1. Stepper Motor: Concept and Construction

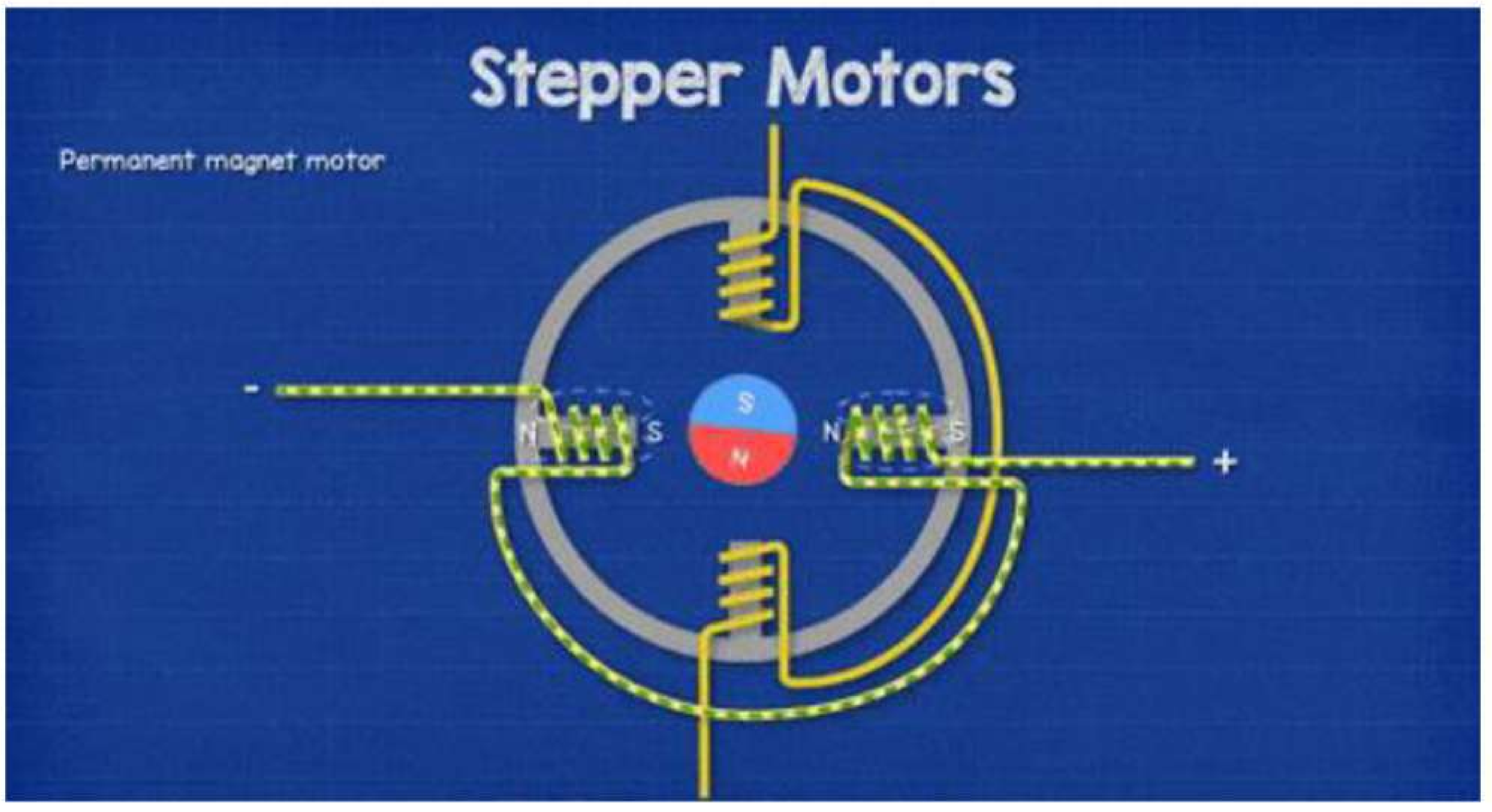
1.1 Basic concept

Statement

A stepper motor is an electromechanical device that converts a sequence of electrical pulses into a series of discrete angular steps of the rotor.[1][2]

Physical meaning

Each input pulse energizes a particular stator phase (or phase combination), shifting the stator magnetic field to a new position. The rotor then "jumps" to align with this new field position, producing a finite angular displacement instead of continuous rotation.



Engineering interpretation

- Position is controlled by **counting pulses**, not by measuring shaft feedback (in open loop).
- Speed is proportional to pulse frequency; direction is determined by the **sequence** in which phases are excited.
- Because there is a known mechanical angle per pulse, stepper motors are naturally suited to digital control and interfacing with microprocessors or microcontrollers.

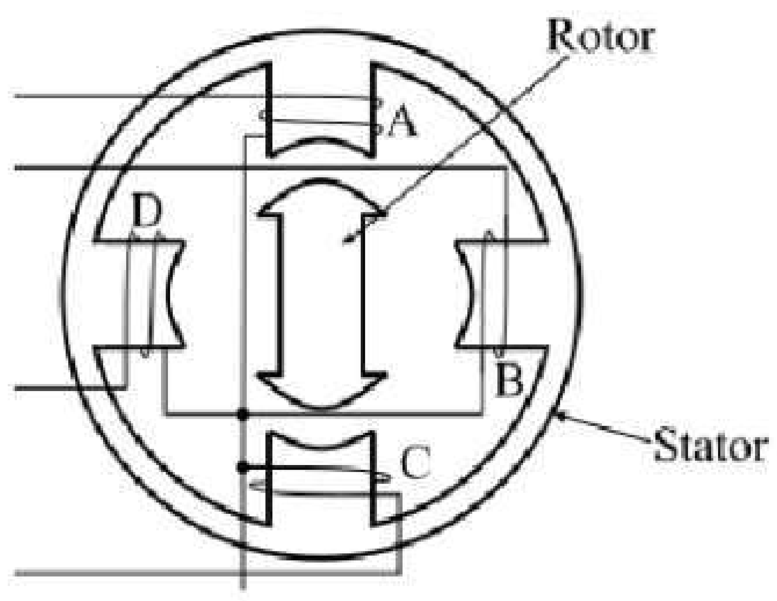
Insight line

"Stepper motor = digital input → quantized mechanical output."

1.2 Constructional features

Statement

Most stepper motors are doubly salient machines: both stator and rotor have salient poles or teeth with concentrated stator windings grouped into phases.[1]



Physical meaning

Salient teeth create strong spatial variation in magnetic reluctance as the rotor moves. This variation in reluctance is what allows electromagnetic torque to be produced whenever the magnetic field shifts from one tooth alignment to the next.

Engineering interpretation

- **Stator**: laminated steel core with many teeth; teeth are connected to phase windings A, B, C, etc.
- **Rotor**:
  - Soft-iron toothed structure (VR type), or
  - Permanent-magnet rotor with toothed iron caps (hybrid type).
- The **air-gap** is small and toothed, so small movements in rotor angle significantly change reluctance and inductance.

Limitation

The doubly salient geometry makes stepper motors more prone to **torque ripple and resonance**; sophisticated drive schemes (half-stepping, micro-stepping) are often used to smooth motion.[3][4]

Comparative micro-line

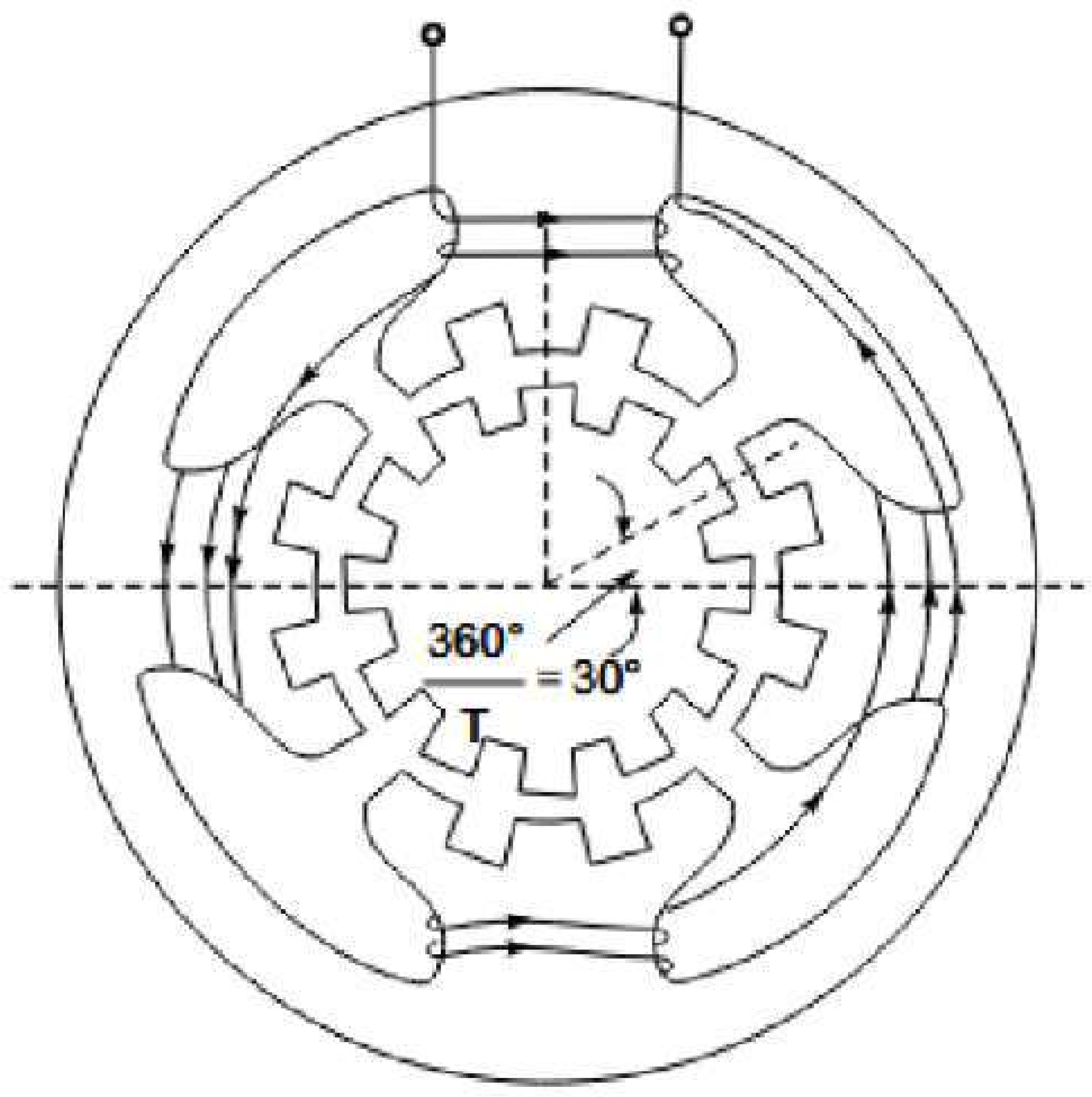
"Unlike smooth-rotor induction motors, stepper motors deliberately use teeth and saliencies to *amplify* the effect of small movements."

2. Variable Reluctance (VR) Stepper Motor

2.1 Construction

Statement

A VR stepper motor has a toothed soft-iron rotor with no windings or magnets; only the stator carries multiphase windings.[1][5]



Physical meaning

Since the rotor is just a piece of shaped steel, it cannot produce its own field; it only responds to the stator's field. The rotor moves to minimize magnetic reluctance between the energized stator teeth and rotor teeth.

Engineering interpretation

- Very **rugged and inexpensive rotor** (no magnets, no windings).
- All copper is on the stator, simplifying cooling and wiring.
- VR steppers are well suited for environments where magnets might demagnetize (high temperature).

Limitation

Because there is no permanent-magnet torque, **holding torque with coils off is practically zero**; the rotor can freely rotate when unenergized.[1]

2.2 Principle of operation (reluctance torque)

Statement

When a stator phase is energized, the rotor moves to a position of minimum reluctance where rotor teeth align with energized stator teeth; sequential energization of phases causes stepwise motion.[1][6]

Physical meaning

Magnetic field lines prefer paths of low reluctance (analogous to electric current preferring low resistance paths). Aligning teeth increases the effective cross-section for flux and reduces air-gap reluctance, lowering magnetic energy.

Energy-based explanation

The stored magnetic co-energy in the motor is

$$W' = \frac{1}{2} L(\theta) I^2.$$

When current flows in a stator winding, energy is stored in the magnetic field, and this energy depends on the inductance $L(\theta)$, which varies with rotor position. As the rotor moves, the inductance changes due to variation in reluctance. In a current-driven system, the rotor tends to move toward the position where inductance is **maximum and reluctance is minimum** (aligned position). This occurs because that position corresponds to the most favorable magnetic path and hence the most stable state.

Engineering interpretation

- By energizing different phases in sequence (A → B → C → A ...) the stator's low-reluctance axis "rotates", and the rotor follow these discrete changes.
- Direction of rotation is set by the **order** of phase excitation (A→B→C vs A→C→B).
- Speed is set by the **rate** at which phases are switched.

Limiting cases

- If only one phase is excited and rotor already perfectly aligned → inductance is maximum → no torque.

- If phases are alternately excited but rotor is heavily loaded beyond pull-out torque → rotor cannot reach each new minimum-reluctance position → loss of steps.

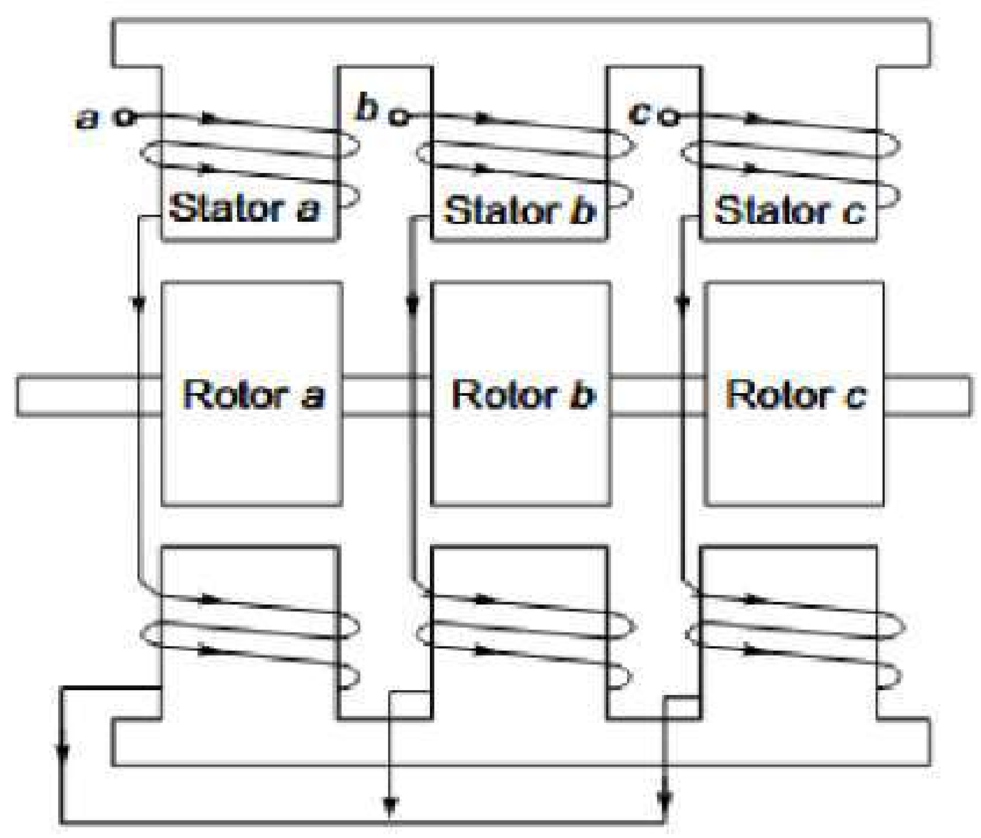
Insight line

"Rotor does not spin because it is pushed continuously; it *jumps* from one minimum-reluctance well to the next as the stator field pattern shifts."

2.3 Single-stack vs multistack VR configurations

Statement

- **Single-stack VR**: one stator-rotor pair with all phases in a single axial stack.
- **Multi-stack VR**: several stator-rotor stacks on a single shaft, each with its own phase, axially shifted by a fraction of a tooth pitch.[2][5]



Physical meaning

In a multi-stack machine, when one stack is fully aligned (no torque), another stack is in a transition region where inductance is changing, so torque is available. The total effect is finer resolution (smaller step angle) and smoother overall torque.

Engineering interpretation

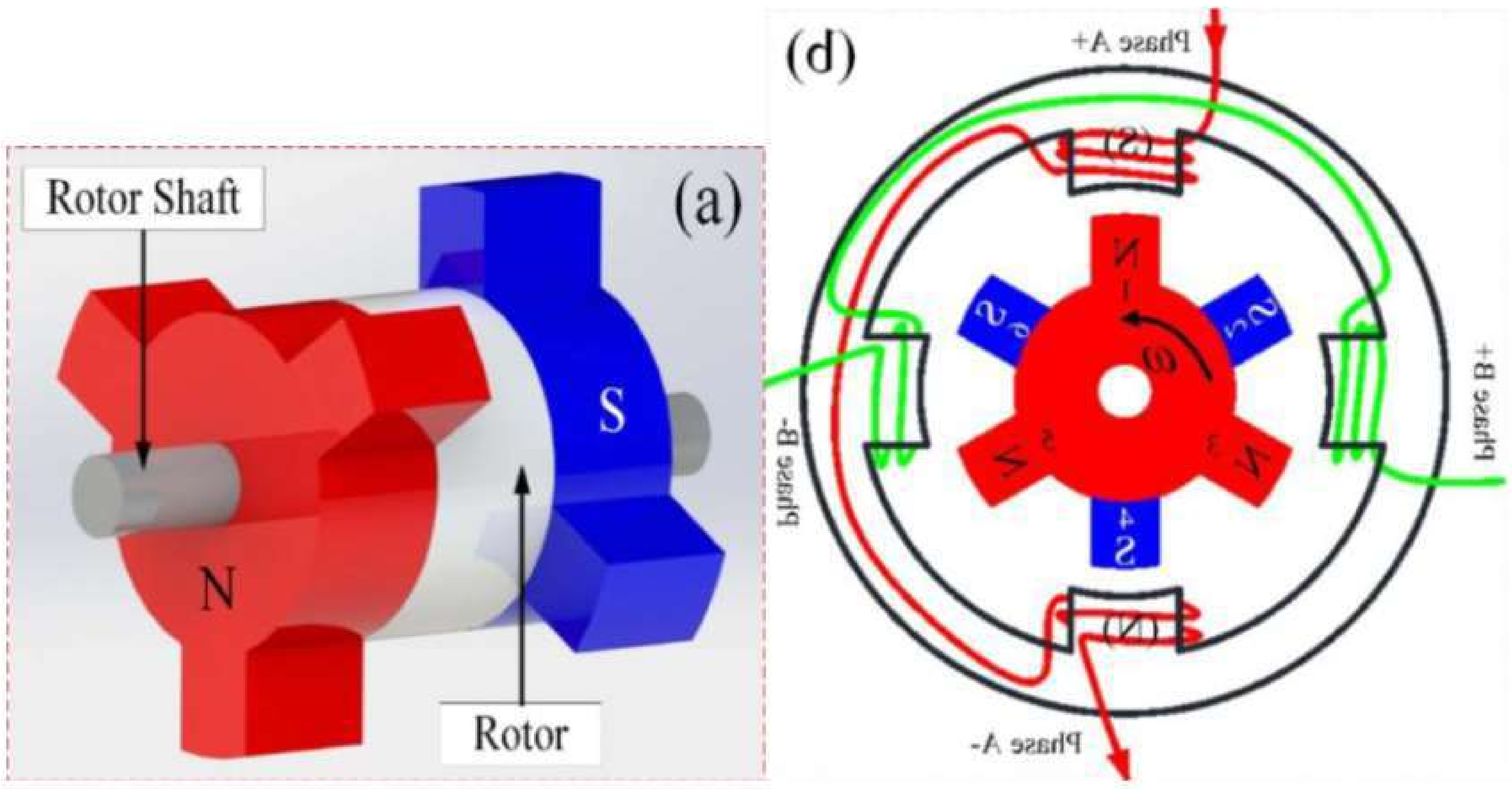
- If each stack contributes N_r rotor teeth, and there are m stacks/phases, the effective step angle becomes very small without making individual teeth absurdly fine.
- This approach increases torque and step resolution at the expense of mechanical complexity and length.

3. Hybrid Stepper Motor

3.1 Construction

Statement

A hybrid stepper motor combines a permanent-magnet rotor with toothed rotor and stator structures typical of VR motors.[2][7]



Physical meaning

The permanent magnet provides a constant rotor field, while the stator teeth and rotor teeth create sharp inductance variations with position. Torque arises both from the **PM interaction** and from **reluctance torque**.

