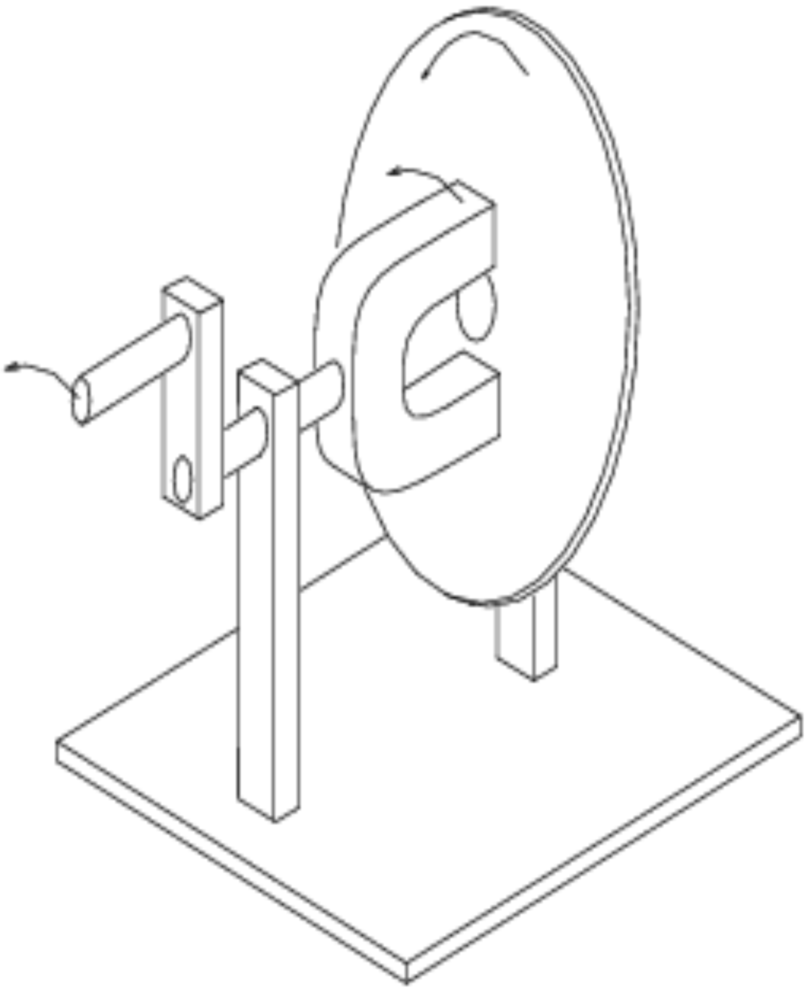
ROCO222: Intro to sensors and actuators

Lecture 9

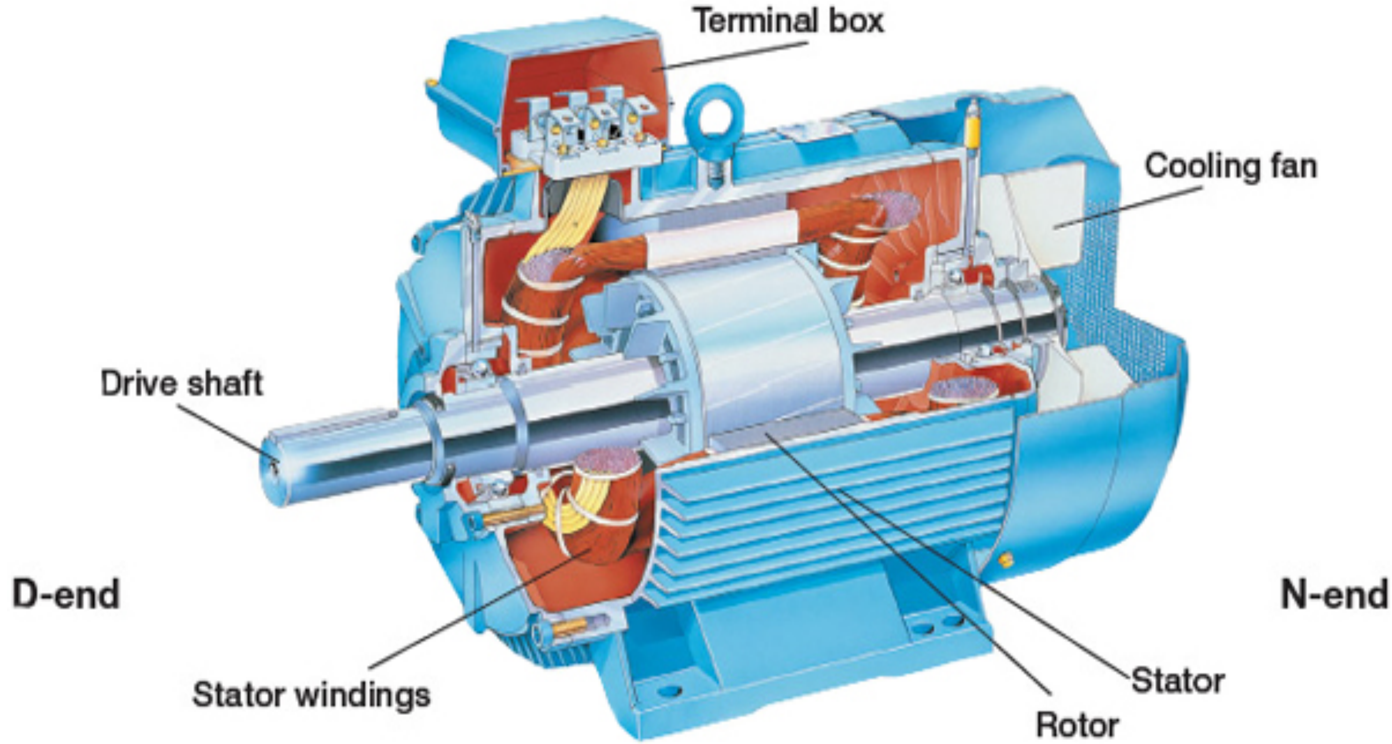
3-phase induction motors

Principle of induction motor operation



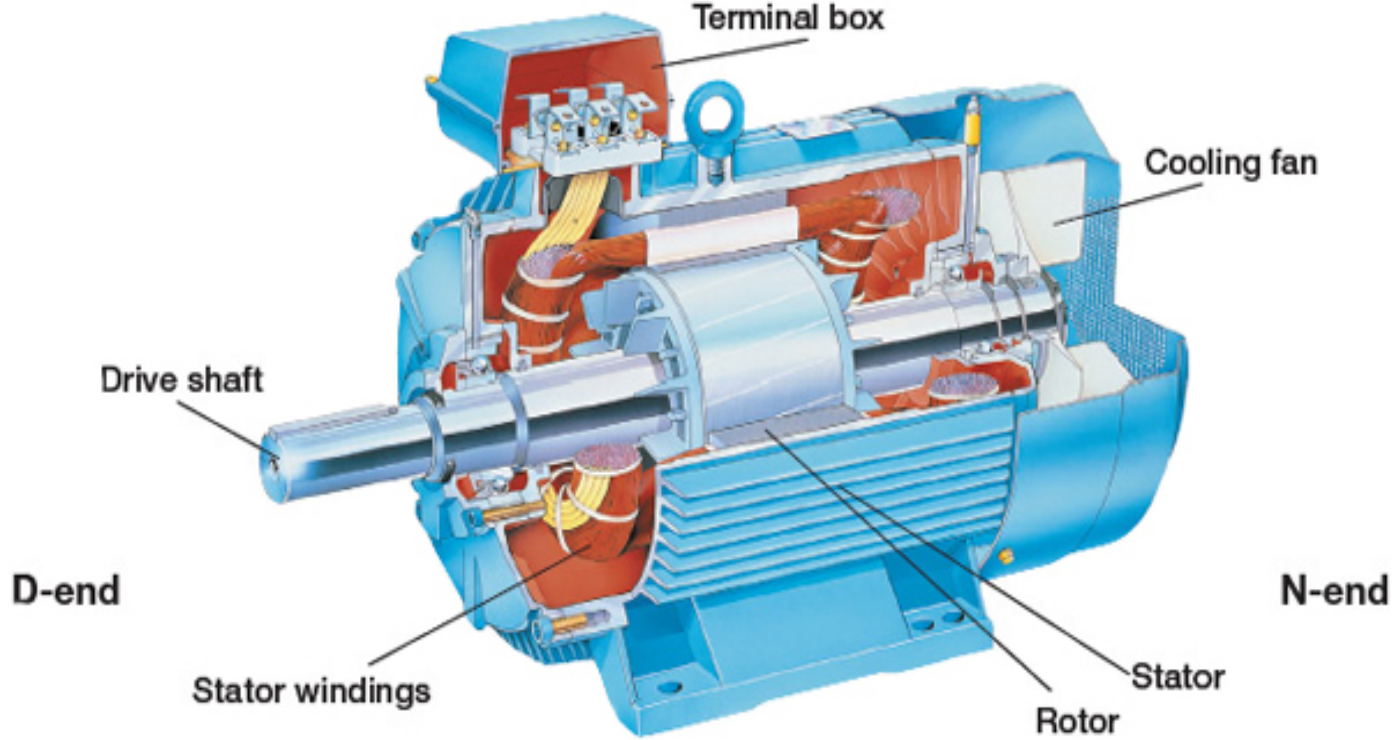
- The lines of flux cutting the conductor will induce a voltage, and consequent current flow, in the conductive disk
- This current flow creates an electromagnet whose polarity opposes the motion of the permanent magnet
- The polarity of the electromagnet is such that it pulls against the permanent magnet

Typical induction motor



- The induction motor is the most commonly used type of AC motor
- They are simple, low cost and rugged in construction
- They do not require commutation do there are no brushes to wear out
- Indeed life generally limited by life of the bearings
- The induction motor derives its name from the fact that ac voltages are induced in the rotor circuit by the rotating magnetic field of the stator
- An induction motor is a constant speed device

