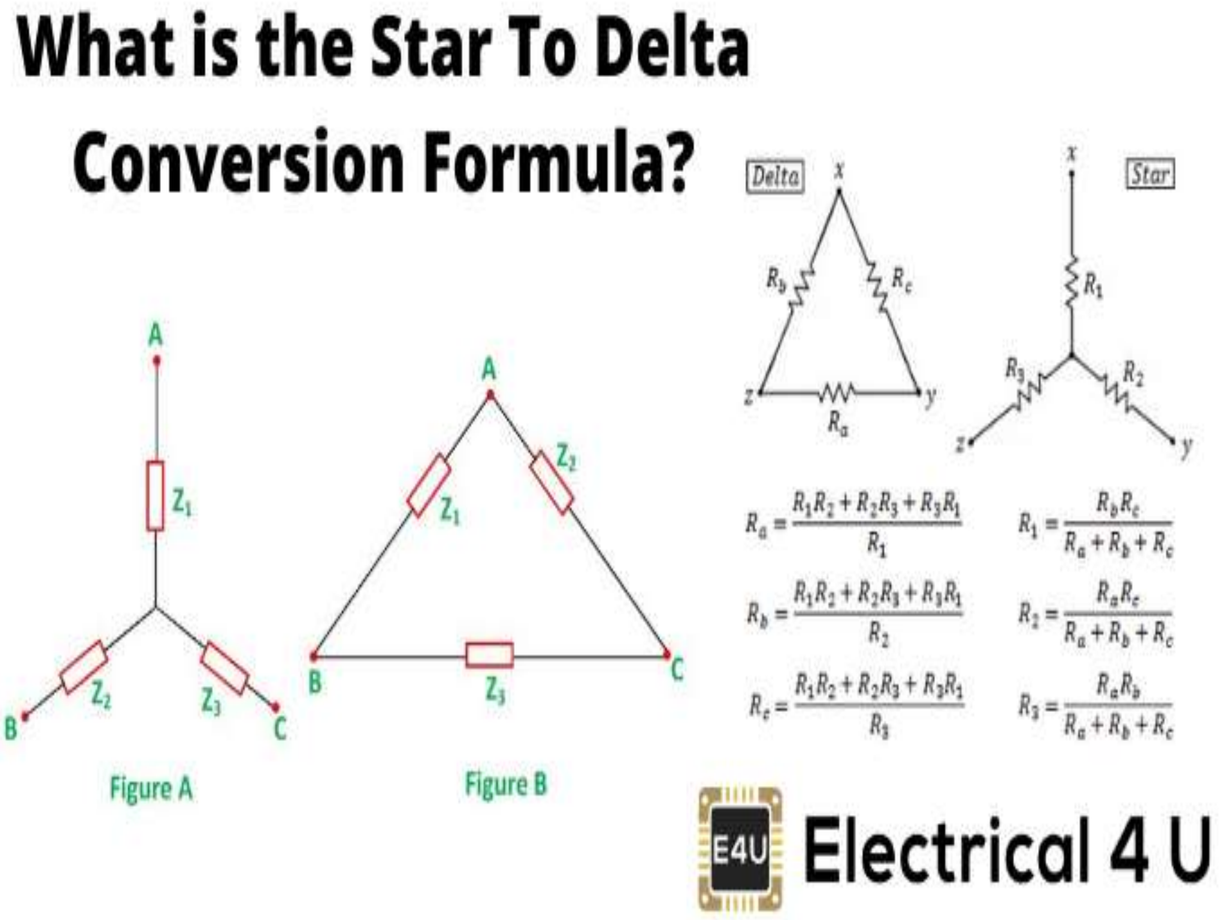
SINGLE PHASE CIRCUITS AND POWER

- Single Phase AC circuits become DC circuits in phasor analysis.
- Assumptions (for phasor analysis and the corresponding power calculation)
  - Linear Elements (like RLC).
  - Single frequency sinusoid.
  - Steady state analysis.
- Single phase power:
  - Instantaneous power across a device: oscillatory.
  - Real power (P): Instantaneous power averaged over a cycle.
  - Reactive Power (Q): A mathematical construct.
  - Apparent Power $\boldsymbol{S} = \boldsymbol{VI}^* = P + jQ$.
  - $P = VI\cos\varphi$, $\cos\varphi$ is power factor and φ is the p.f. angle

THREE PHASE CIRCUITS: BALANCED CIRCUITS

- Assumptions from single phase analysis are carried forward here, in addition:
- A balanced circuit has:
  - Identical loading on all 3 arms
  - Source voltages of equal magnitude and 120^o phase.
- Phase sequence:
  - +ve sequence – b lags a, c lags b.
  - -ve sequence – b leads a, c leads b.
- Line-line voltage: $\boldsymbol{V}_{ab} = \boldsymbol{V}_a - \boldsymbol{V}_b$ leads $\boldsymbol{V}_a$ by 30^o. In addition, $V_{ab} = \sqrt{3}V_a$.
- Instantaneous power is a constant in a balanced 3-phase circuit so $p(t) = P = \sqrt{3}V_{LL}I_L \cos\varphi$.
- **WARNING!** φ is the p.f. angle taking the phase voltage at the device or the source as the reference. $\boldsymbol{V}_{LL}$ is not the reference phasor for the p.f. angle!

Y – Δ CONVERSIONS



Source: https://www.electrical4u.com/delta-star-transformation-star-delta-transformation/

SOLVING THREE PHASE CIRCUITS

- Check if circuit is balanced:
  - For balanced load $Z_{\mathrm{Y}} = \frac{Z_{\Delta}}{3}$.
  - Solve as if solving for a single phase.
  - Single phase approach works only when circuit is balanced.
- General approach:
  - Convert source voltage into Δ configuration.
  - Convert impedances into equivalent Δ configuration.
  - Each arm of the $\Delta - \Delta$ connection is solved like 3 decoupled single phase circuits.
  - Obtain line currents from device currents by vectorially adding the relevant currents.