Engineering interpretation

- Axially magnetized rotor magnet (N–S) sandwiched between two toothed iron caps shifted by half a tooth pitch.
- Stator has many fine teeth (e.g., 50) and multiple phases (commonly 2).
- Step angles as small as **1.8°** (200 steps/rev) or **0.9°** (400 steps/rev) are standard.[7]

Limiting case / advantage

Even with **no current**, the PM field produces **detent torque**, holding the rotor in preferred positions—useful for applications that must retain approximate position when power is removed.

3.2 Principle of operation

Statement

Hybrid steppers operate via the combined effect of permanent-magnet torque and reluctance torque; two-phase currents are typically excited in sequence or in quadrature to produce a rotating mmf vector.[3][7]

Physical meaning

The PM field acts like the rotor field of a synchronous machine, while the stator currents create a rotating field. Rotor teeth “lock” to discrete positions aligned with the resultant stator field, but motion occurs in steps as currents change.

Engineering interpretation

- Two-phase excitation (A, B) can produce four basic positions: A only, B only, A+B, A−B, etc. Combining this with fine rotor teeth yields small step angles.
- Using sine-cosine current profiles (micro-stepping), the hybrid motor behaves almost like a smooth **PM synchronous servo** but with inherent stepping capability.[4]

Insight line

“Hybrid stepper = synchronous PM motor + built-in discrete ‘teeth’ for quantized motion.”

4. Step Angle and Torque Equation

4.1 Step angle

Statement

For an m-phase VR or hybrid stepper with N_r rotor teeth (or equivalent teeth per stack), the step angle is approximately

$$\alpha = \frac{360^\circ}{mN_r}.$$

Physical meaning

This formula expresses that one complete mechanical revolution is divided into mN_r discrete stable rotor positions, each separated by angle α.

Engineering interpretation

- Increasing **number of phases** or **number of rotor teeth** gives finer steps and higher positioning resolution.
- There is a practical limit: too many very fine teeth become hard to manufacture and may saturate; that's why multi-stack designs and hybrids are useful.

Limiting cases

- If $m = 1$ (single-phase, unrealistic for stepping) → 360°/N_r: coarse and poor control.
- Large mN_r → very small α but also more switching events and more driver complexity.

Insight line

"Resolution is a design choice: more electrical phases and more mechanical teeth give smaller steps."

4.2 Torque equation

Statement

The electromagnetic torque in a reluctance-type stepper motor phase is

$$T_e = \frac{1}{2} I^2 \frac{dL(\theta)}{d\theta}$$

where I is phase current and $L(\theta)$ is phase inductance as a function of rotor position.

Physical meaning

- Torque is produced **only while inductance is changing** with angle; i.e., when the rotor is moving through a region between misalignment and alignment.
- At perfectly aligned or anti-aligned positions, inductance is locally constant ($dL/d\theta = 0$), so torque is zero – those are equilibrium points.

Engineering interpretation

- Higher current → torque $\propto I^2$ → strong sensitivity to current; current control is effectively torque control.
- Sharper inductance variation with position (steeper $dL/d\theta$) → higher torque for the same current, motivating narrow, high-permeability teeth and small air-gaps.
- The sign of $dL/d\theta$ determines torque direction: rotor moves toward increasing inductance (minimum reluctance).

Limiting cases

- If $I = 0 \rightarrow T_e = 0$: without excitation, VR rotor cannot generate torque (only detent torque in hybrids).
- If $dL/d\theta = 0$ (aligned position) $\rightarrow T_e = 0$: rotor is at an energy extremum.
- If inductance variation is large over a small angular interval → high peak torque but also more pronounced torque ripple.

Important observation

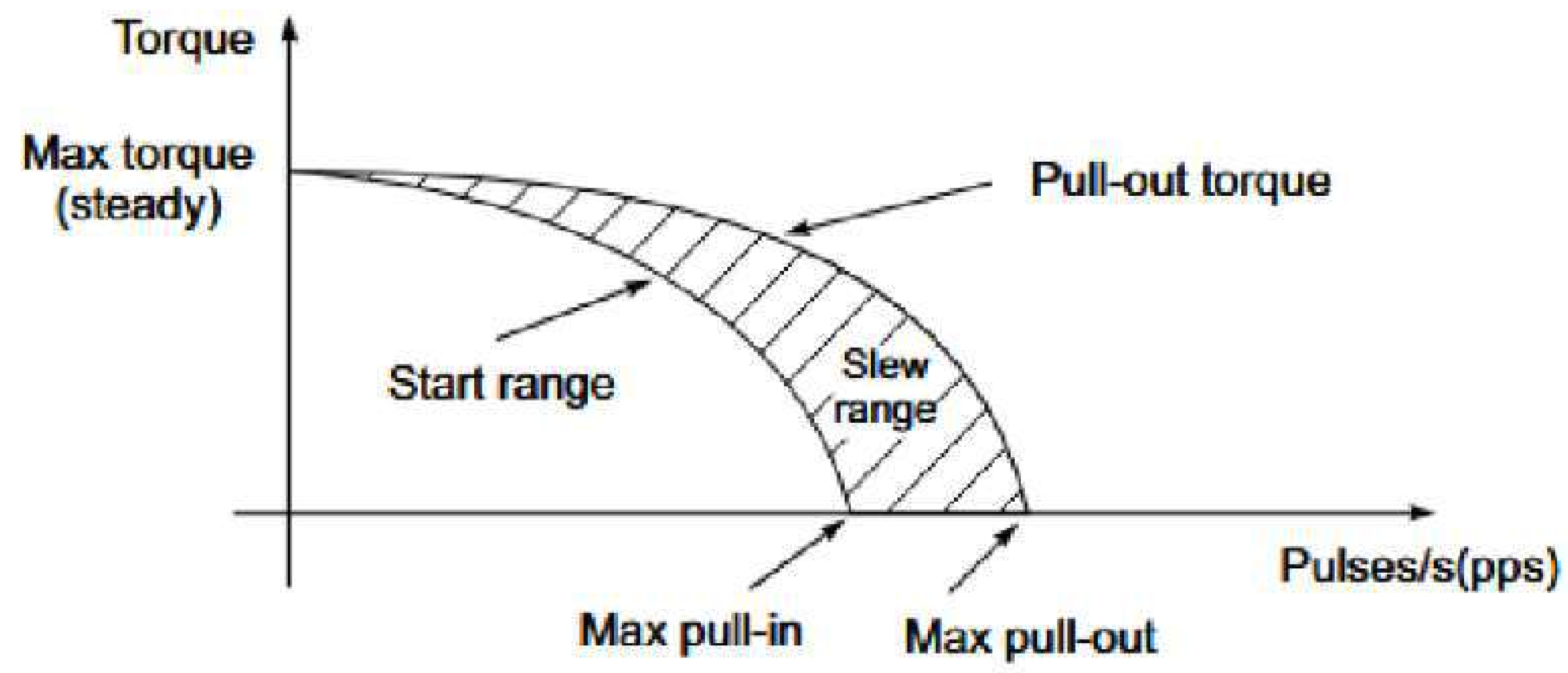
Torque is **not continuous** around the whole revolution; it is strong in certain angular windows and zero at alignment. This is why phase sequencing and overlap (e.g., half-stepping, micro-stepping) are crucial to achieving smooth motion.

Insight line

“Torque exists during **change**—no $dL/d\theta$, no torque.”

5. Static and Dynamic Characteristics

5.1 Holding, detent, pull-in, pull-out torque



The torque–speed characteristic of a stepper motor shows how available torque decreases with increasing stepping rate (pulses per second). At low speeds, the motor can produce maximum torque and operate within the **pull-in region**, where it can start, stop, or reverse without losing steps. The **pull-in curve** defines this safe starting range. As speed increases, torque reduces due to limited current rise, and the motor enters the **slew range**, where it cannot start directly but can continue running if already in motion. The **pull-out curve** represents the maximum torque the motor can sustain during operation. Thus, the region between pull-in and pull-out curves highlights that a stepper motor must be started at low speed and then accelerated to higher speeds to avoid loss of synchronism.

- **Holding torque**: the maximum torque that can be applied to the motor shaft when the windings are energized at rated current without causing the rotor to lose its position.
- **Detent torque**: the residual torque present when all windings are de-energized, arising mainly due to the permanent magnet and toothed rotor structure.
- **Pull-in torque**: the maximum load torque under which the motor can start, stop, or reverse at a given stepping rate without losing synchronism.
- **Pull-out torque**: maximum load the motor can sustain at a given rate once already running.

Physical meaning

These torques describe the **“stability margin”** of each equilibrium position under different dynamic conditions (start, stop, run). They are essentially how much “disturbance” the discrete stepping process can tolerate.

6. Drive Circuits – Unipolar, Bipolar, Chopper

6.1 Need for dedicated drive circuits

A stepper motor cannot simply be connected across a DC or AC supply because its operation depends on **precisely timed, sequential excitation of stator phases**, not on a continuous sinusoidal or DC voltage. Each phase winding has significant inductance; therefore, the current cannot change instantaneously, and the electromagnetic torque is highly sensitive to the **shape and timing** of the current pulses.[1][2]

From the circuit viewpoint, each phase behaves approximately as an **RL load**. If a fixed DC voltage V is suddenly applied, the current rises according to

$$i(t) = I_{\max}\left(1 - e^{-t/\tau}\right), \tau = \frac{L}{R},$$

where L is phase inductance and R is resistance. At high stepping rates, the available time per step becomes comparable to or smaller than τ, so the current may not reach its rated value, directly reducing torque.

Therefore, the drive circuit must:

1. **Control current** in each phase to the desired level and polarity.
2. **Switch phases in the correct sequence** to realize the intended stepping mode (full-step, half-step, micro-step).
3. **Shape current transients** (rise and fall) so that sufficient torque is available even at high stepping speeds.
4. **Provide protection** against inductive over-voltages and over-currents (freewheel paths, current limiting, thermal protection).[2][1]

Engineering-wise, the drive circuit is as important as the mechanical motor: torque, speed range, smoothness, and even audible noise are strongly influenced by drive topology and control algorithms.

6.2 Unipolar drive – why it exists

Statement

Unipolar stepper drives energize each phase with current in only one direction, using center-tapped windings and simpler switching.[8][10]

Operation

In a unipolar drive, each phase winding has a **center tap**. The center tap is connected to the supply (for NPN low-side switching) or to ground (for PNP high-side switching), and the two ends are alternately switched.[1][2]

- When transistor T_1 is ON, current flows through the **first half-winding** from center tap to end A and through T_1.
- When T_1 is OFF and T_2 is ON, current flows through the **second half-winding** from center tap to end B and through T_2.

The **direction of current in copper is always the same** (from center tap toward the active end); however, because the half-windings are wound in opposite directions, the net magnetic polarity at the stator pole reverses.

Engineering interpretation

- Fewer power switches (one transistor per half-winding) and simpler drive ICs.
- Torque is lower than bipolar for same frame size because only half the copper is active at once.
- Well suited for **VR steppers**, where torque does not depend on current direction.

Limiting case

If the application demands maximum torque from a given motor frame, a unipolar configuration effectively "throws away" half of the winding; reconfiguring as bipolar can yield ≈30–40% more torque for the same current rating.

6.3 Bipolar H-bridge with chopper current control

Statement

Bipolar drives use **H-bridge converters** to reverse current in each phase, fully utilizing winding copper and often regulating current with a chopper scheme.[9][10][12]

Operation

In bipolar drive, each phase consists of a **single full winding** without center tap. To reverse magnetic polarity, the **current direction** through the winding is reversed. This is implemented with an **H-bridge**: four power switches (MOSFETs or BJTs) arranged so that either diagonal pair can be turned ON to drive current in one direction or the other.[4][1]

- Turn ON Q_1 and Q_4 → current flows from left to right.

- Turn ON Q_2 and Q_3 → current flows from right to left.
- Diodes across each switch provide freewheel paths when switches are turned OFF.

Engineering interpretation

- Higher torque for given motor size; better high-speed performance because higher voltage accelerates current buildup.
- Constant-current chopping makes torque nearly independent of speed (up to magnetic limits).
- Modern driver ICs (TI, ST, etc.) integrate H-bridges, current sensing, and micro-stepping tables, simplifying design.

Insight line

"High supply voltage + chopper = fast current ⇒ fast torque ⇒ higher usable stepping rate."

6.4 Chopper (constant-current) drive

Need for chopper control

Because each phase winding is inductive, at high stepping rates the effective pulse duration per step **may be shorter than the electrical time constant** $\tau = L/R$. If a low DC bus voltage is used, current will not reach the rated value within one step interval. Torque, which for reluctance-type stepper phases is roughly proportional to I^2, then falls sharply.[5][4]

Simply increasing the DC voltage would cause excessive current at low speed or standstill, overheating the motor. The chopper drive solves this conflict.

Principle of constant-current chopper

Chopper drives use:

- A **higher DC bus voltage** (often several times the rated phase voltage).
- A **current-sensing resistor** and control circuit that rapidly turns the phase switches ON and OFF (PWM).

Basic behaviour :

1. When switches are ON, a high voltage forces current to ramp up quickly in the winding: $di/dt \approx V/L$.

2. When the current reaches an upper threshold I_{ref}, switches are turned OFF; current then circulates through freewheel diodes or synchronous switches, decaying until it reaches a lower threshold.
3. This ON/OFF pattern repeats at tens of kHz, maintaining an approximately **constant average current** in each phase.[5][2]

Physical meaning

The high supply voltage overcomes inductance and allows current to reach the desired level within each step interval, while average current is limited by PWM duty cycle so that copper heating remains within ratings.

Engineering interpretation

- Torque becomes nearly **independent of stepping rate** over a wide range, limited mainly by magnetic saturation and mechanical constraints.
- Torque–speed characteristics are greatly extended compared with simple L/R drives; usable top speed increases dramatically.[4]
- Chopper schemes also enable **micro-stepping**, because they can regulate phase currents according to arbitrary references (e.g., sine and cosine).

Limiting cases

- At very low stepping rates, current ripple is small and phase current is almost constant.
- At extremely high stepping rates where the PWM controller itself cannot respond fast enough, current may still lag the reference, leading to eventual torque loss.

Key insight

"Torque depends on current, not directly on voltage; high voltage is merely a tool to make the current follow the reference quickly."

7. Microprocessor / Microcontroller Control of Stepper Motors

7.1 Digital nature of stepper control

Stepper motors are inherently **digital actuators**: rotor displacement is directly proportional to the number of input pulses, and the update of phase states is a discrete event. A microprocessor or microcontroller is therefore a natural controller:[6][1]

Microprocessor → Translator / Driver → Power Stage → Motor.

The microcontroller supplies low-power **logic-level signals** (step, direction, enable, mode bits), while the driver translates these into phase currents using unipolar or bipolar chopper circuits.

Engineering interpretation

- Motion profiles (position vs. time, velocity ramps, jerk limits) are defined in software as tables or real-time calculations.
- High-level communication (e.g., CAN, UART, SPI) allows integration into CNC controllers, PLCs, or robotics systems.
- Firmware can incorporate compensation for backlash, lost motion, and even resonance avoidance.

7.2 Control of position, speed, and direction

Position control

For a motor with step angle α (degrees/step), a commanded move of N steps ideally produces a mechanical displacement:

$$\Delta\theta = N \times \alpha.$$

The microcontroller simply counts pulses; each pulse corresponds to one internal state transition in the drive and hence one step of the rotor.

Physical meaning

The motor's "memory" of position is purely **logical**—in open loop the system assumes that each pulse succeeded. There is no physical feedback unless an encoder is added.

Speed control

If step frequency is f_s (steps/s), the average speed is

$$\omega = f_s \times \alpha$$

(in deg/s or rad/s after conversion).

In practice, the microcontroller generates a train of step pulses whose **period** is varied to implement acceleration and deceleration ramps—linear, S-curve, or application-specific.[6]

Engineering interpretation

- Sharp, instantaneous changes of pulse frequency can exceed the pull-in capability, leading to loss of synchronism. Ramping avoids this by gradually matching rotor acceleration to electromagnetic torque.
- Speed regulation is simply a matter of adjusting timer reload values or PWM comparators in the MCU.

Direction control

Direction is set by the **phase sequence**:

- Sequence A → B → C → D → A corresponds to forward rotation.
- Sequence A → D → C → B → A corresponds to reverse.

The microcontroller typically drives a single **direction bit**; the translator IC internally reverses the look-up table of coil activations.

Insight

"In open-loop stepper systems, motion planning reduces to carefully scheduling **when** pulses occur and in **what order** the phases are excited."

7.3 Excitation modes: full-step, half-step, micro-stepping

Full-step excitation

In full-step mode, either:

- One phase at a time (wave drive), or
- Two phases simultaneously (dual-phase drive)

are energized. Dual-phase excitation yields maximum holding torque; wave drive reduces copper loss at the cost of torque.

Engineering interpretation

Full-step operation offers the **highest per-step torque** but also the highest torque ripple and mechanical vibration, particularly at low speeds.[7]

Half-step excitation

Half-stepping alternates between one-phase and two-phase excitation:

$$A \to A + B \to B \to B + C \to C \to C + A \to A \ldots$$

The effective step angle is halved; the magnetic torque profile is smoother because some intermediate positions are introduced.

Physical meaning

The rotor sees intermediate energy wells between the main full-step stable positions; it moves in smaller jumps, reducing oscillation amplitude.

Limitation

Despite improvement over full-step, some torque ripple remains, and intermediate steps may have slightly lower torque (when only one phase is on).

Micro-stepping

In micro-stepping, **phase currents are regulated according to sinusoidal or quasi-sinusoidal waveforms**:

$$I_A = I_{\max} \sin\ \theta, I_B = I_{\max} \cos\ \theta,$$

where θ is the electrical angle corresponding to rotor position command.[8][9][10]

Physical meaning

The resultant stator MMF vector rotates in small angular increments with nearly constant magnitude. Because total torque is proportional to the vector sum of the torques from each phase, and since $\sin^2\ \theta + \cos^2\ \theta = 1$, the **available torque magnitude remains almost constant** over micro-steps.[8][7]

Engineering interpretation

- Micro-stepping greatly reduces resonance, audible noise, and mechanical vibration.

- It allows finer positioning resolution (e.g. 16, 32, 64 micro-steps per full step) even though actual mechanical accuracy may be limited by friction and non-linearity.[11][10]
- Implementation requires a chopper drive and a microcontroller that outputs current references (sine/cosine values) via DACs or PWM.

Limiting cases

- With 1 micro-step/full step, micro-stepping degenerates to full-step.
- At extremely high micro-step counts, differences between adjacent positions approach the motor's friction and detent limits; **incremental accuracy no longer improves**, though smoothness continues to benefit.

Insight

"Micro-stepping uses analog current shaping to make a digital stepper behave mechanically like a smooth servo."

8. Closed-Loop Control of Stepper Motors

8.1 Limitations of classical open-loop operation

Open-loop stepper control assumes that there is a one-to-one mapping between **commanded steps** and **actual mechanical steps**. This assumption holds as long as:

- Load torque remains below the pull-out torque for the chosen speed, and
- Acceleration and deceleration are within allowable limits.

When these conditions are violated—due to sudden load changes, collisions, or overly aggressive ramps—the rotor can **fall out of synchronism**, missing steps or even stalling.[12][2]

Since no positional feedback is used, the controller is **blind** to these events; applications such as CNC machining or precision robotics cannot tolerate such undetected errors.

8.2 Structure of a closed-loop stepper system

Closed-loop stepper systems, often marketed as **stepper-servo drives**, add feedback to the traditional architecture:[13][14][15]

- Stepper motor (usually hybrid, two-phase).
- Position/speed sensor: incremental encoder, resolver, or sensorless estimator.[16]
- Motion controller: generates position/velocity commands.
- Drive electronics: implement current control, micro-stepping, and feedback loops.

Conceptually:

Reference position → Controller → Current commands → Motor → Encoder → Feedback to controller.

Physical meaning

The motor “knows” its actual position and speed at all times. If the rotor lags behind due to a load disturbance, the controller senses this **error** and increases phase currents (torque) until the error is corrected.

8.3 Control behaviour

In many implementations, the closed-loop stepper is controlled very similarly to a **two-phase brushless servo**:[15][17]

- Inner loop: current (or torque) control using chopper PWM and sine/cosine references.

- Outer loops: speed and/or position control using PID or more advanced algorithms, based on encoder feedback.

Key behaviours:

- At low speeds, the controller can reduce current while still maintaining position, improving efficiency and reducing heating.
- At high speeds or under disturbance, it temporarily increases current (within limits) to preserve synchronism and avoid step loss.
- Velocity ripple is significantly reduced compared with open-loop micro-stepping; smoothness approaches that of high-end servos.[18][15]

Advantages

- **No missed steps**: the system detects and corrects any deviation.
- **Higher usable speed** for a given motor size due to adaptive torque control.[17][12]
- **Better positioning accuracy and stiffness**, as feedback compensates for friction, backlash, and load variations.