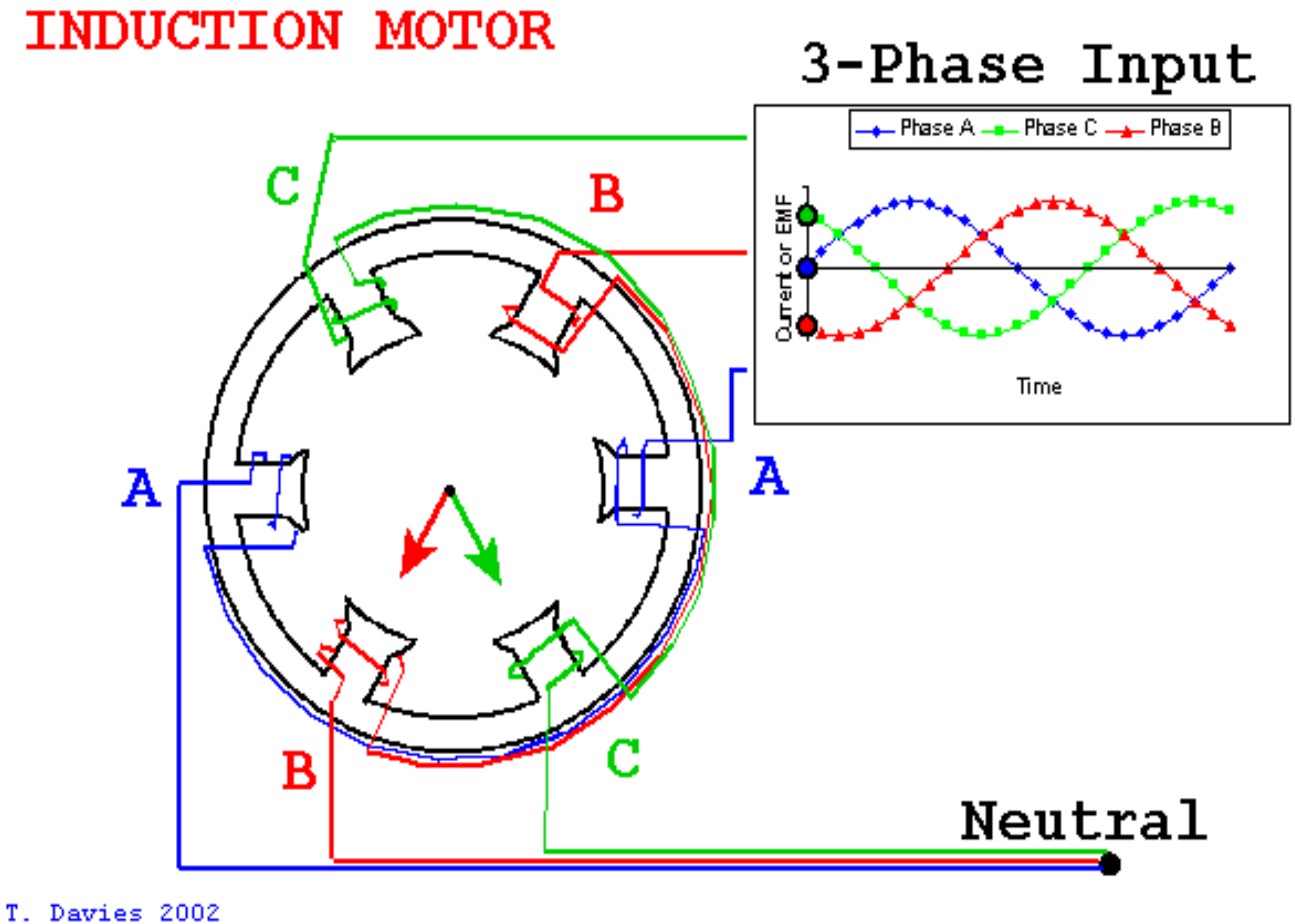
Typical induction motor



- Stator carries the motor primary windings, which are coils of wire, which are connected to the power source
- Current is induced in the rotor windings (conductors) by transformer action
- Torque is produced by the reaction between the induced rotor currents and the air-gap flux created by the stator currents
- Drive shaft attached to and driven by rotor and supported by ball bearings each end
- Cooling fan causes air to circulate and reduce temperature of windings and rotor
- Frame needed to support stator and bearings and provide attachment point
- Terminal block provides power connection point

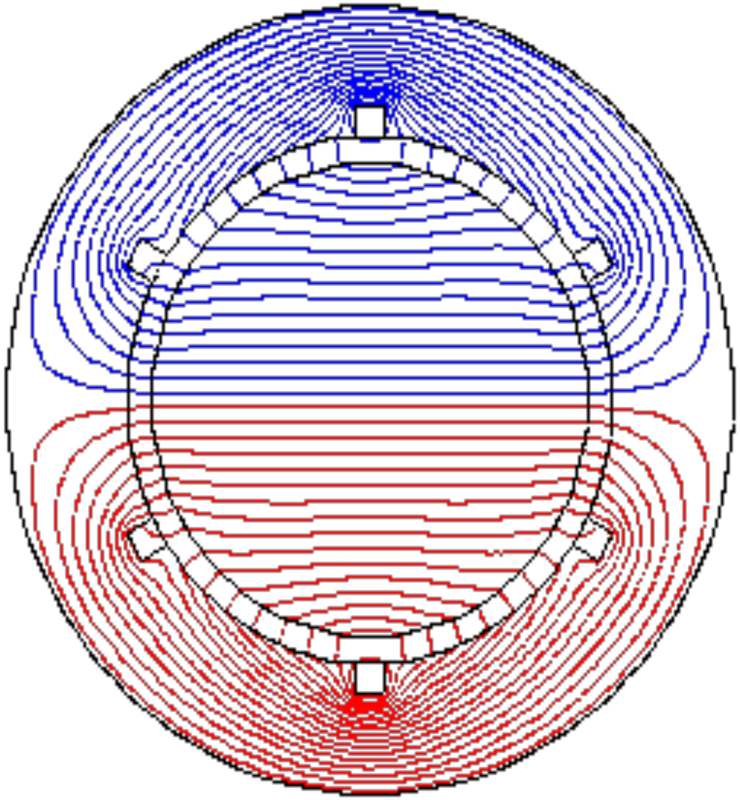
3-phase drive to stator coils

- AC 3-phase supply driving 3 sets of coil (2 poles per phase) positioned 120 degrees around the circumference of the stator circle results in a rotating magnetic field

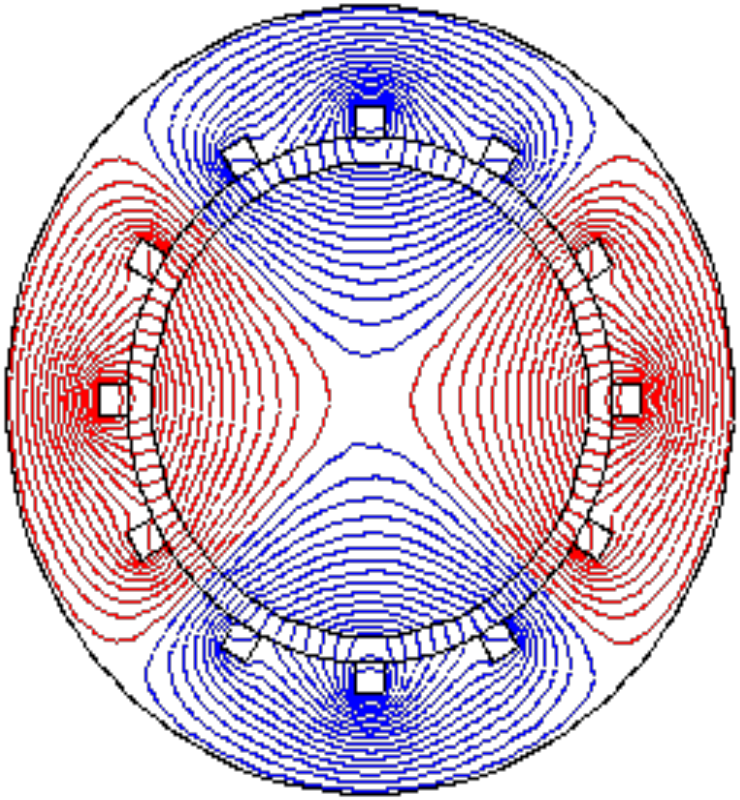


3-phase drive results in rotating fields

- If there are 2 poles per phase then field rotates at supply frequency
- If there are 4 poles per phase then field rotates at half supply frequency