Limitations

- Increased complexity and cost (encoder, more powerful controller).
- Tuning of control loops is required; poor tuning may cause oscillations or overshoot.

Insight

“Closed-loop control upgrades a stepper from an open-loop ‘pulse counter’ to a true servo drive, while still retaining high low-speed torque and simple digital interfacing.”

9. Applications of Stepper Motors

9.1 General suitability

Stepper motors excel where **precise incremental motion**, **moderate speeds**, and **tight integration with digital control systems** are required. Their discrete step nature, high holding torque, and compatibility with microcontrollers make them natural choices for:[19][6]

- Motion systems with many short moves and dwell periods.
- Systems where absolute feedback is either unnecessary or can be added only on demand.
- Environments where the deterministic relationship between pulses and position simplifies software.

9.2 Typical industrial and commercial applications

1. **CNC machines and machine tools**
   Stepper motors drive linear axes or rotary tables in small and medium CNC equipment. The controller generates interpolated motion profiles; because each pulse is a known angle, complex paths are executed by counting pulses on each axis. Closed-loop versions are increasingly used where cutting forces are variable.

2. **3D printers and additive manufacturing**
   In FDM/FFF printers, stepper motors control X–Y gantry motion, Z-axis bed height, and filament extrusion. Micro-stepping yields sufficiently fine resolution for layer heights of tens of micrometres, while open-loop control keeps cost low.

3. **Robotics and automation**
   Small robot arms, pan–tilt units, and mobile-robot wheel drives often use steppers for joints or wheels, especially when loads are predictable and speeds moderate. Closed-loop stepper drives are used where high duty cycles and variable payloads demand better robustness.[20]

4. **Office and consumer equipment**
   Printers, scanners, photocopiers and disk drives use steppers to move print heads, paper carriages, and optical pickups with repeatable precision.

5. **Automotive and medical systems**
   Actuators for EGR valves, throttle bodies, HVAC blend doors, or medical dosing pumps employ small hybrid steppers with fine steps and high holding torque, sometimes in dedicated micro-step drives.[21]

6. **Specialized roles**
   Laboratory instruments, optical systems (lens zoom/focus), and small positioning stages use steppers where quiet, precise, and programmable motion is required.

9.3 Application-driven limitations

While versatile, steppers are **not universal**:

- For **very high speeds** and inertias, torque falls off due to inductance and supply-voltage limits; AC or brushless servos perform better.
- Where **maximum efficiency** or continuous operation at high power is required, rotor losses in steppers and constant current operation can be disadvantageous.
- If extremely **smooth, ripple-free motion** at moderate and high speed is mandatory, a well-tuned servo system outperforms open-loop steppers; closed-loop steppers narrow the gap but still inherit some saliency-based torque ripple.[14][17]

Integrated picture

A complete stepper system can usefully be summarized as:

$$\text{Digital motion command} \rightarrow \text{Control algorithm} \rightarrow \text{Drive circuit (unipolar / bipolar / chopper)} \rightarrow \text{Controlled phase currents} \rightarrow \text{Time-varying magnetic field} \rightarrow \text{Discrete rotor motion.}$$

In closed-loop systems an additional path

$$\text{Rotor position / speed} \rightarrow \text{Feedback} \rightarrow \text{Controller}$$

ensures that the actual motion faithfully tracks the commanded trajectory.

⁂

1. https://www.eeeguide.com/stepper-motor-classification/
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12. https://www.st.com/resource/en/application_note/an468-constantcurrent-chopper-drive-ups-steppermotor-performance-stmicroelectronics.pdf
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14. https://www.casunsteppermotor.com/news/application-of-closed-loop-control-in-improving-the-performance-of-stepper-motor-193288.html
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D. C MACHINES

* DC MOTOR-

→ **Constructions** -

(a) **Stator**- Stationary parts of dc motor having field wdg on the poles.

(b) **Rotor**- It is also called armature wdg, It is free to move.

(c) **Commutator**- It is used to produce unidirectional torque in dc motor.

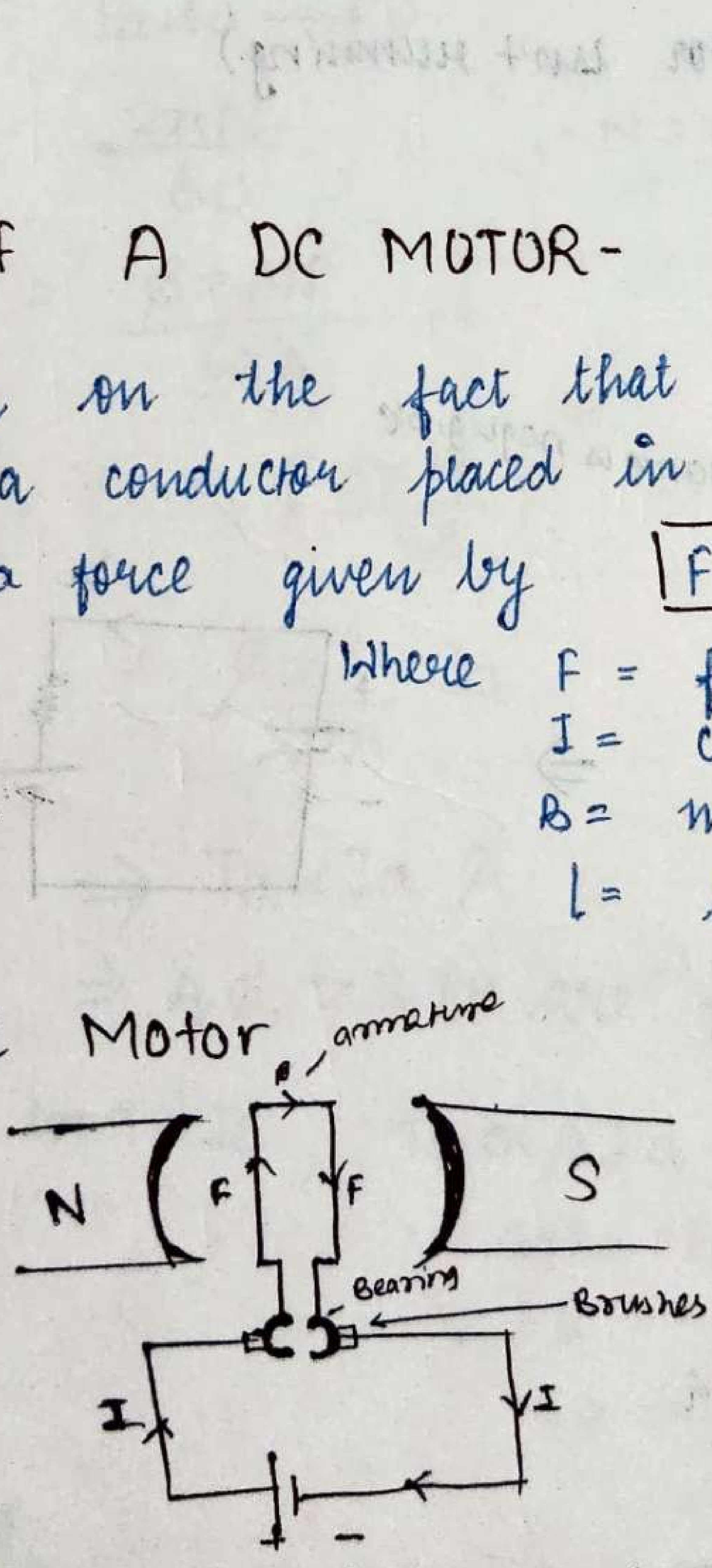
- Brushes
- Brushgear
- Shaft & Poles

* PRINCIPLE OF A DC MOTOR-

This motor works on the fact that when a current is passed through a conductor placed in a magnetic fields, it will experience a force given by $F = IBL$

Where F = force
I = current
B = mag flux density
l = length (of conductor)

- Layout of DC Motor



- In DC Motor, torque is produced by the interaction of fields flux φ the current flowing in armature.

• Back EMF equation (E_b) -

→ It is the EMF induced in the armature exists when the motor starts running. The EMF is induced due to
→ the Faraday law of electromagnetic induction
→ This EMF induced oppose the applied EMF.
→ It is also called counter EMF.
→ It's value is given by

$$E_b = \frac{\phi Z N P}{60 A}$$

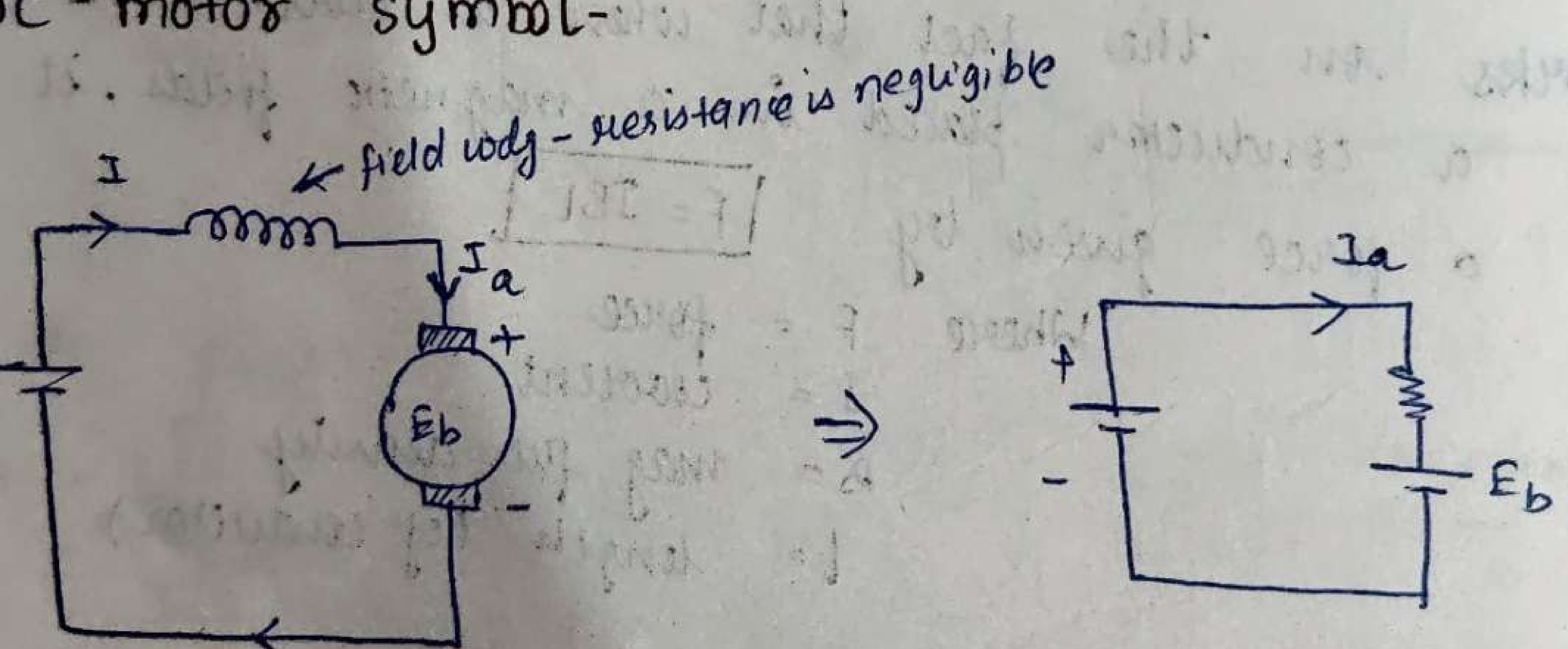
where,

ϕ = magnetic flux
Z = no of conductors
N = speed of motor in rps
P = No of poles
A = No of ||r paths through the armature b/w brushes of opp polarity.

⇒ $E_b \propto N\phi$

⇒ if $N = 0$ (i.e. motor isn't running)
so, $E_b = 0$

• DC - motor symbol-



From KVL

$V = I_a R_a + E_b$ —— ①

Multiplying eq ① by I_a

$V I_a = I_a^2 R_a + E_b I_a$

∴ → I/P = Output + losses
→ $V I_a$ = P_i (Input power)

|| connection = same voltage

$\times I_a$

$VI_a - I_a^2 R_a = E_b I_a$ —— (2)

$P_i - P_c = P_m$

$$\boxed{P_m = P_i - P_c}$$

where P_m = mechanical output

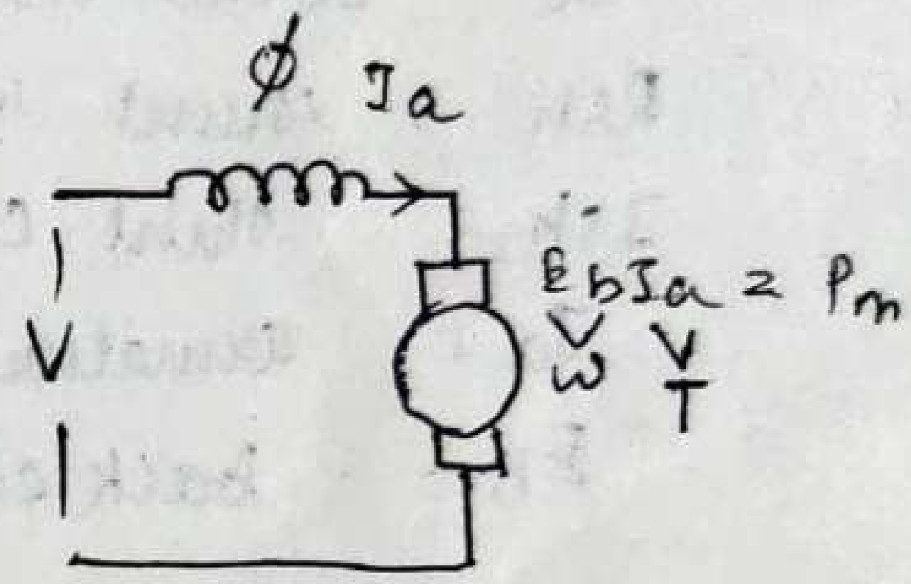
$$\boxed{P_m = E_b I_a}$$

P_i = input power supplied by dc source

P_c = armature copper loss

$$\therefore \boxed{P_c = I_a^2 R_a}$$

(4) (b) Torque - equation of DC Motor.

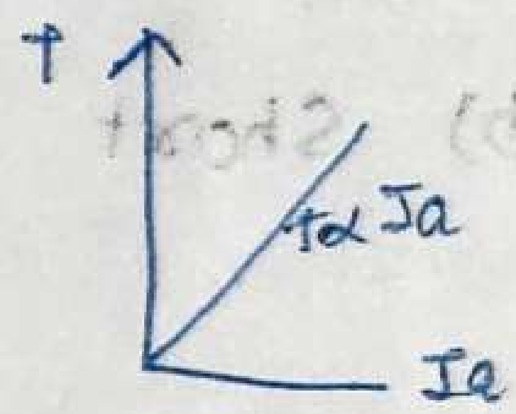


We know $P = T\omega$

$P_m = T_a \omega$

$E_b I_a = T_a . \omega$ —— (1)

$\omega = \frac{2\pi N}{60}$ $\therefore N = rpm$



$E_b = \frac{\phi Z N P}{60 A}$

$N \propto E_b$

$V = E_b + I_a R_a$

$E_b = V - I_a R$

$I_a . \frac{\phi Z N P}{60 A} = T_a \left(\frac{2\pi N}{60} \right)$

$T_a = \frac{\phi Z P}{2\pi A} . I_a$

$\Rightarrow T_a \propto I_a \phi$

$\Rightarrow A, \phi, Z, P, N$ are fixed

I_{sh} - constant

V - constant

Mechanical load $\propto I_a$, $T_a \propto \phi I_a$

$V - I_a R_a = E_b$

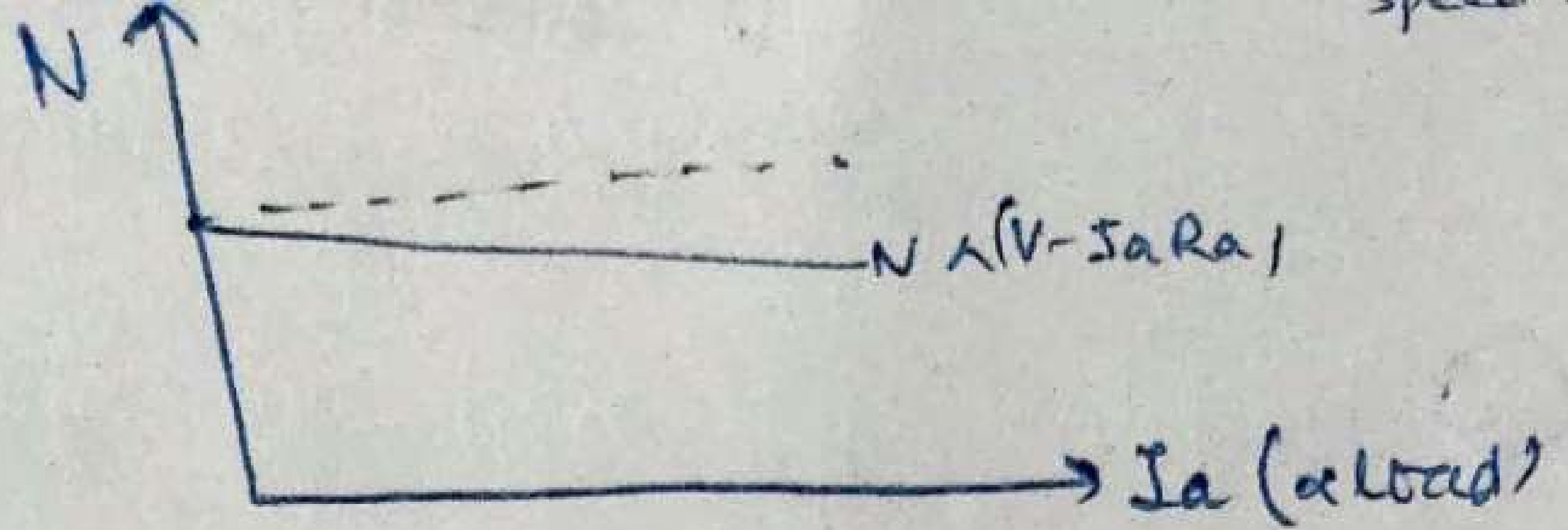
$V - E_b = I_a R_a$

$I_a = \frac{V - E_b}{R_a}$

$E_b \propto N\phi$

$$\boxed{I_a = \frac{V - N\phi}{R_a}}$$

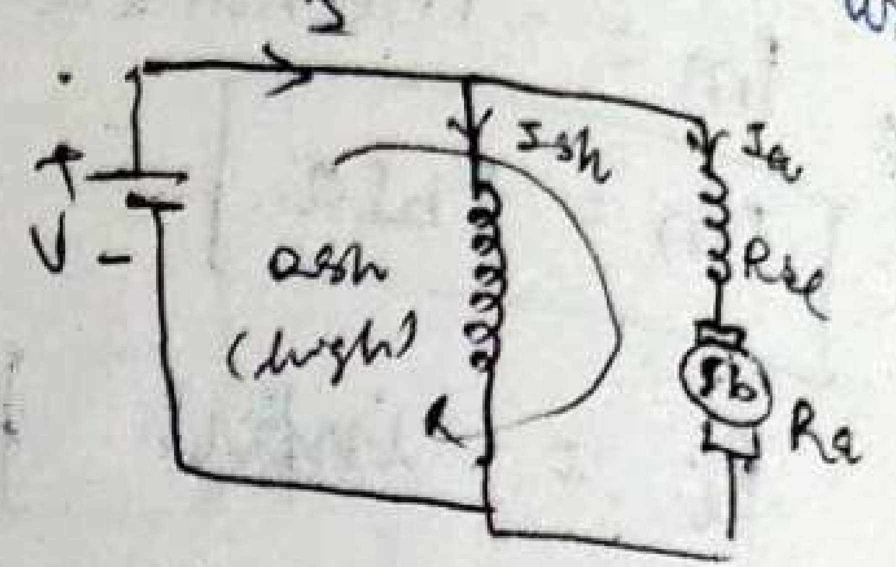
This is a constant speed motor bcoz there is very slight change in speed due to change in load



* DC COMPOUND MOTOR -

In this motor we have a combination of series & shunt wdg ...