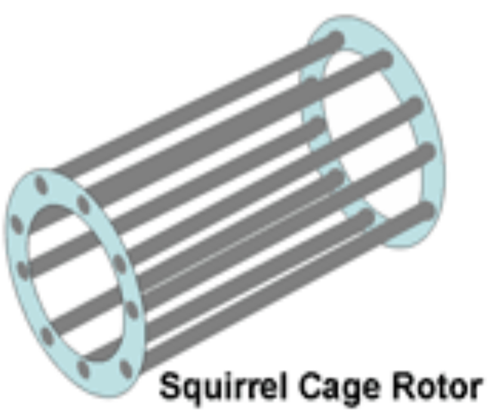
2-pole stator

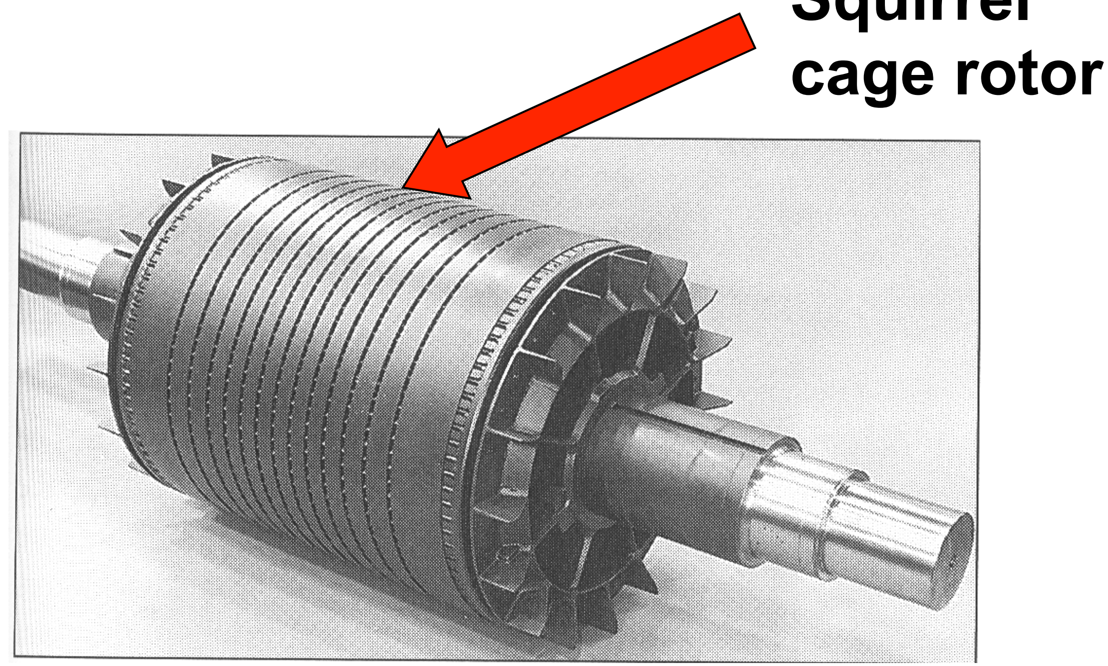


4-pole stator

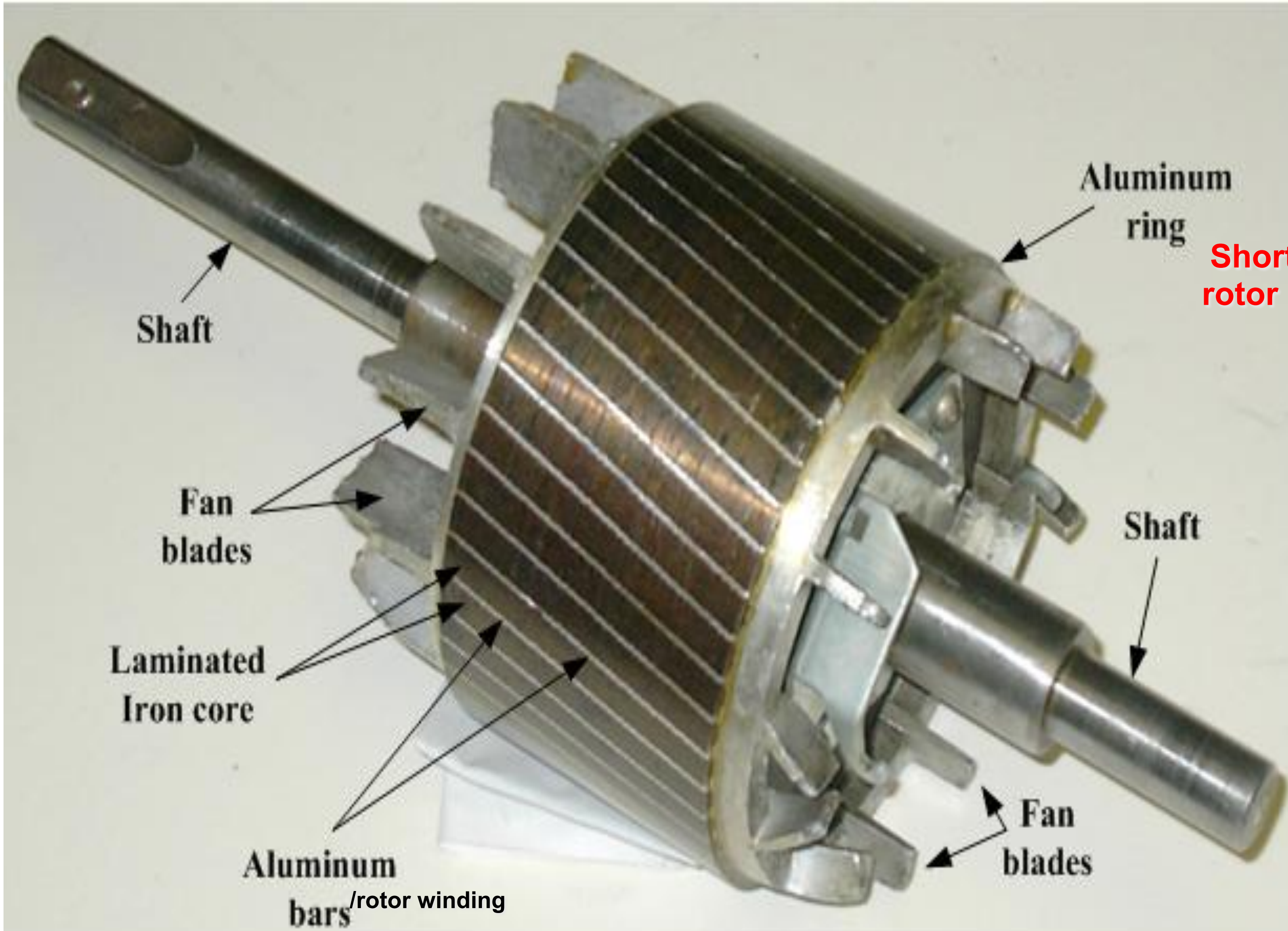
Squirrel cage induction motor

- A squirrel cage rotor is a simple, low cost, robust,
- Its rotor winding is composed of copper or aluminum bars embedded in the rotor slots and shorted at both end by end rings
- Often the conductors are skewed to reduce cogging, improve starting and make rotation smoother
- A ferromagnetic core is used to ensure magnetic flux density B is high