(a) Long shunt compound motor -



$I = I_{sh} + I_a$

$I_{se} = I_a$

$I = I_a + I_{sh}$ —— (1)

apply KVL, $V - I_a R_a - I_a R_{se} - E_b = 0$ —— (2)

$V = E_b + I_a (R_a + R_{se})$ —— (3)

where, R_{se} - series wdg resistance

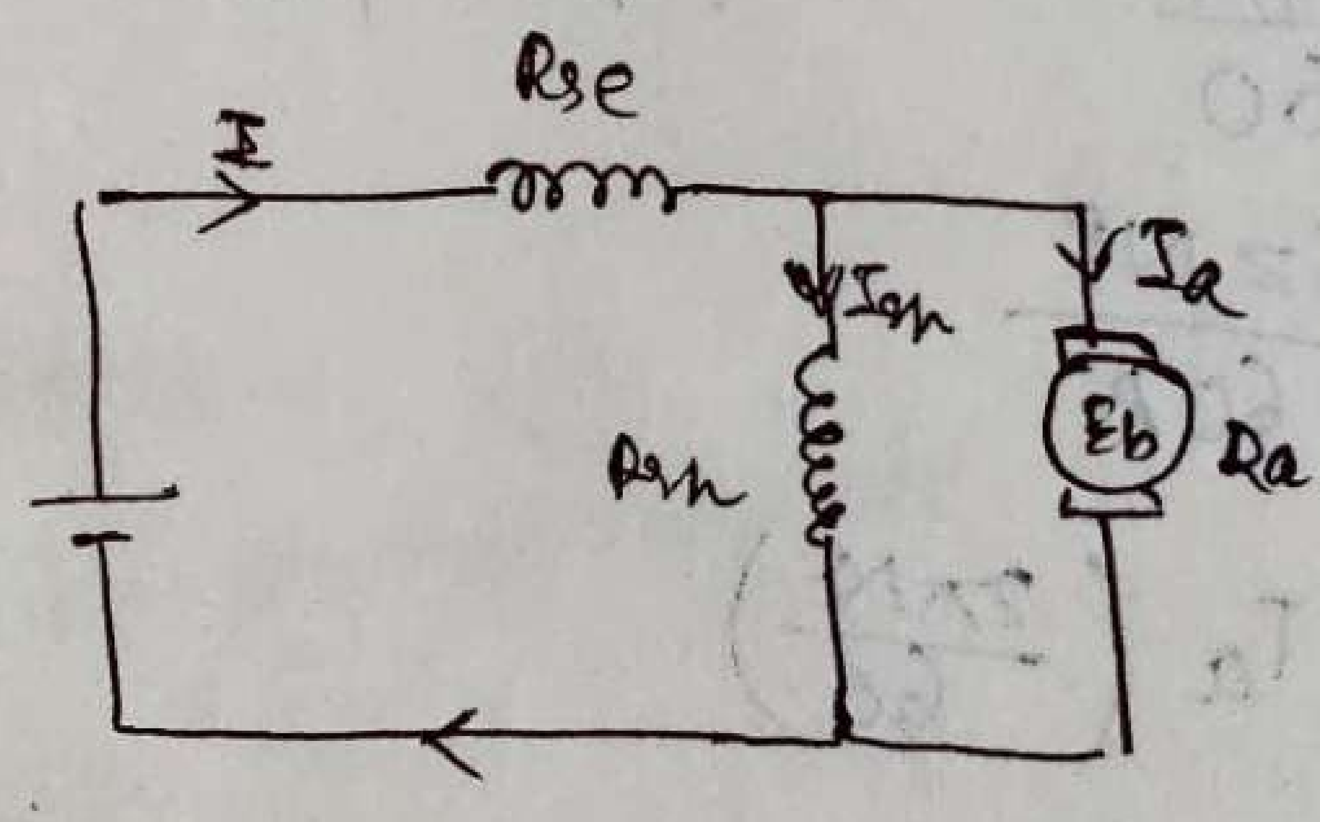
R_{sh} → shunt " "

I_{sh} = shunt current

I_a = armature current.

E_b = back emf.

(b) Short shunt compound motor.



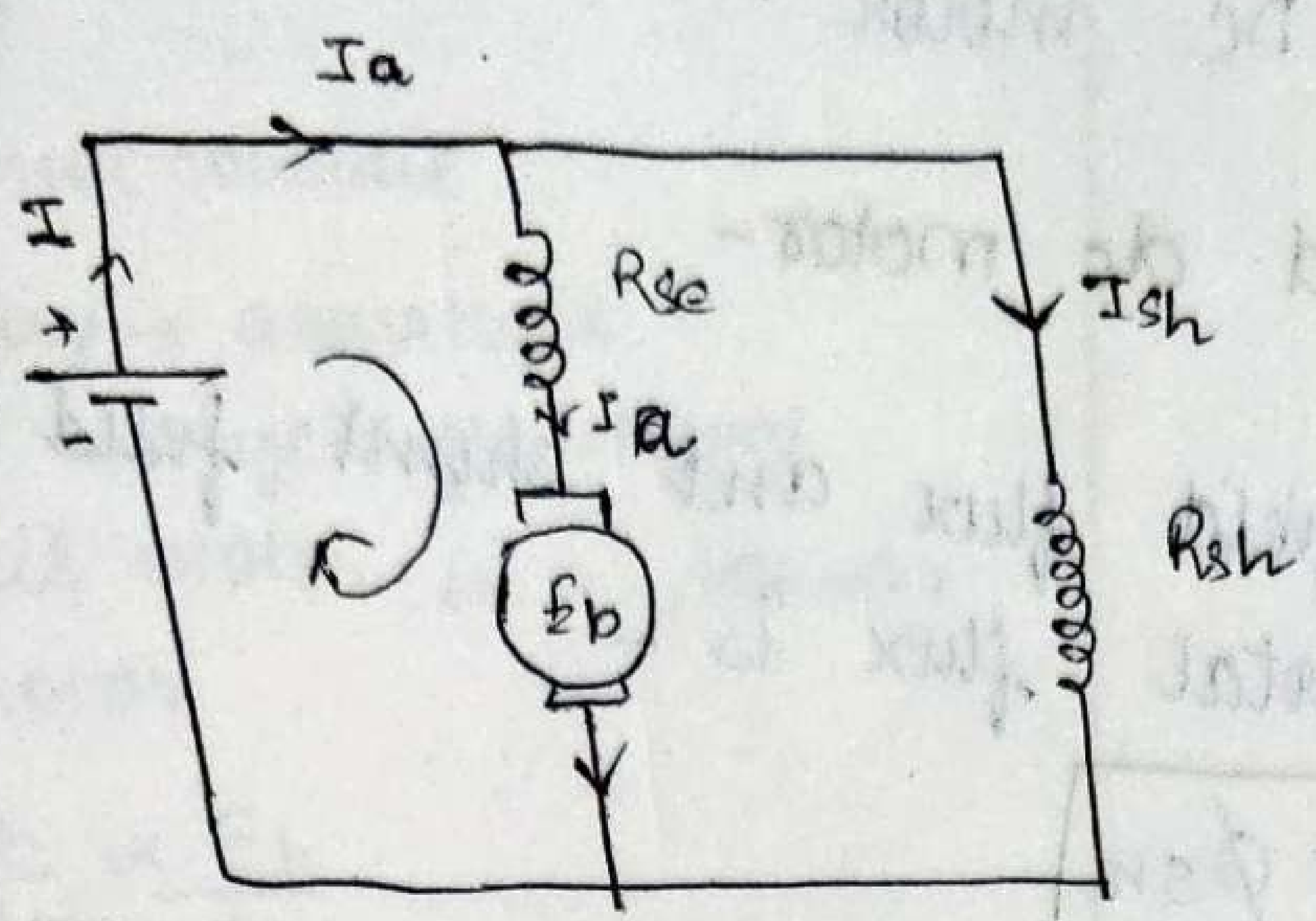
$I = I_a + I_{sh}$ —— (1)

$I = I_{se}$ —— (2)

$V - I_{se} R_{se} - I_a R_a - E_b = 0$ —— (3)

$$V = I_{se} R_{se} + I_a R_a + E_b$$

* LONG SHUNT DC MOTOR :-



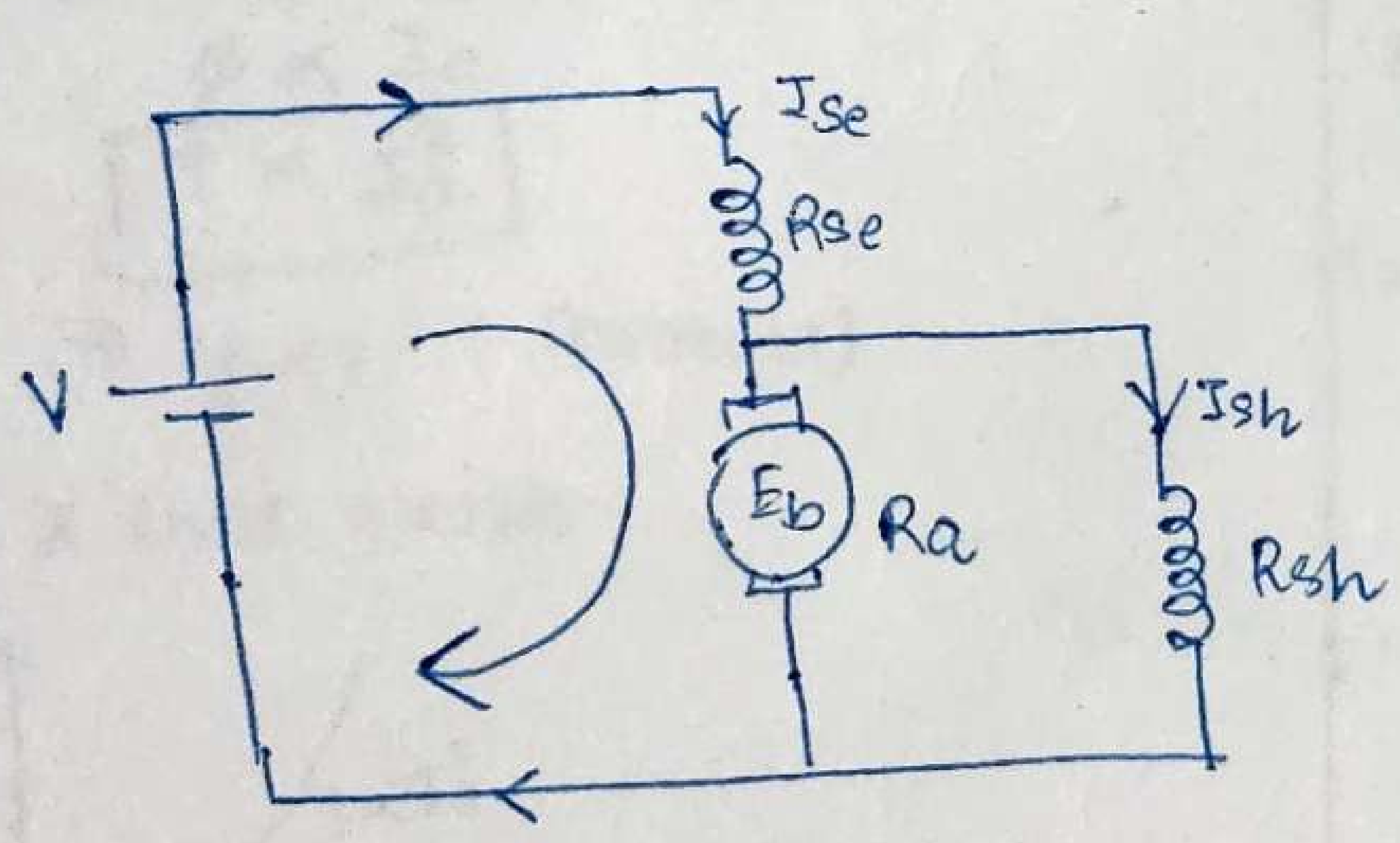
$I = I_a + I_{sh}$ —— ①

$I_{sh} = \frac{V}{R_{sh}} = \text{constant}$ —— ②

By KCL

$V - I_a R_{se} - I_a R_a - E_b = 0$ —— ③

* SHORT SHUNT DC MOTOR-



$I = I_a + I_{sh}$ —— ①

$I = I_{se}$ —— ②

Apply KCL

$V - I_{se} R_{se} - I_a R_a - E_b = 0$ —— ③

* COMPOUND MOTORS-

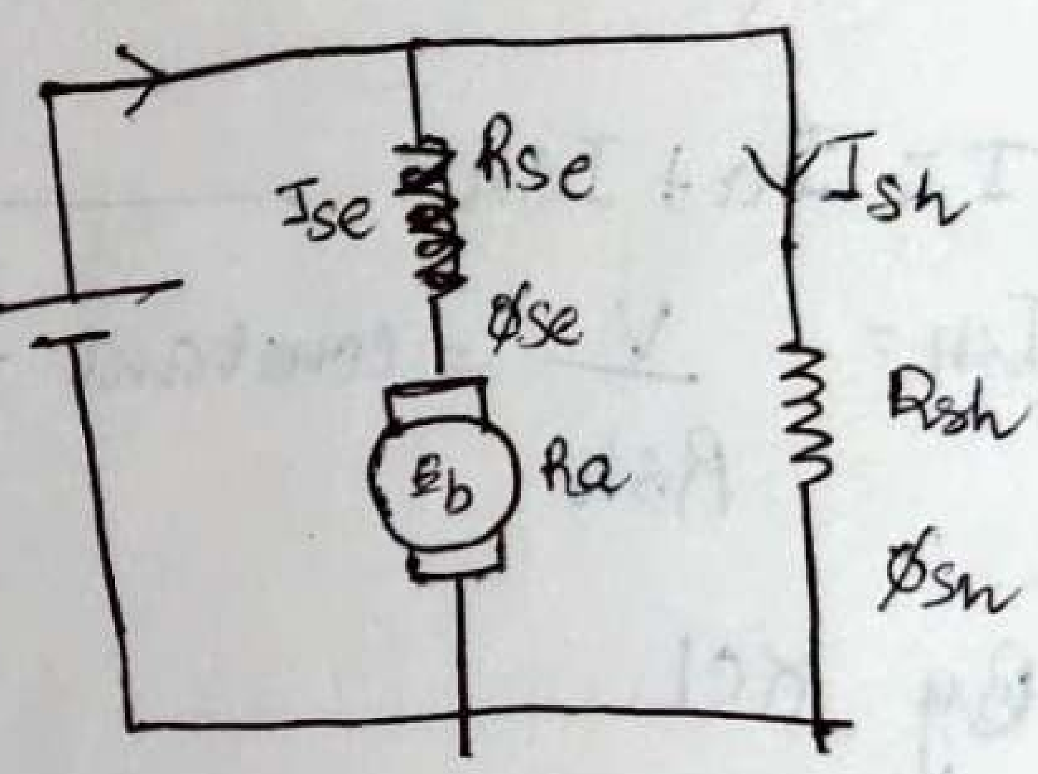
They are of two types depending upon the combination of fluxes in series and shunt wdgs.

- Cumulatively compounded DC motor
- Differentially compound DC motor.

(i) Cumulatively compounded dc motor-

In this motor series field flux and shunt field flux add each other. So, total flux is -

$$\boxed{\phi_T = \phi_{se} + \phi_{sh}}$$



$\Rightarrow \phi_{se} \propto I_{se}$

$I_{se} = I_a$

$\phi_{se} \propto I_a$

$$\boxed{\phi_{se} = k_1 I_a}$$

$\Rightarrow \phi_{sh} \propto I_{sh}$

$I_{sh} = \frac{V}{R_{sh}} = \text{constant}$

$\phi_{sh} = \text{constant}$

$$\boxed{\phi_{sh} = k_2}$$

So, $\phi_T = \phi_{se} + \phi_{sh}$

$$\boxed{\phi_T = k_1 I_a + k_2}$$

(ii) Differentially compounded dc motor-

In this motor series flux and shunt flux oppose each other such that total flux is -

$$\boxed{\phi_T = \phi_{sh} - \phi_{se}}$$

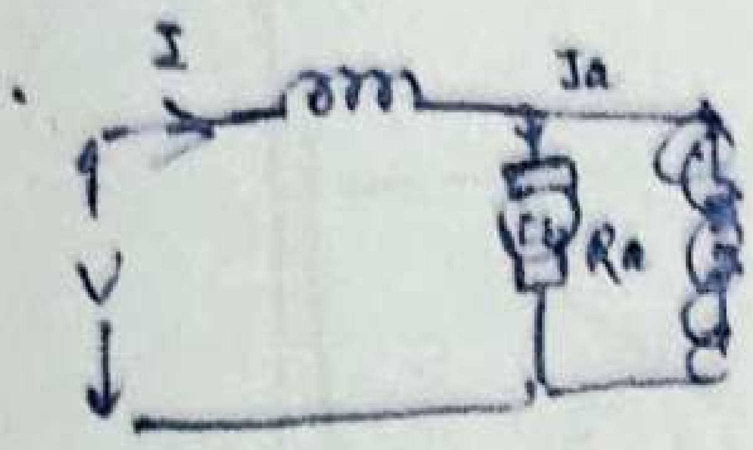
$$\boxed{\phi_T = k_2 - k_1 I_a}$$

- load↑ current↑ speed ↓
- Torque↑ load↑,

But in differentially compounded d...

• In d.c series motor, $T \propto \phi I_a$, $T \propto I_a^2$, $\phi \propto I_a$ ...

DC Series



$N \propto \frac{E_b}{\phi}$

ϕ is not constant

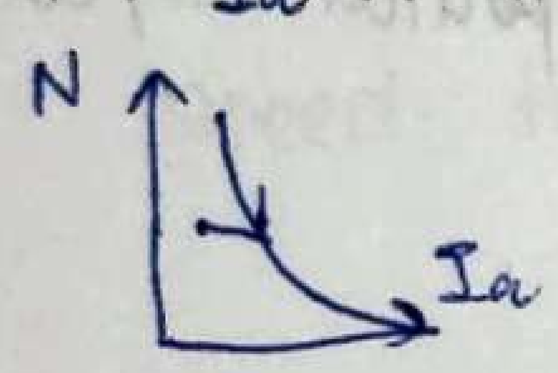
- load change → armature current change → flux change. DC series motor is a variable flux motor

$N \propto \frac{E_b}{\phi} \propto \frac{E_b}{I_a}$

- Load ↑, I_a ↑ & N (speed) ↓.

$N \propto \frac{E_b}{I_a}$

$N \propto \frac{1}{I_a}$



variable speed motor.

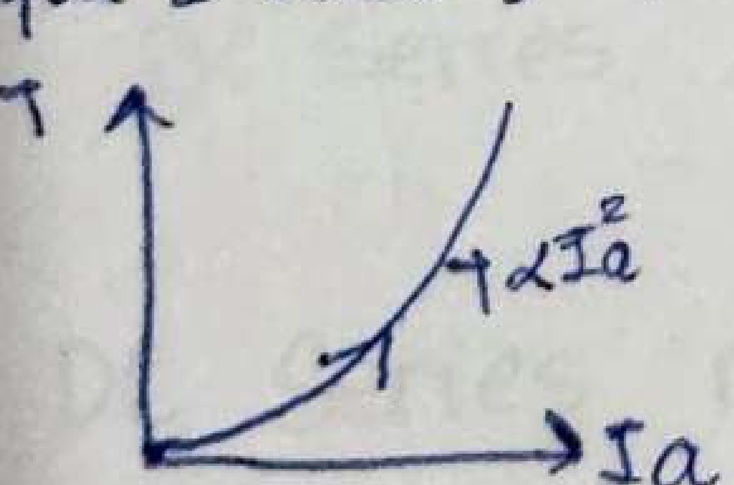
- Torque ⇒ $T \propto \phi I_a$

$\phi \propto I_a$

$T \propto I_a^2$

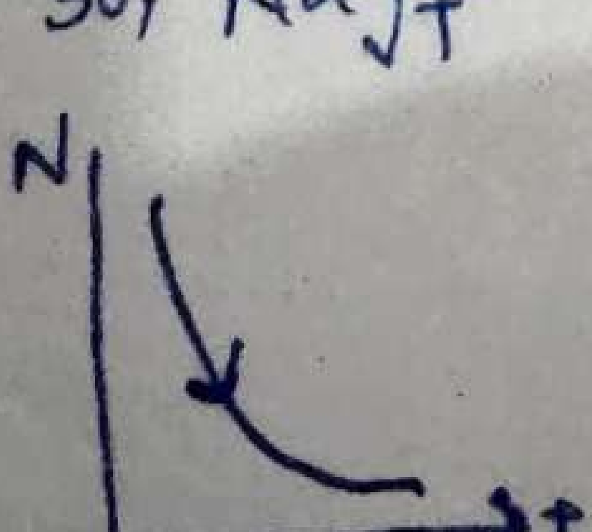
⇒ $y \propto x^2$ (Parabola)

Torque & load graph

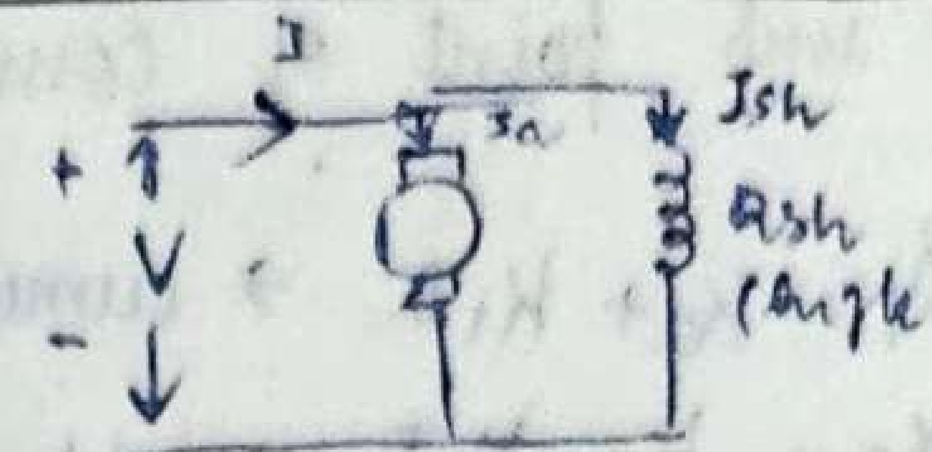


- $N \propto I_a$, $T \propto I_a^2$

so, $N \propto \frac{1}{\sqrt{T}}$



D.C Shunt



$T \propto \phi I_a$

$MMF = N_{sh} I_{sh}$

$\phi \propto MMF$

- $\phi = \frac{MMF}{reluctance}$.

$I = I_a + I_{sh}$

$I_{sh} = \frac{V}{R_{sh}}$ = constant.

ϕ = constant.

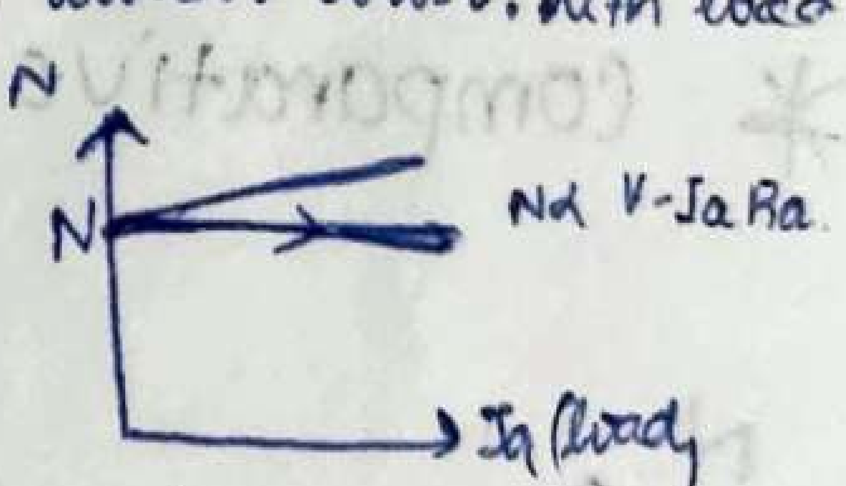
DC shunt motor is a const. flux motor.

$N \propto E_b/\phi$

$N \propto (V - I_a R_a)$ $E_b = V - I_a R_a$

$N \propto V$. R_a is very small

- speed (N) is almost const. with load.

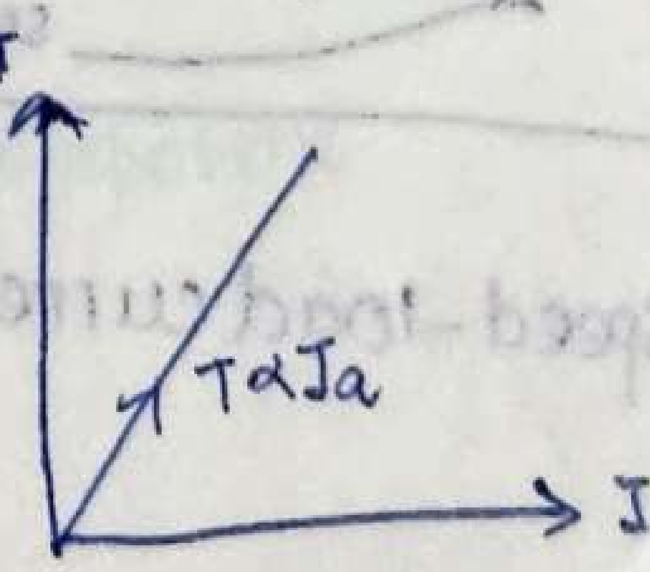


almost const speed motor.

- Torque ⇒ $T \propto \phi I_a$ ∴ ϕ constant in shunt.

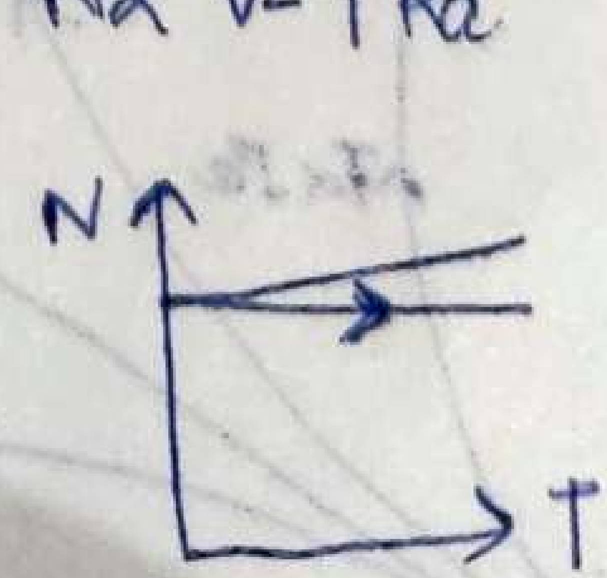
$T \propto I_a$

⇒ ($y \propto x$) straight linear



- $N \propto V - I_a R_a$, $T \propto I_a$

$N \propto V - T R_a$ if T↑ speed↓



Some imp point of compound motor -

$\phi_T = K_2 + K_1 I$ → cumulative motor

$\phi_T = K_2 - K_1 I$ → differential motor.

$N \propto \frac{E_b}{\phi_T}$

$N \propto \frac{E_b}{\phi_{sh} \pm \phi_{se}}$

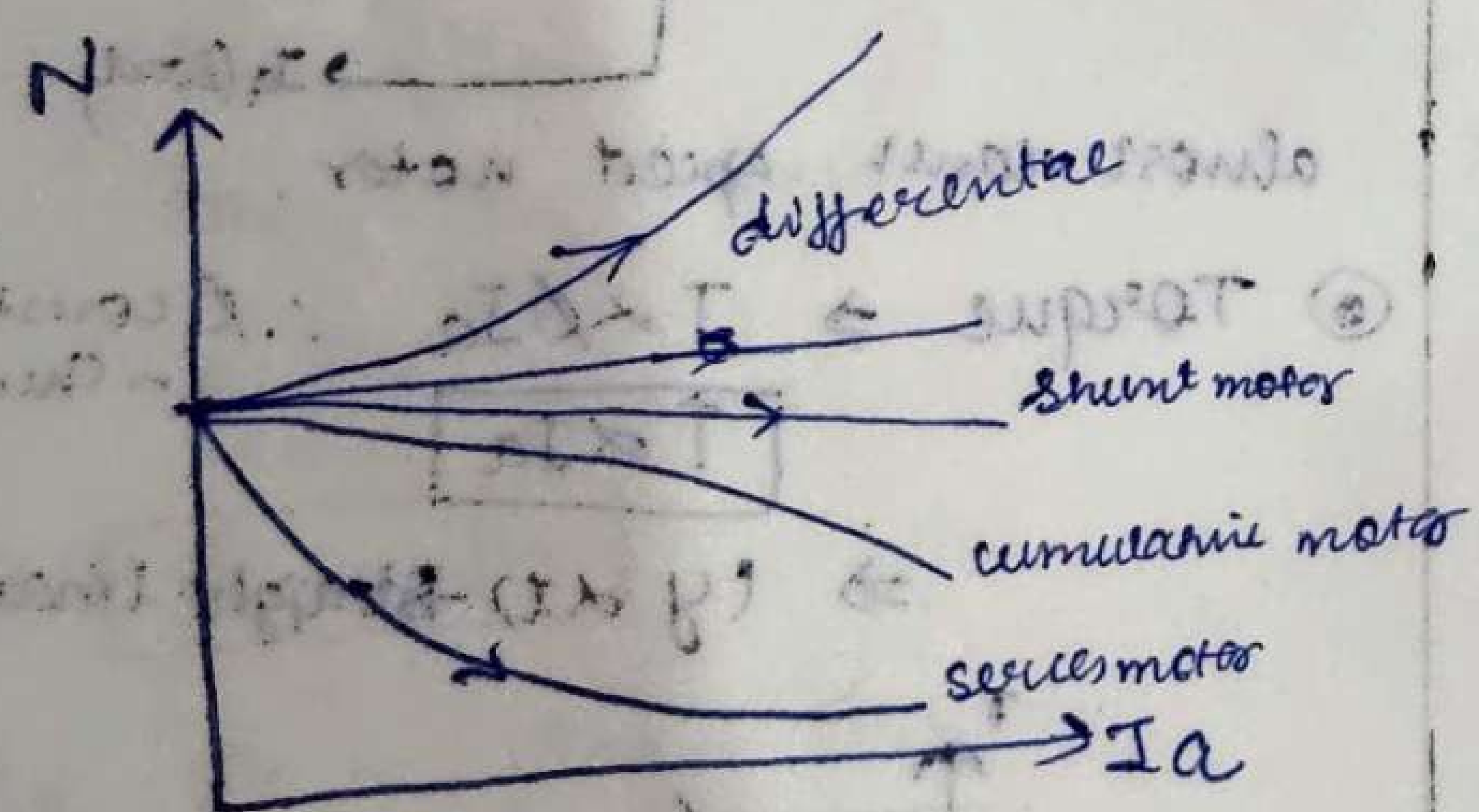
$N \propto \frac{E_b}{K_2 \pm K_1 I}$

$N \propto \frac{E_b}{K_2 + K_1 I}$ cumulative motor

$N \propto \frac{E_b}{K_2 - K_1 I}$ diff motor.

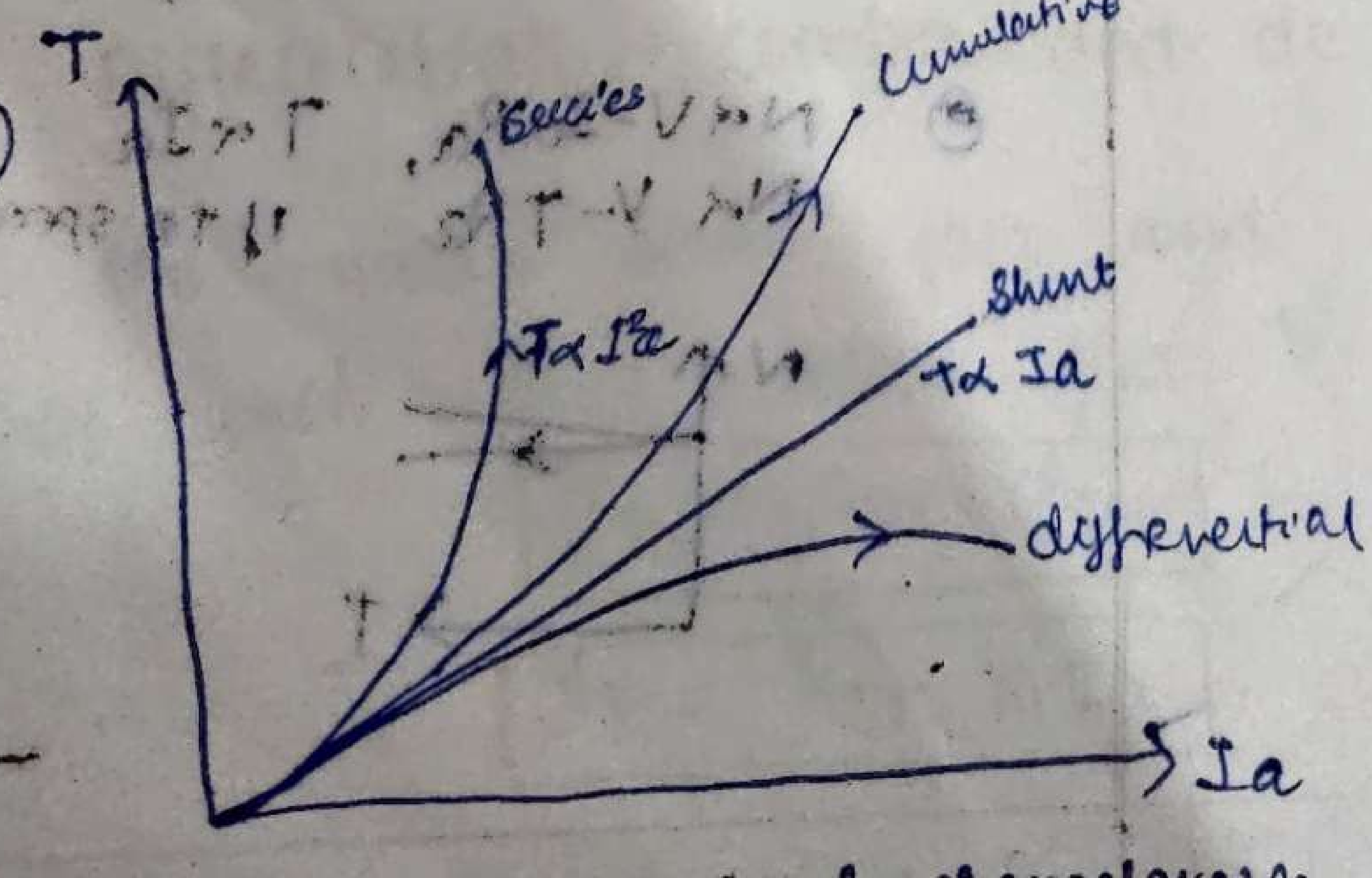
* Comparative study b/w series, shunt, compoulative, differenti motor -

(1)

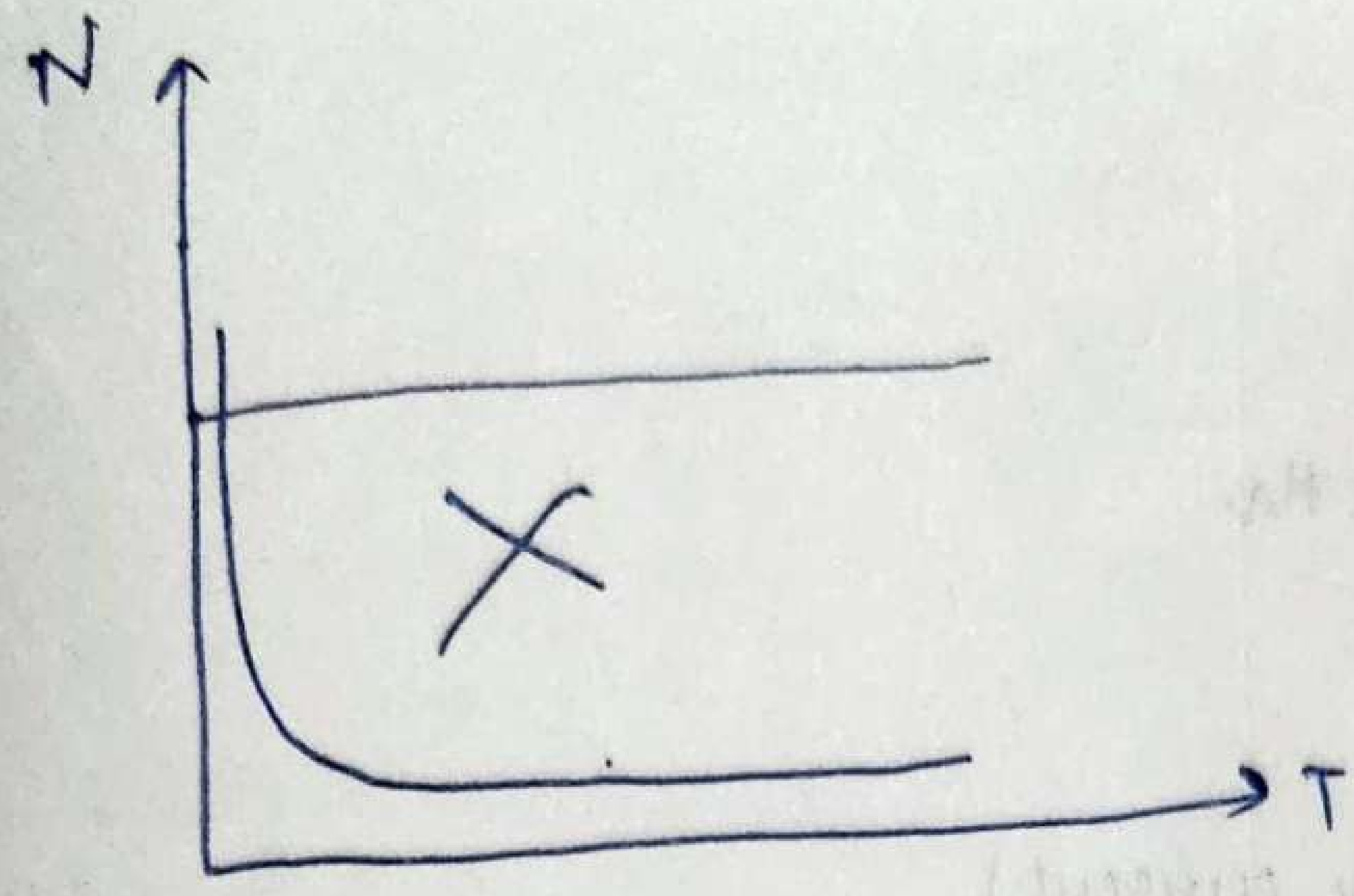


Speed-load current characterstic

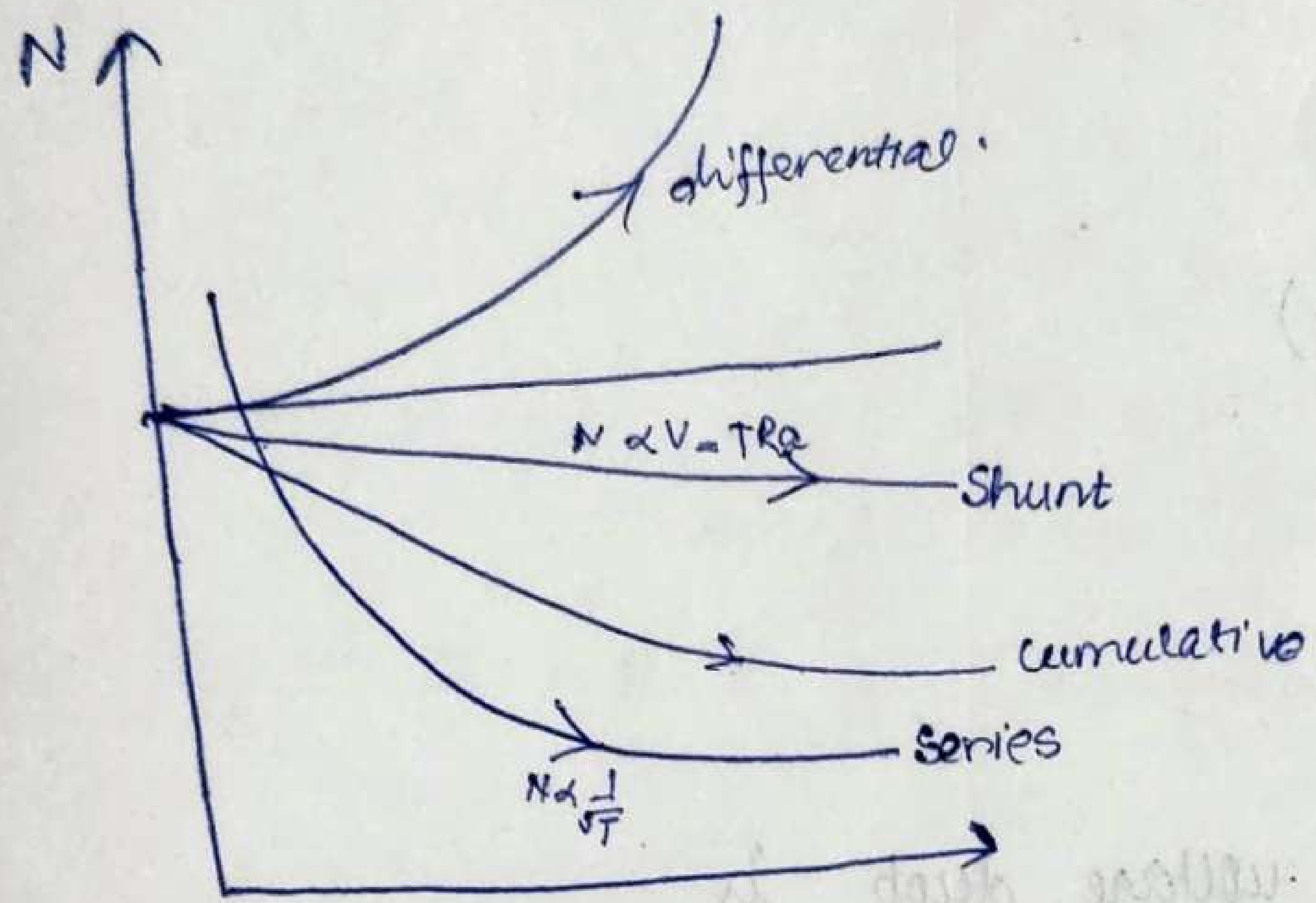
(2)



(3)



(3)



speed- torque characterstics.