- The core is usually laminated ferromagnetic material to reduce eddy current





Squirrel cage rotor



/rotor winding

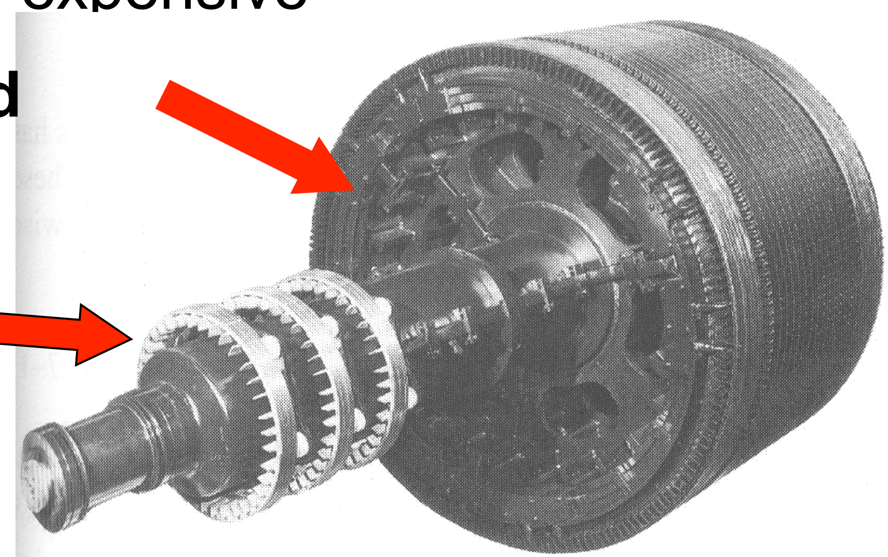
Short circuits all rotor bars.

Wound rotor induction motor

- Rotor winding is wound by wires.
- The winding terminals can be connected to external circuits through slip rings and brushes.
- Purpose is to allow resistance to be placed in series with the rotor windings while starting - to reduce current
- Resistance is shorted out once the motor is started
- Easy to control speed, more expensive