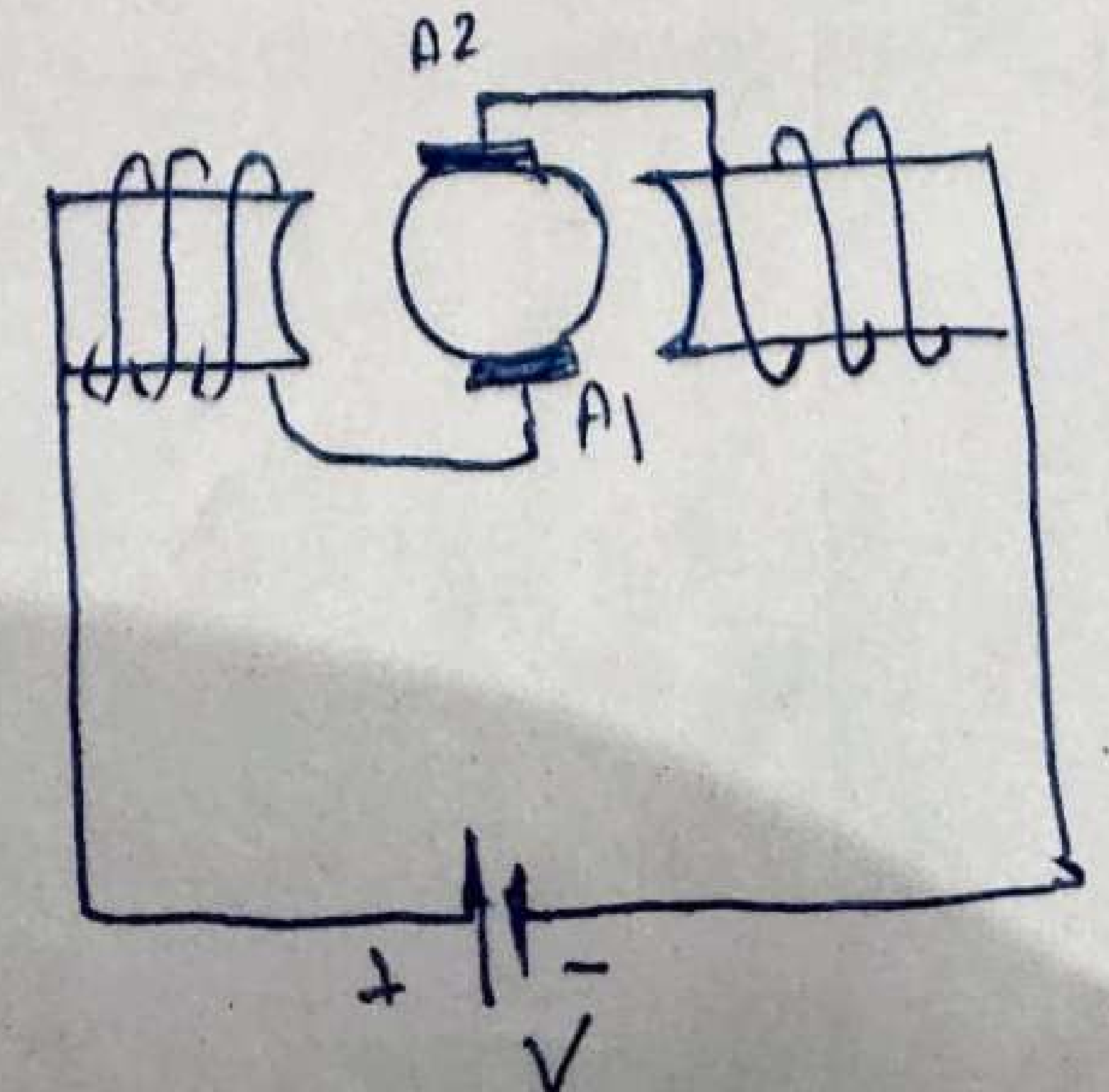
* TYPES OF DC MOTOR-

DC motors are classified acc. to connection of field wdg-

DC MOTOR

- DC Series
- DC Shunt
- DC compound.

(i) DC Series motor-



Explain why starter is required for starting a dc motor. With neat sketch explain the function of 3-point starter.

A starter is a device to start and accelerate a motor.
A controller is a device to start, control speed, reverse, stop and protect the motor.

Need for Starters -

Yes, We know, The armature current of a motor -

$$I_a = \frac{V - E}{R_a} \quad \text{——— (1)}$$

Thus Ia depends upon E and Ra if V is kept constant when motor is first switched on, the armature is stationary so the back emf 'E' is zero. The initial starting armature current Ias is -

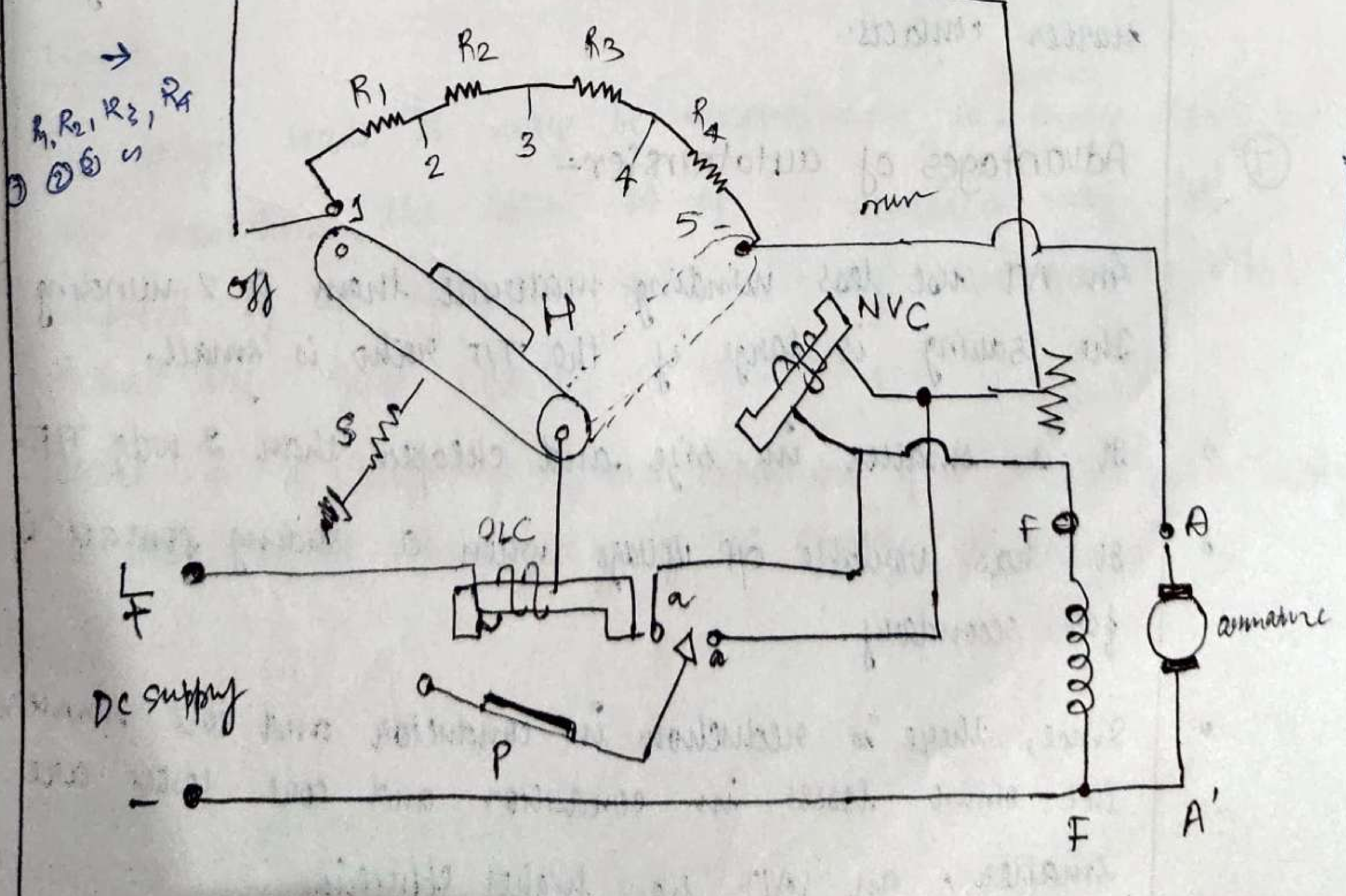
$$I_{as} = \frac{V-0}{R_a}$$

$$= \frac{V}{R_a}.$$

∴ The armature resistance of motor is very small, the starting armature current Ias would be very large. so this could damage the brushes, commutator, or windings.

- Since, the starting current is very large, at the time of starting of all d.c. motors an extra resistance must be connected in series with armature. This would limit the initial current to safe value until motor has built up stable speed and back emf.

Three point Starter



It consist of a graded resistance R to limit the starting current.

Prior to starting, the handle H is kept in the off position by a spring S.

For starting the motor, the handle H is moved. when it makes contact with resistance. R

The motor attains full speed, the supply is directly across both windings of the motor and resistance 'R' is completely cut out.

The handle H is held in run position by an electromagnet energised by a no-volt trip coil NVC. The no volt trip coil is connected in series with field winding of motor.

Switching off or when the supply voltage falls below a predetermined value, NVC is digenerised.

The current in motor is cut off, motor is not restarted without 'R' in armature ckt.

If the motor is to be stopped the main switch should be opened. To stop motor, the starter handle should never be pulled back as this would result in burning the starter contacts.

reduced capacity

The transportation of 1-ϕ T/F is more convenient.

Discuss 3-ϕ T/F phasor groups. How displacement is expressed as the clock hour number?

Three phase T/F are divided into 4 main groups acc. to phase diff b/w corresponding line voltages on the hv & lv sides. The phase diff is the angle by which the lv line voltages lags the hv lines voltages, & is measured in units of 30° in clockwise direction.

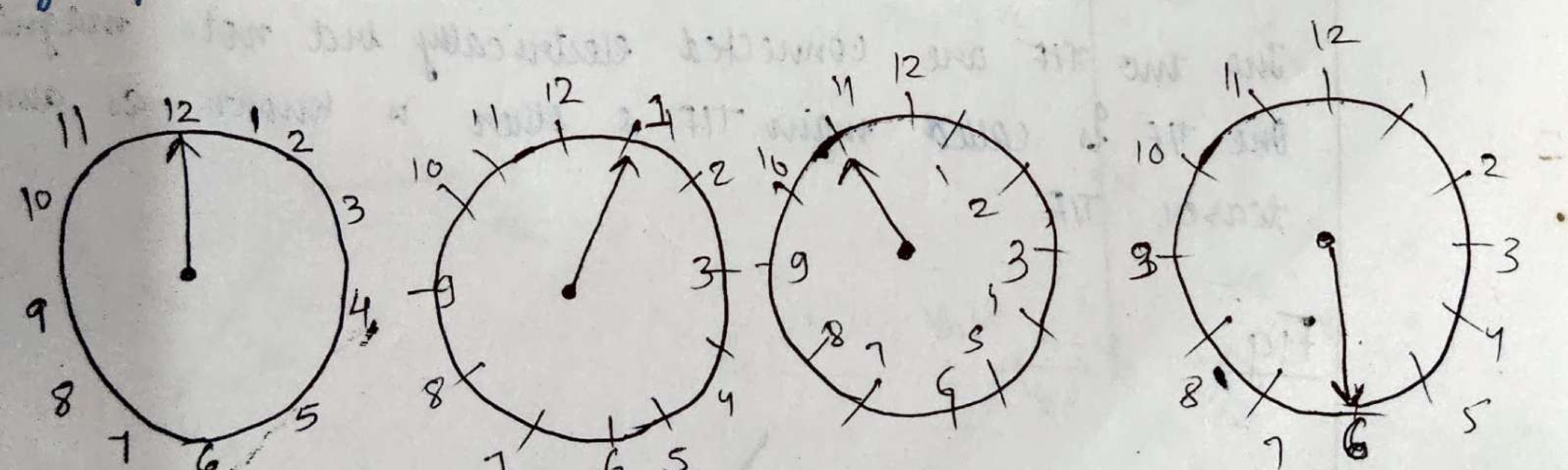
These groups are -

Group no-1 → no ~~paphase~~ phase displacement

Group no-2 → 180° " "

Group no-3 → (-30°) " "

Group no 4 → (+30°) " "



0° Phase shift | -30° phase shift | +30° phase shift | 180° phase shift

We can express the displacement as clock hour number.
For this purpose the phasor of the line voltage on the HV side is considered as minute hand and set at 12 o'clock.
The phasor of line LV side is considered as hour hand and is set on dial acc to their position in relation to the phasor of the line voltage on LV side.
Here the angle of 30° is the angle b/w two adjacent figures on the clock dial & is taken as the unit of disp shaft. When the hour hand of the clock is at 12 o'clock position, the phase displacement is zero. When the hour hand is at 1 o'clock position, the phase shift is −30°. At 6 o'clock position, the phase shift is 6×30° = 180°.. & similary when hour hand is 11 o'clock position, phase shift 11×30° = 330°.
Thus no. 0, 6, 1 & 11 in group refence no. indicate the primary to secondary phase shift in terms of hours of the clock.

Explain Scott connection in 3-ϕ T/F.

The Scott connection is the most comon method of connecting two single-phase T/F to perform the 3-phase to two-phase conversion vice-versa.

The two T/F are connected electrically but not magnetically. One T/F is called main T/F & other is known as auxiallary teaser T/F.

Fig →

⟹

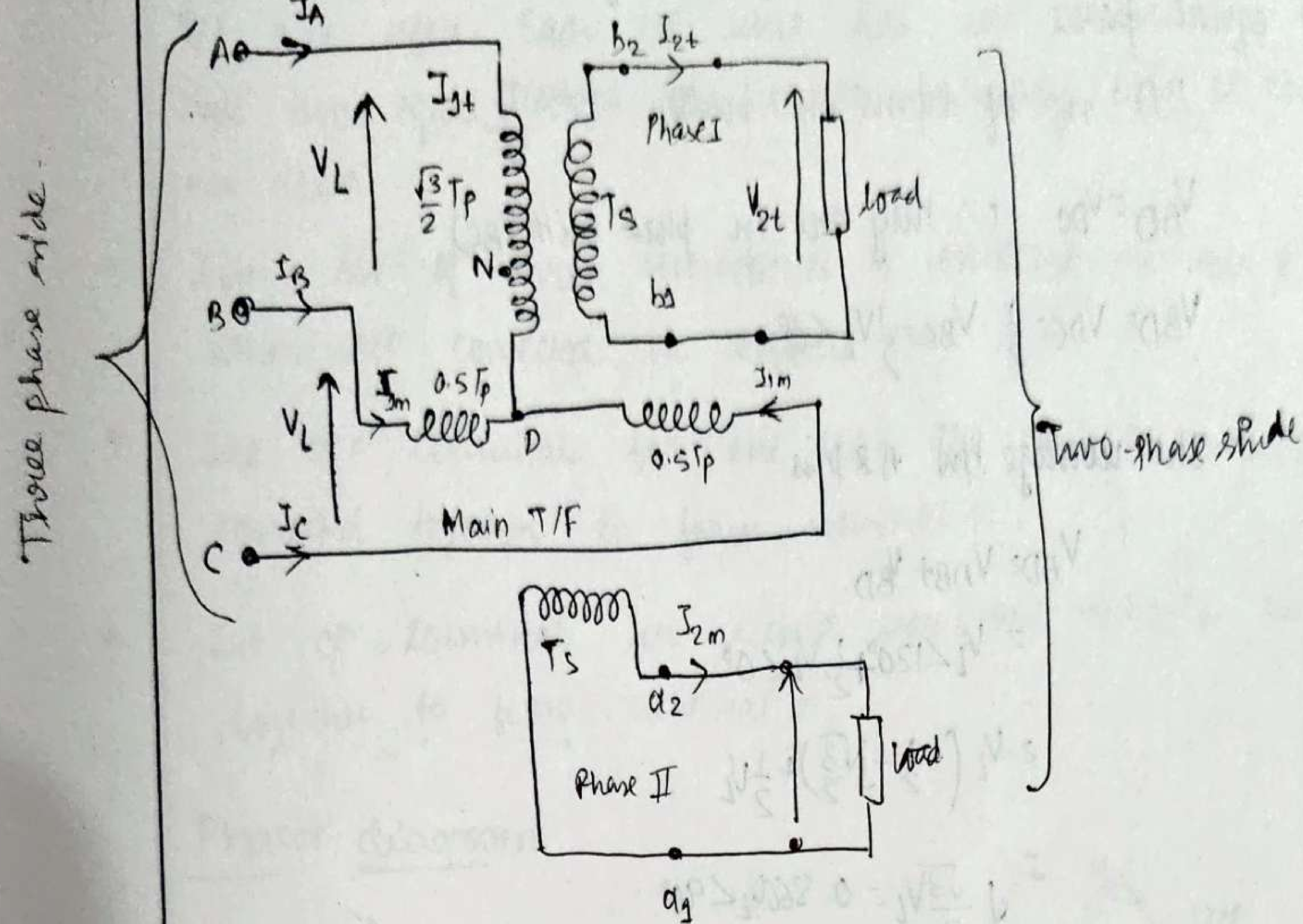
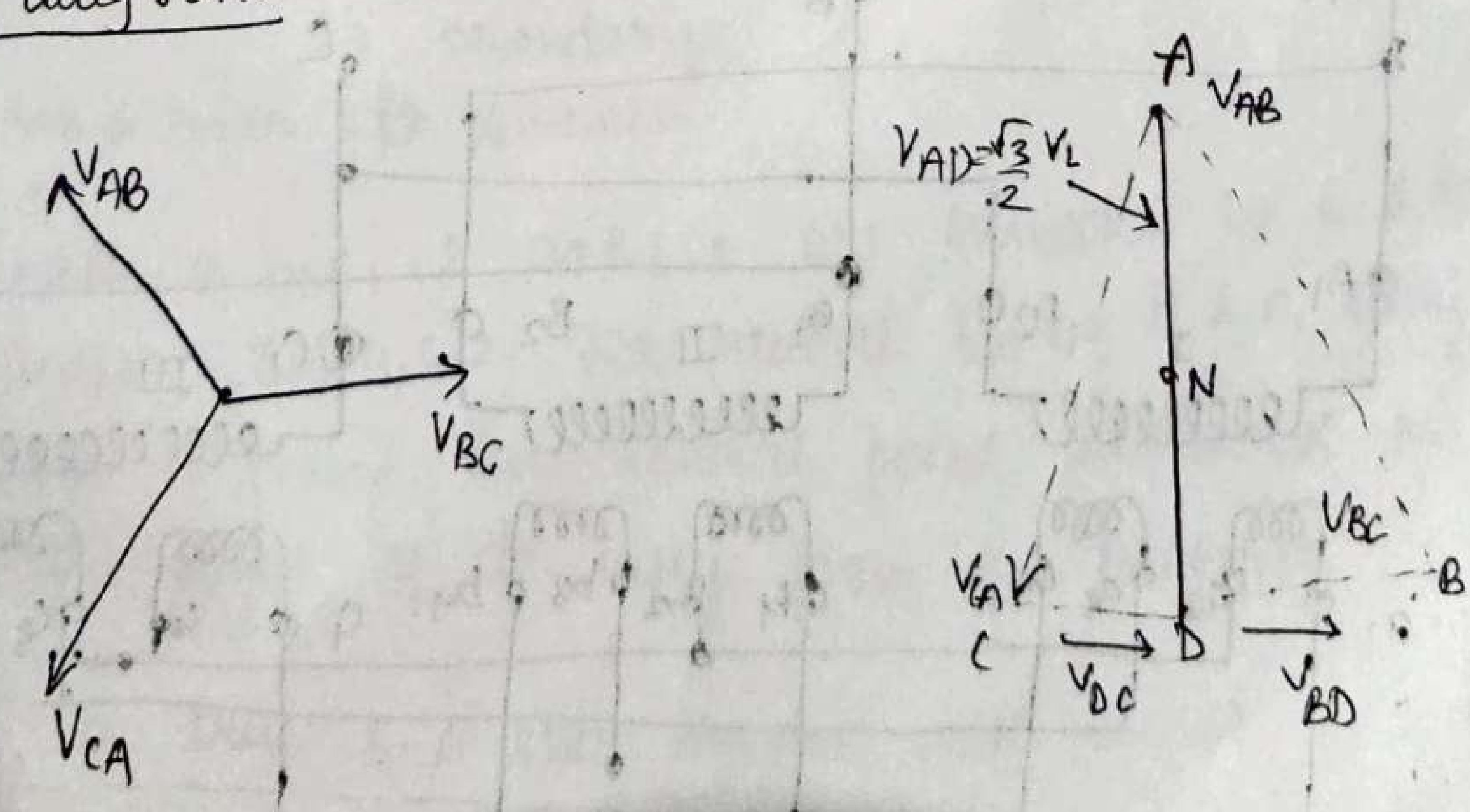


fig - Scott connection of T/F.