Wound rotor

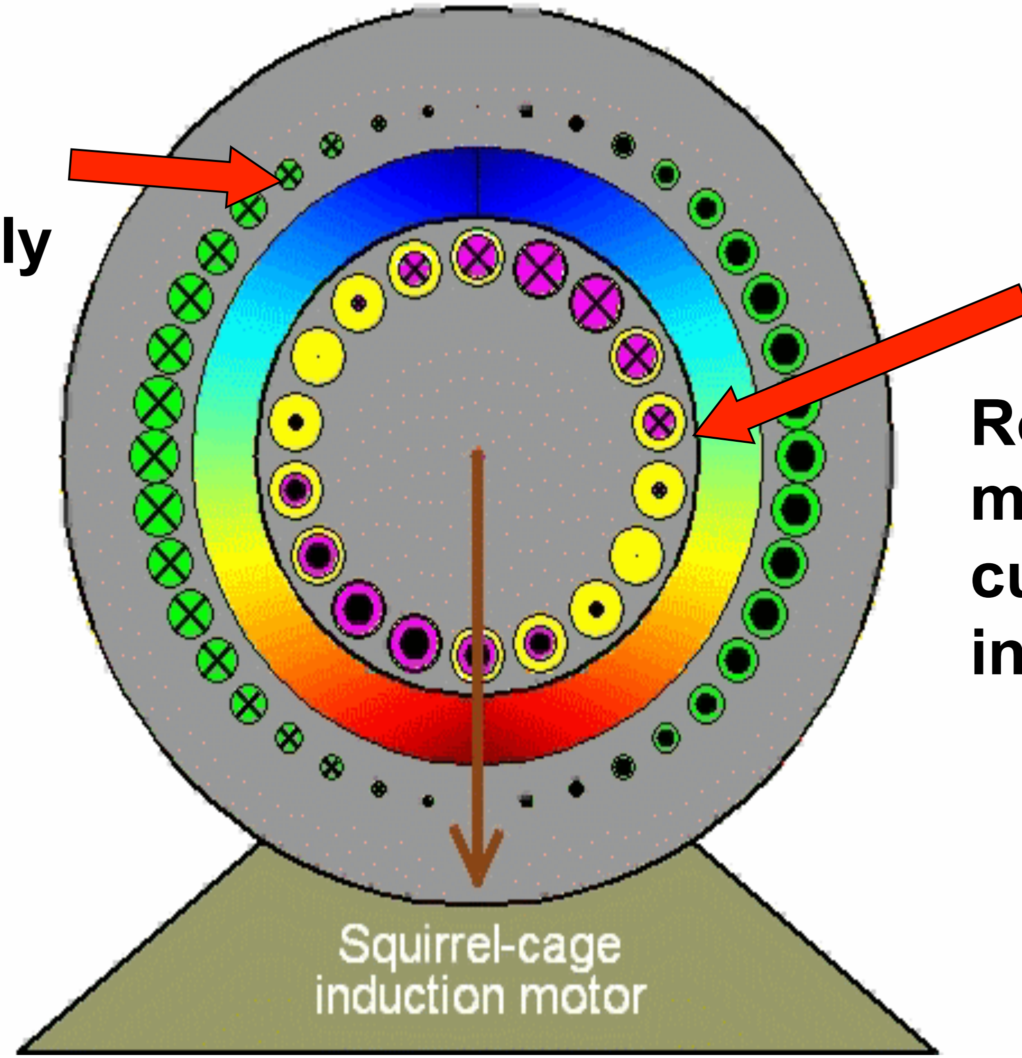
Notice the slip rings



Induced current animation

Field rotates synchronously with supply frequency

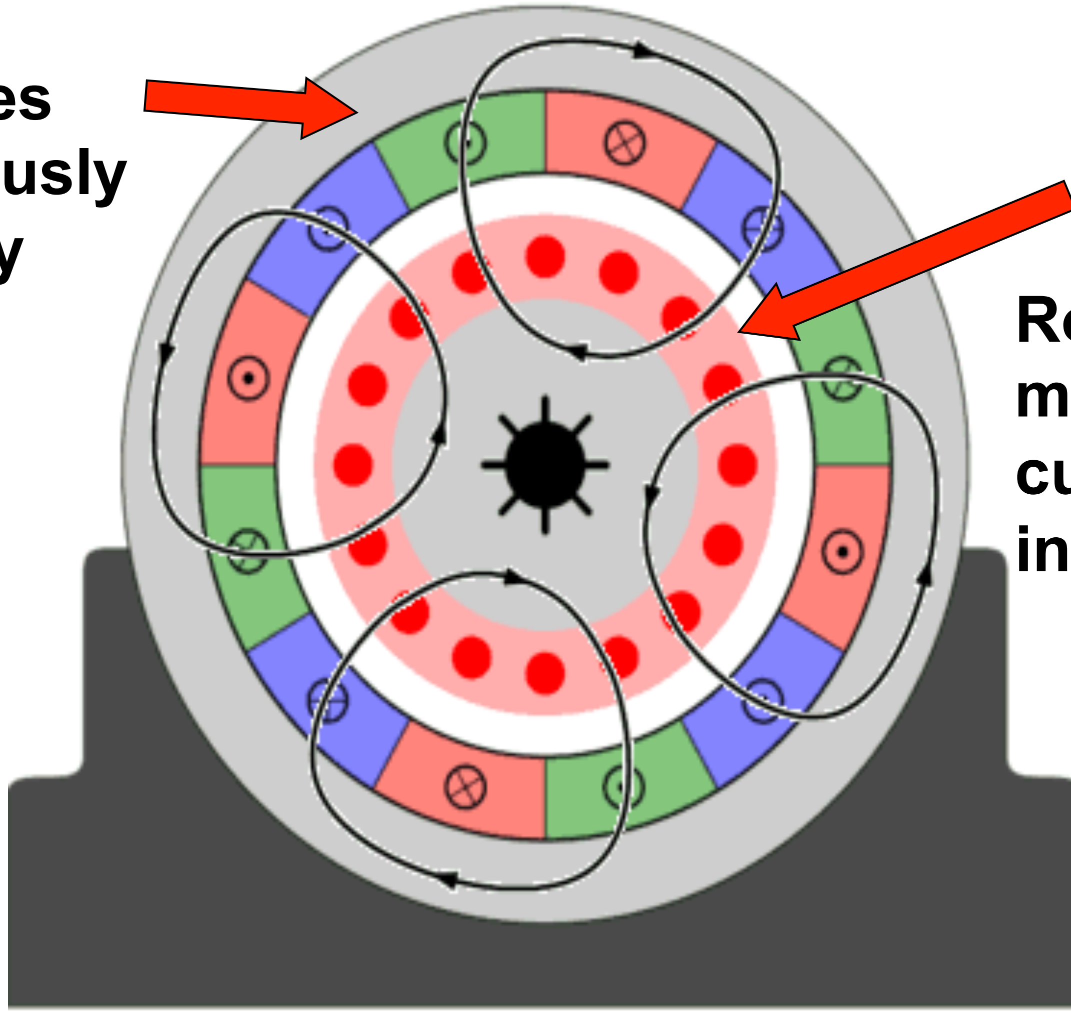
Rotor rotates more slowly so current induced into it



2-pole stator

Rotating fields causes rotor to rotate

Field rotates synchronously with supply frequency



Rotor rotates more slowly so current induced into it

4-pole stator

Induction motor rotational speed

- Primary factors that affect running speed of an induction motor are the supply frequency and its number of pole
- Also the loading will affect running speed
- In no-load conditions it will approach synchronous speed
- At full rated load there will be some slip – which will be specified in the motor specifications

Synchronous speed (in RPM)