- The T/F is centre tapped at D & is connected across the lines B & C of the 3-ø side. It has primary BC & secondary a_1, a_2. The teaser T/F is connected b/w the line terminal A & the centre tapping D. It has primary AD & secondary $b_1 b_2$.
- Frequently identical interchangeable T/F are used for the scott connection in which each T/F has primary wdg of T_p turns & is provided with tappings at $0.289T_p$, $0.5T_p$ & $0.866T_p$.

Phasor diagram -



⇒ $|V_{AB}| = |V_{BC}| = |V_{CA}| = V_L$ (The line voltages of 3-ø system). The same voltages are shown as a closed equilateral Δ

⇒ Let V_{BC} taken as refrence voltage so ⇒ $V_{BC} = V_L\angle 0°$; $V_{CA} = V_L\angle -120$, $V_{AB} = V_L\angle$

Since D divides primary BC of main T/Fs. into two equal parts

∴ BD = no. of turns in portion $DC = \frac{T_P}{2}$

$V_{BD} = V_{DC}$ (∴ they are in phase with V_{BC})

$V_{BD} = V_{DC} = \frac{1}{2} V_{BC} = \frac{1}{2} V_L \angle 0^\circ$

The voltage b/w A & D is

$$V_{AD} = V_{AB} + V_{BD}$$
$$= V_L \angle 120^\circ + \frac{1}{2} V_L \angle 0^\circ$$
$$= V_L \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) + \frac{1}{2} V_L$$
$$= j\frac{\sqrt{3}}{2} V_L = 0.866 V_L \angle 90^\circ$$

Discuss 3-φ to 6-φ conversion in 3-φ T/F.

The following schmes of connections are commonly used for 3-phase to six phase -

- Double star
- Double delta
- Six-phase star
- Diametrical

Double-Star connection or conversion -

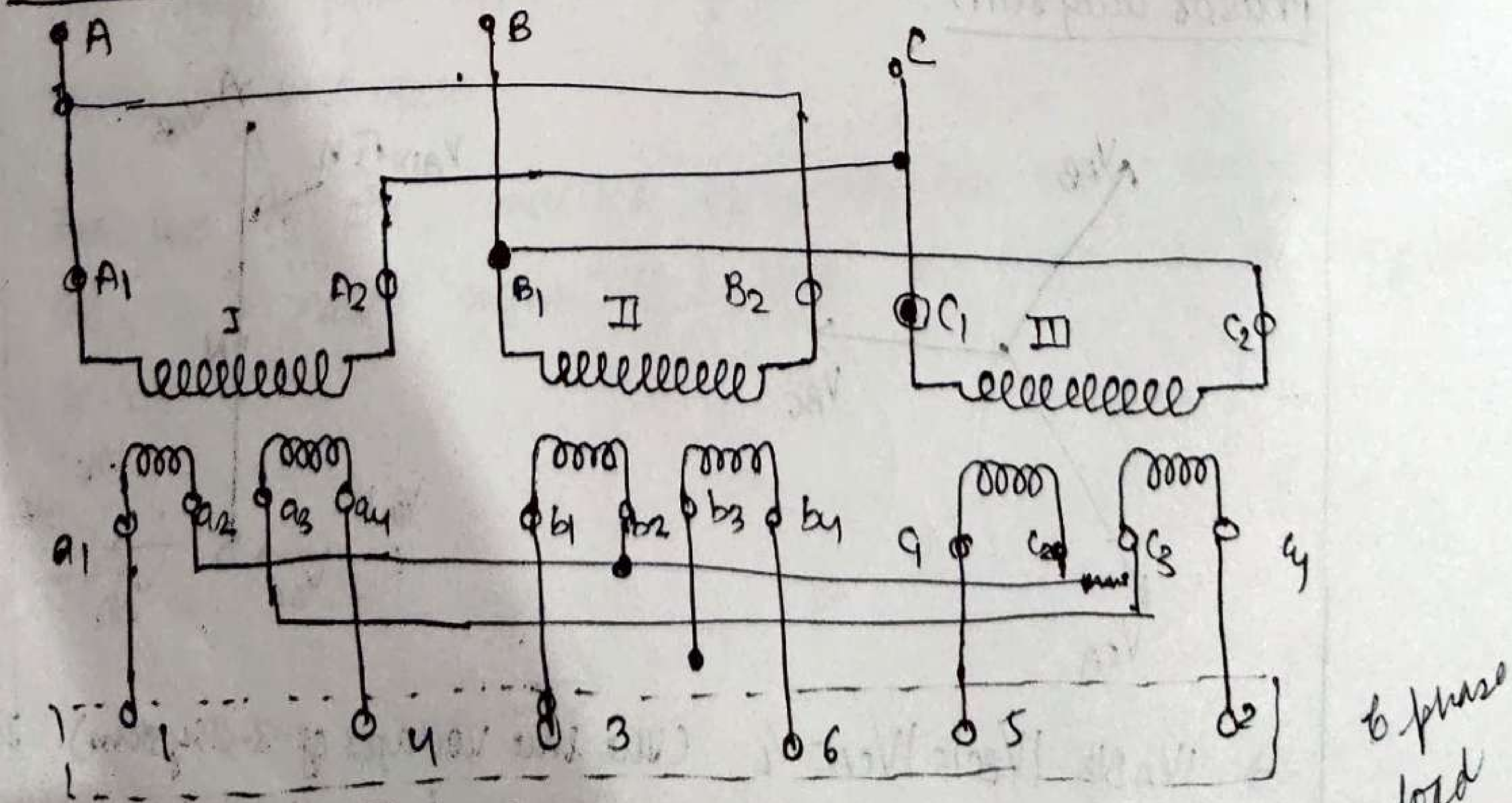
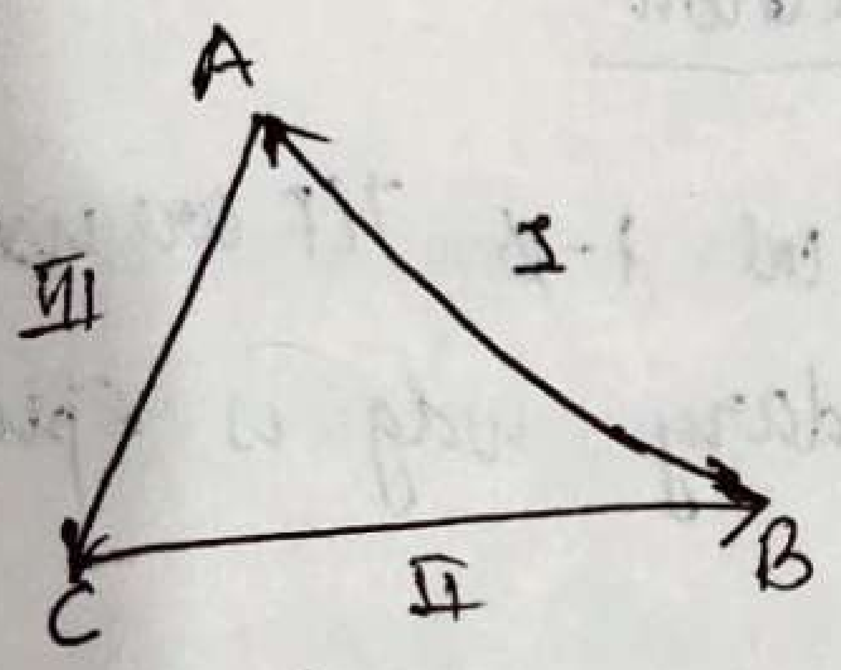


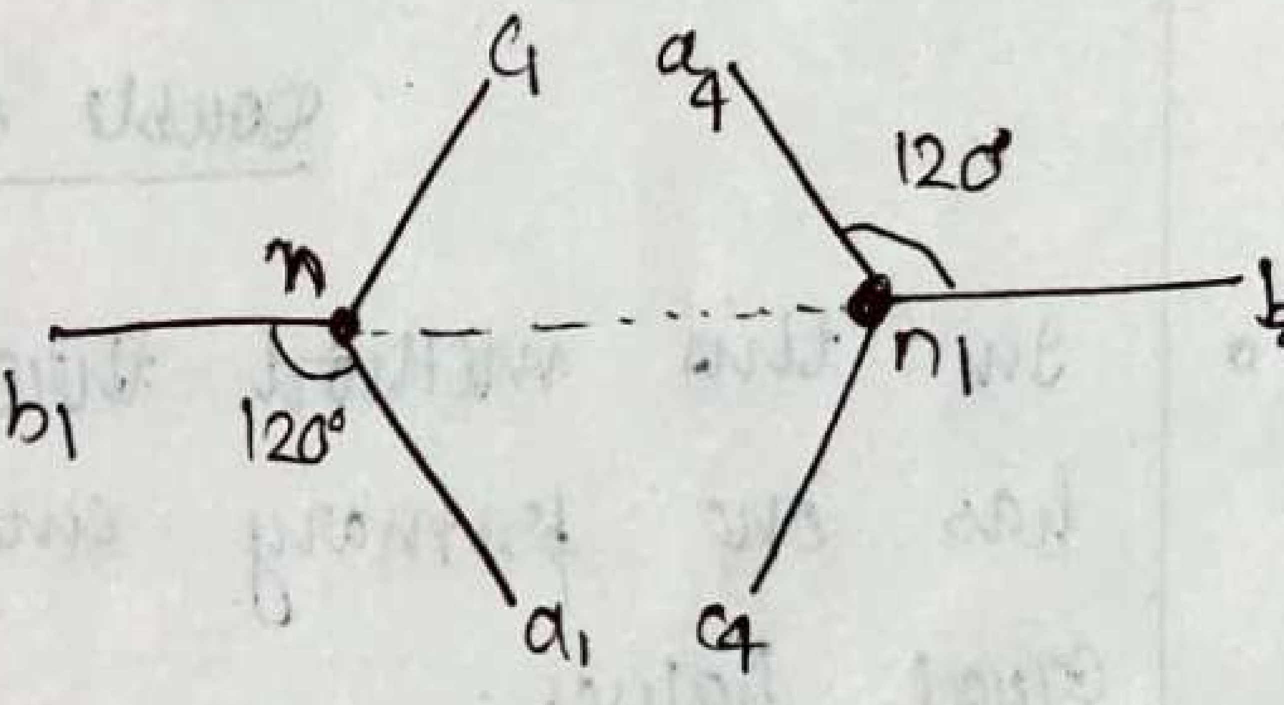
fig - double-star connection

- For three-ϕ to 6-ϕ Transformation, three identical single-ϕ T/F are used. Each T/F unit has its secondary wdg spit into two equal sections. The three primary can be conceted in delta.
- One set of three secondaries is connected in star & the other set conected in reverse star.
- The O/P terminals for one star are $a_1 b_1 c_1$ with $a_2 b_2 c_2$ conected together to form neutral n.
- The o/p terminal for second star are $a_2 b_2 c_2$ with $a_3 b_3 c_3$. together to form neutral n_1.

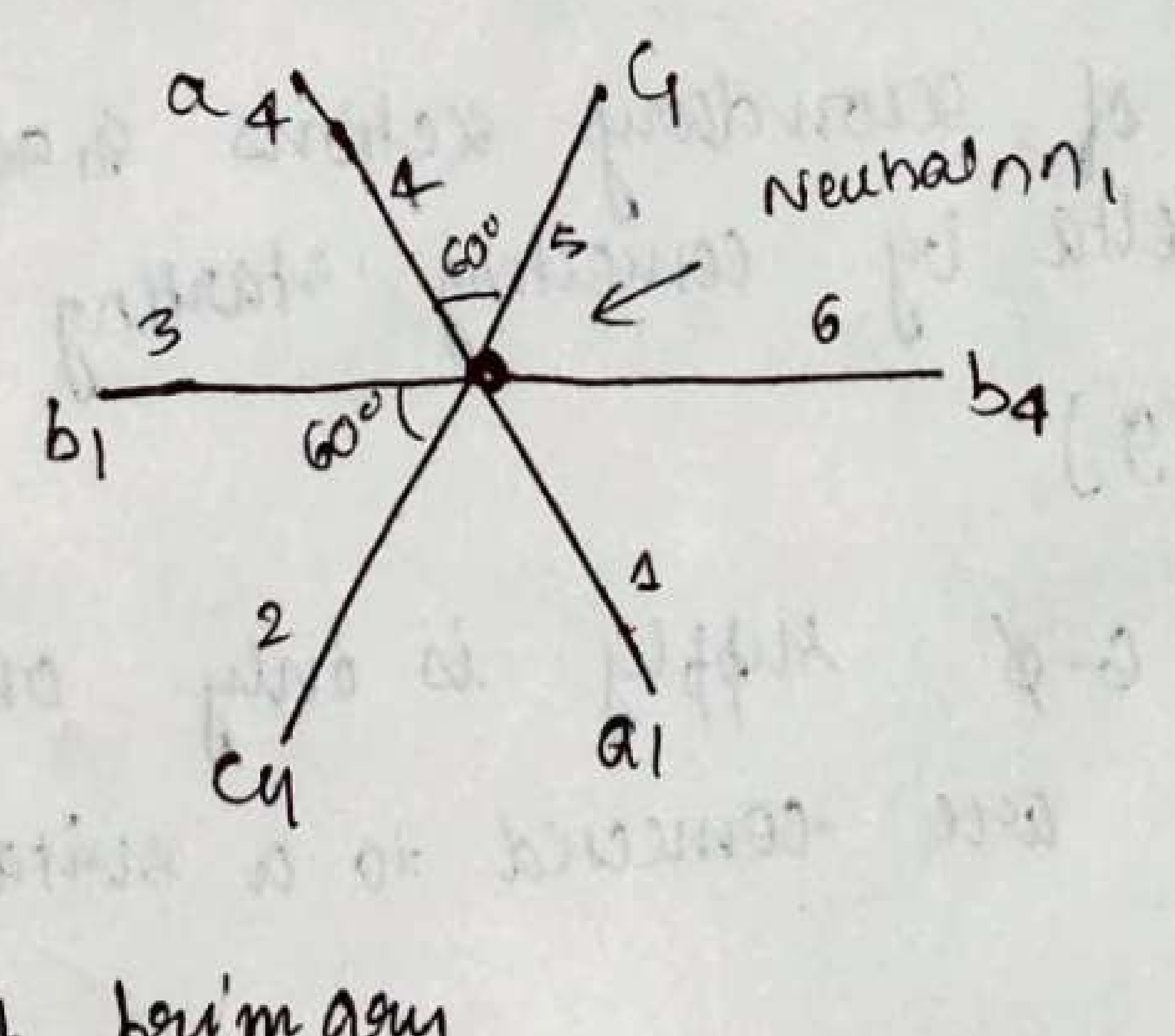
Phasor diagram



(b)



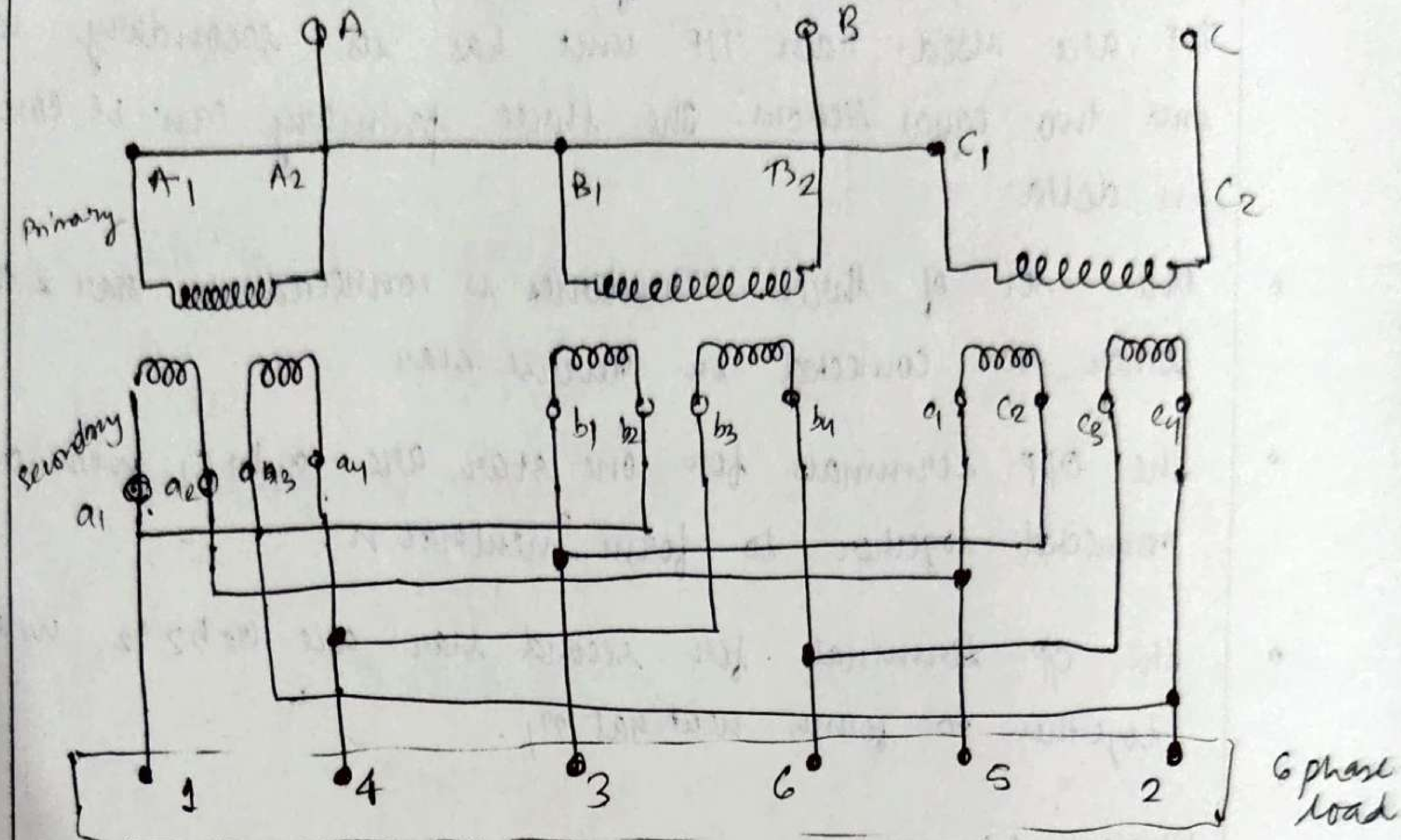
(C)



(a) Phasor diag of primary
(b) " " " secondary
(c) six ϕ star connection

- Terminals $a_1 b_1 c_1$ & $a_4 b_4 c_4$ are connected to 6-ϕ load terminals 1, 3, 5, 4, 6, 2. The neutral points n & n_1 may be conected together. This neutral point will serve as the neutral point of dc suply from the rectifier
- Thus, a true 6-ϕ star system with neutral ϕ is obtained

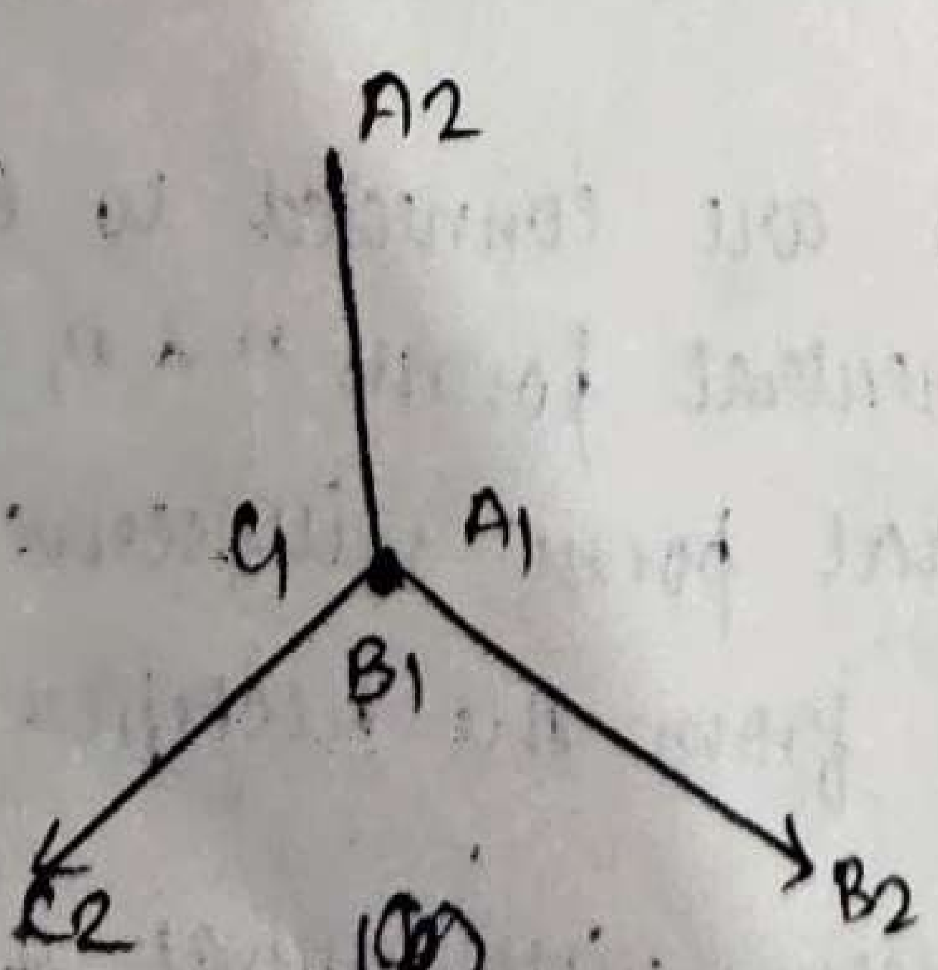
(b) Double-delta connection-



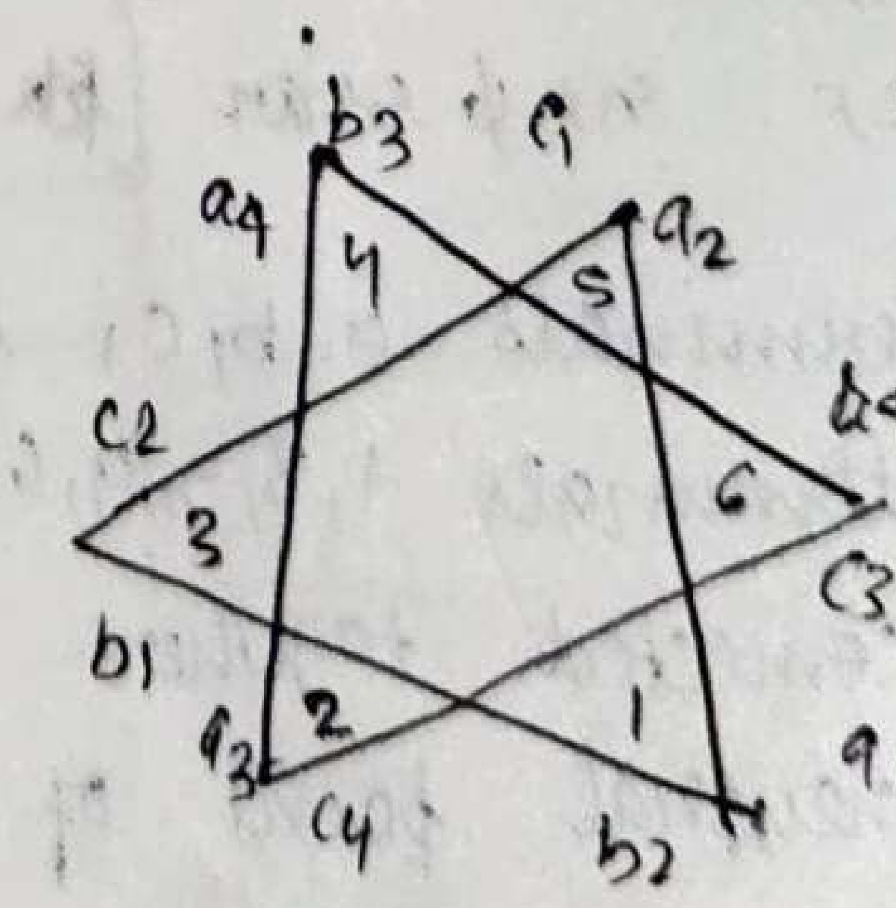
Double delta connection

- In this method three identical 1-Ø T/F are used. Each T/F has one primary and secondary wdg is split into two equal halves.
- One set of secondary sections $a_1 a_2$, $b_1 b_2$, $c_1 c_2$ is connected in normal delta by connecting starting end a_1 at the end of finishing (above fig)
- A true 6-Ø supply is only obtained when the six terminals are connected to a suitable 6-Ø load.

3 Phasor diagram

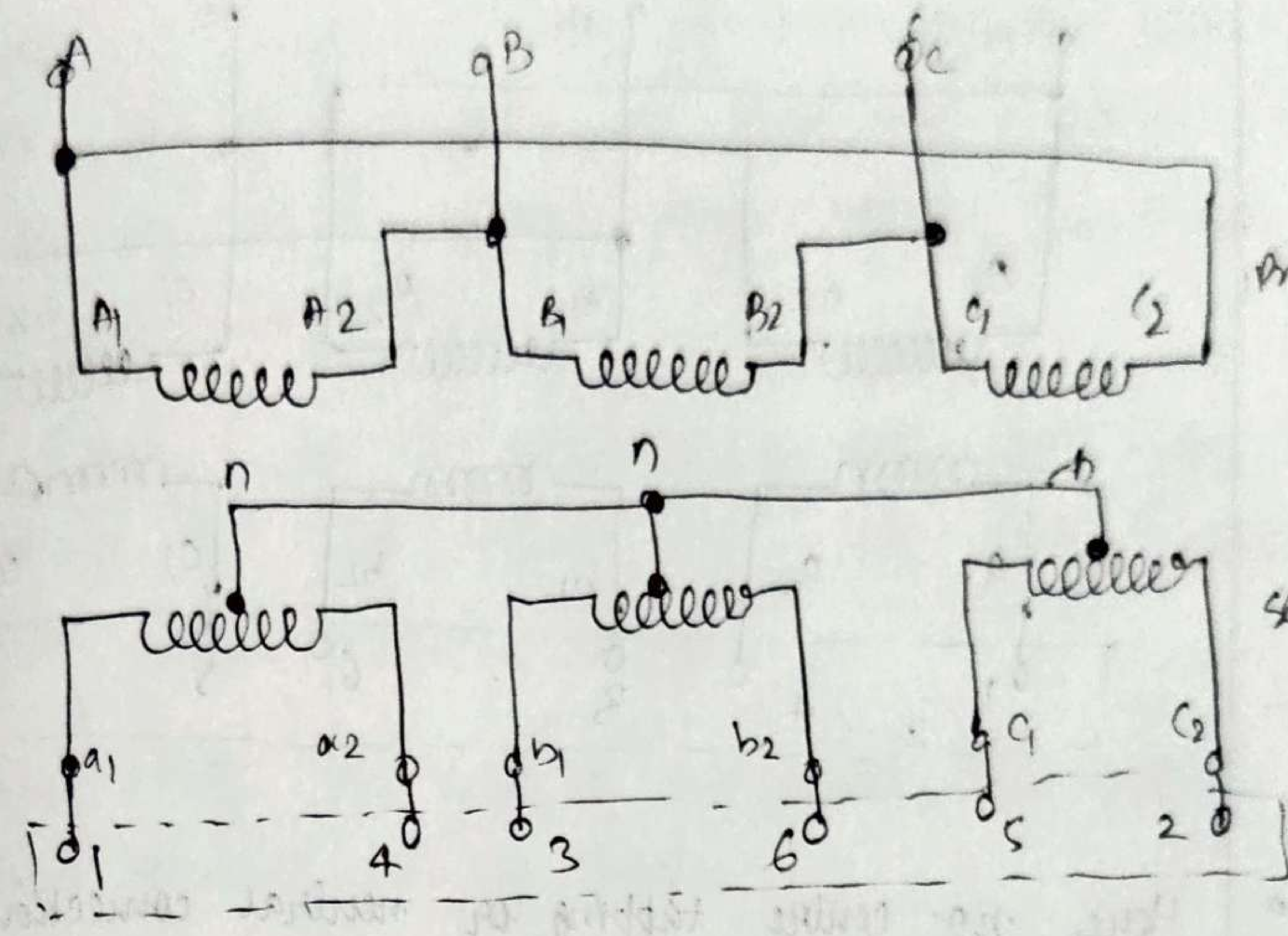


Primary



Secondary

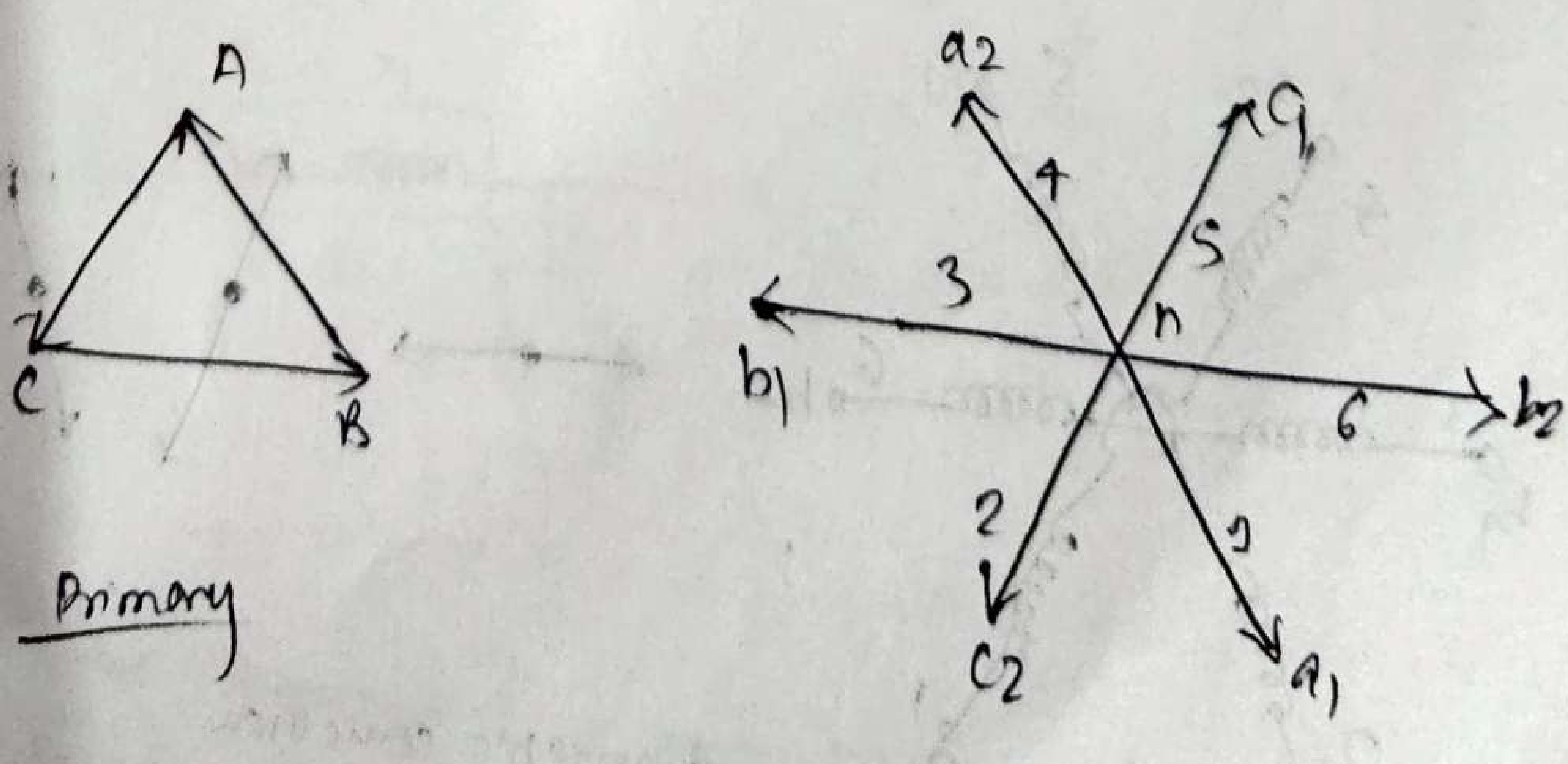
(c) Six phase star connection



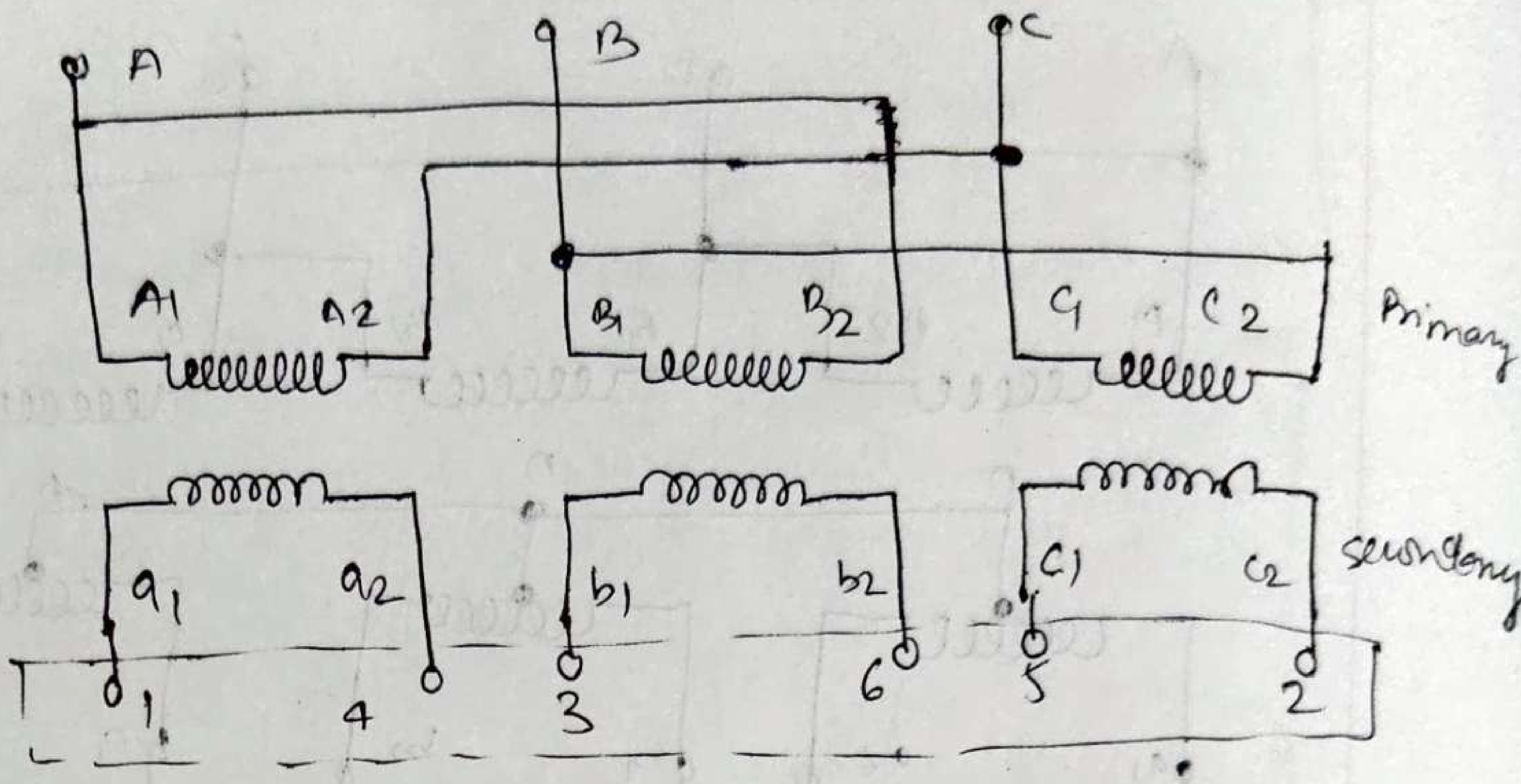
(a)

- The secondary have centre taps which are connected together to form the neutral on the 6-ϕ side.
- The primaries connected in delta, but these may also be connect in star.
- Three 1-ϕ T/F or one three-ϕ T/F may be used for 3 to 6 ϕ T/F
- 6-ϕ load terminals 1, 2, 3, 4, 5, 6 are conneted to 6 T/F secondary terminals a1 c2 b1 a2 c1 b2.

Phasor diag

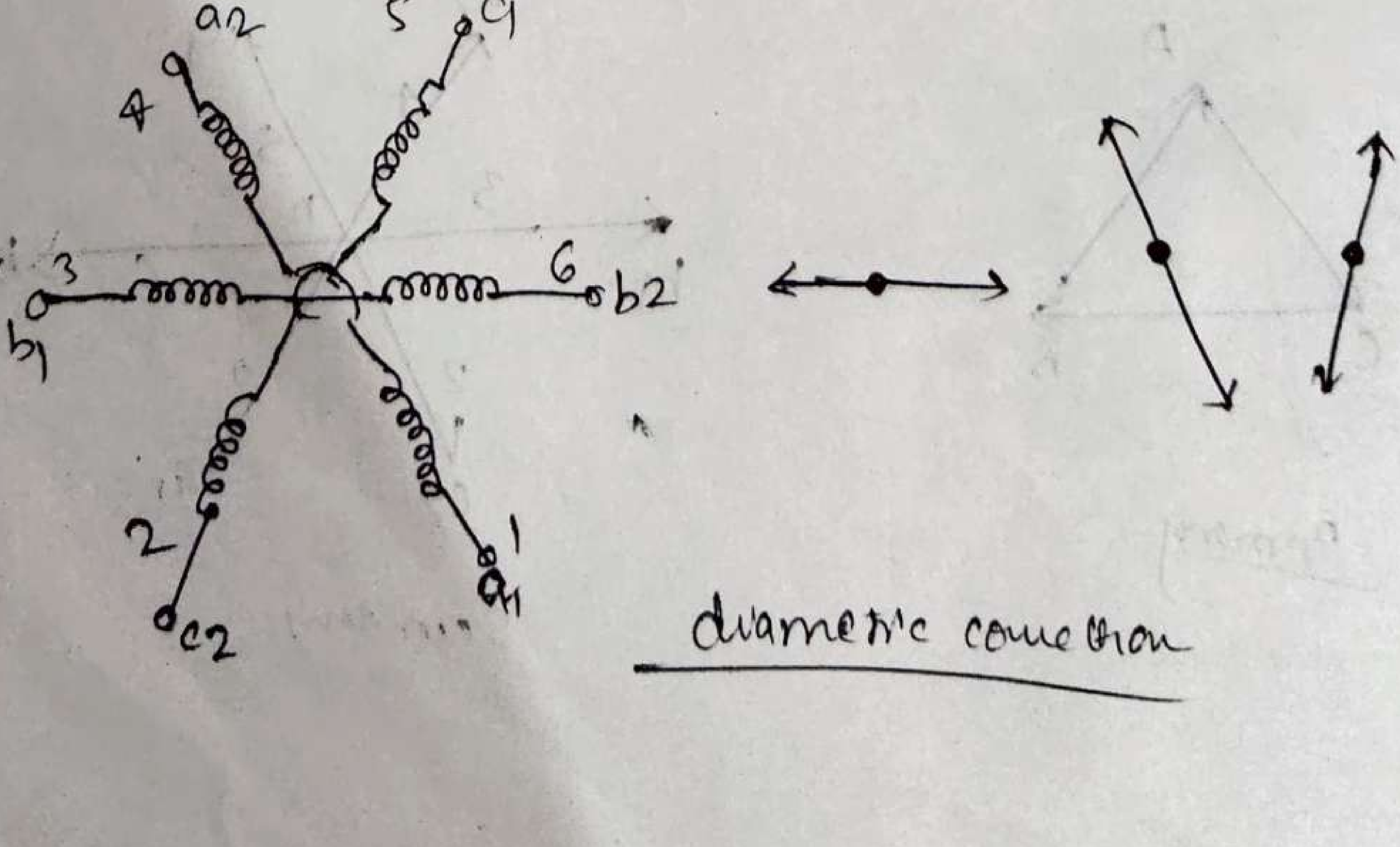


(d) DIAMETRICAL CONNECTION-



- Here no centre tapping or neutral connections required.
- In order to fix the phase relations of voltages & produce a 6-ø supply, it is necessary that the 6. secondary terminals a1 should be connected to 6-ø load (fig)
- Here T/Fs terminals a1 a2 b1 b2 c1 c2 are be conected to load terminals 1 4 3 6 5 2.
- Since, neutral is not available, this method can't be used for rectifier ckts.

Phasor diag.



diametric connection