$$n_s = \frac{120 \times f}{poles}$$

Slip

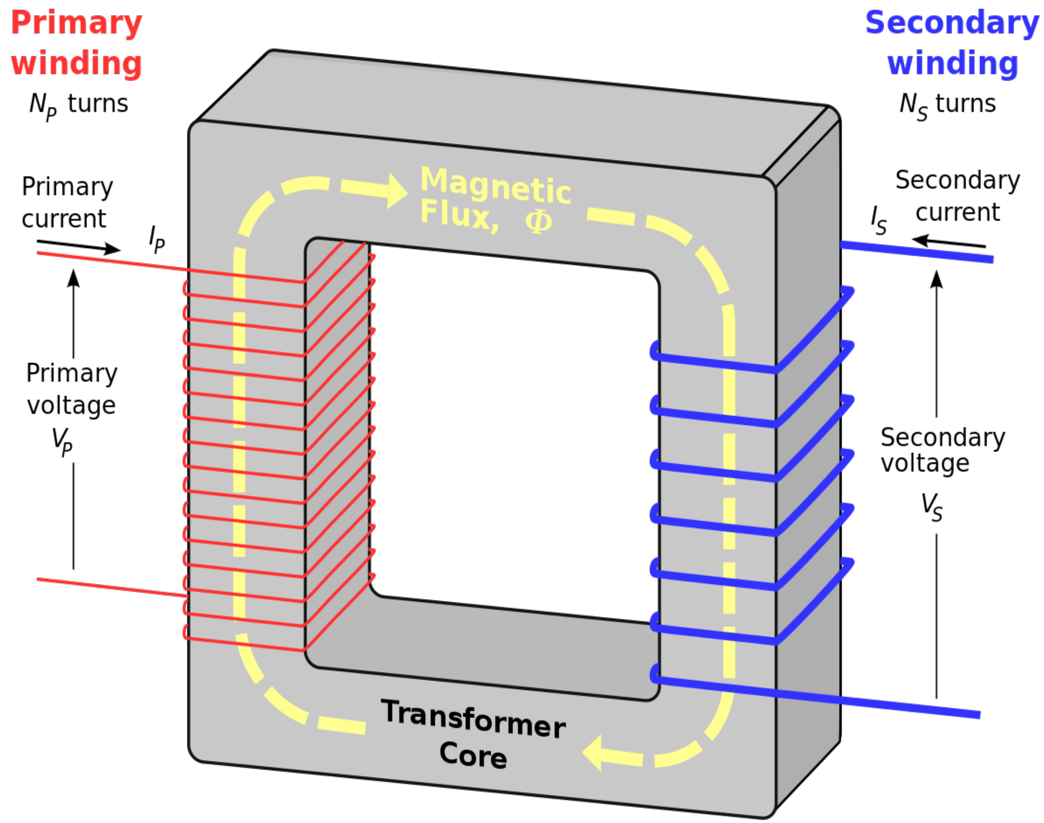
$$s = \frac{n_s - n_r}{n_s}$$

Where n_r is actual rotational speed in RPM

Induction motor synchronous speed (RPM)

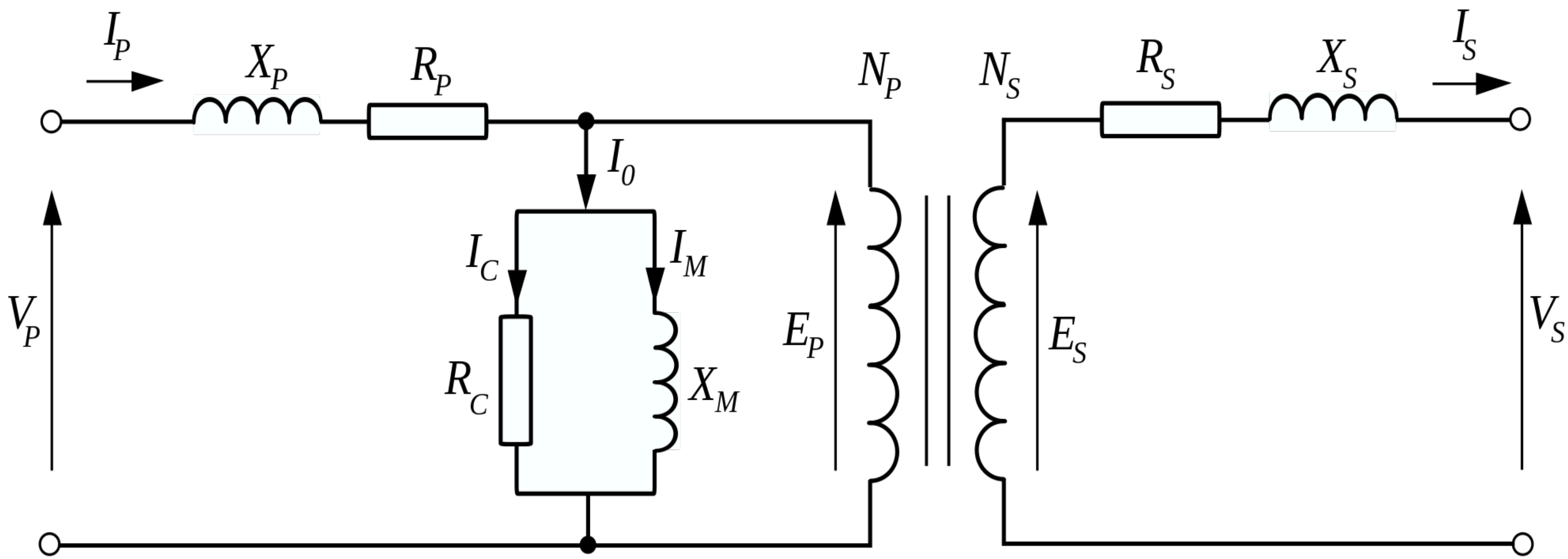
Poles	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

Compare with a transformer



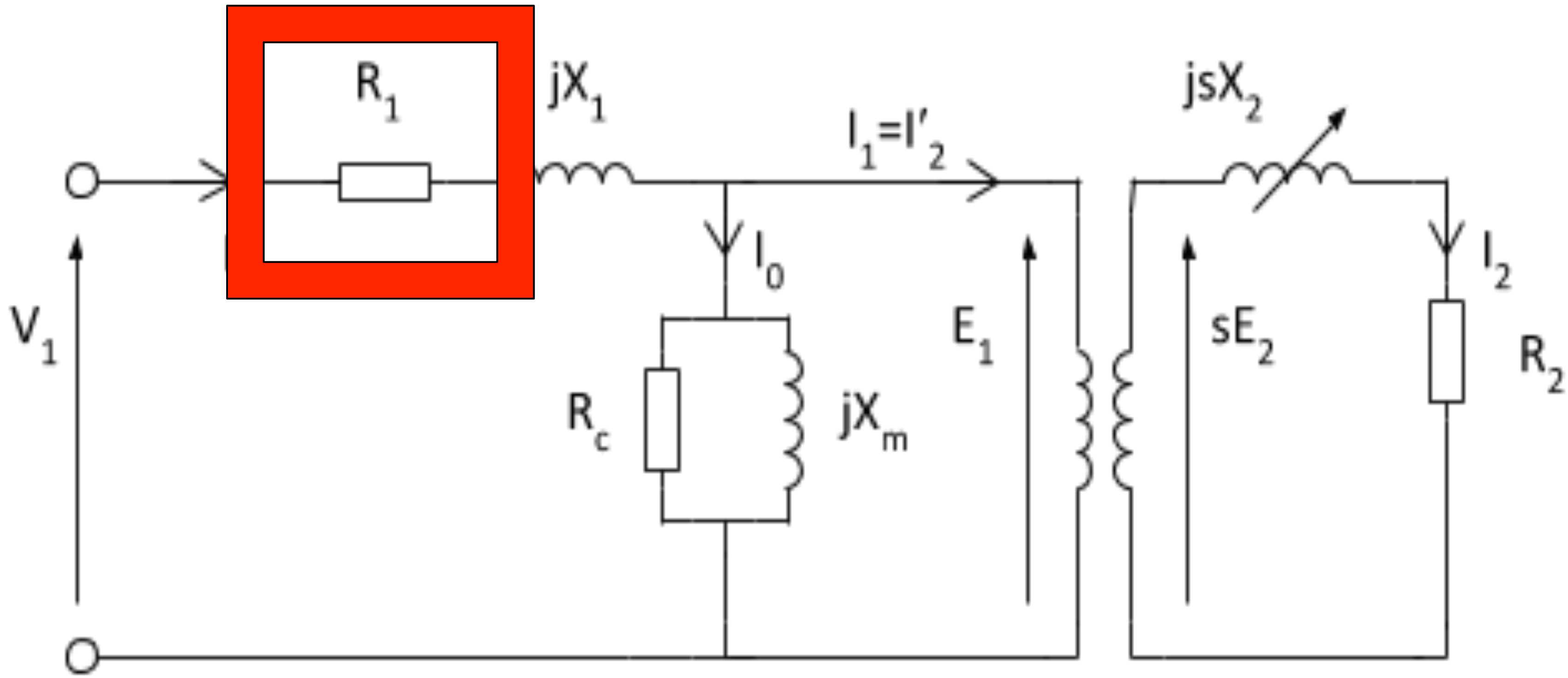
Secondary winding current $$I_s = I_{s_p}\left(\frac{N_p}{N_s}\right)$$

Transformer equivalent circuit



- Primary winding resistance R_P
- Primary leakage reactance X_P
- Secondary winding resistance R_S
- Secondary leakage reactance X_S
- Equivalent core loss resistance R_C and core loss current I_C
- Magnetising reactance X_M and magnetising current I_M
- No-load current I_0
- Primary and secondary EMF E_P and E_S, developed over an ideal transformer
- Primary and secondary terminal voltages and currents V_P, I_P, V_S and I_S

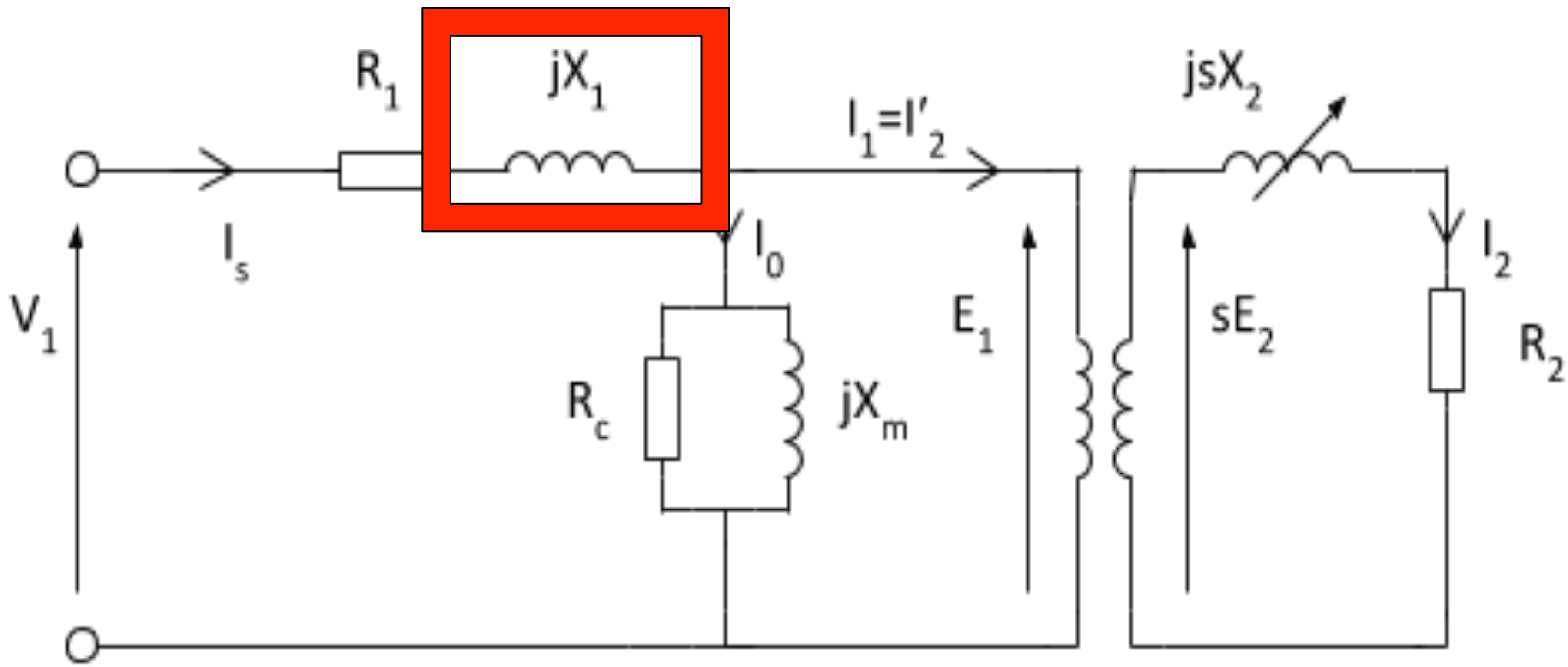
Induction motor equivalent circuit



In the equivalent circuit

- R_1 represents, the resistance of the stator winding

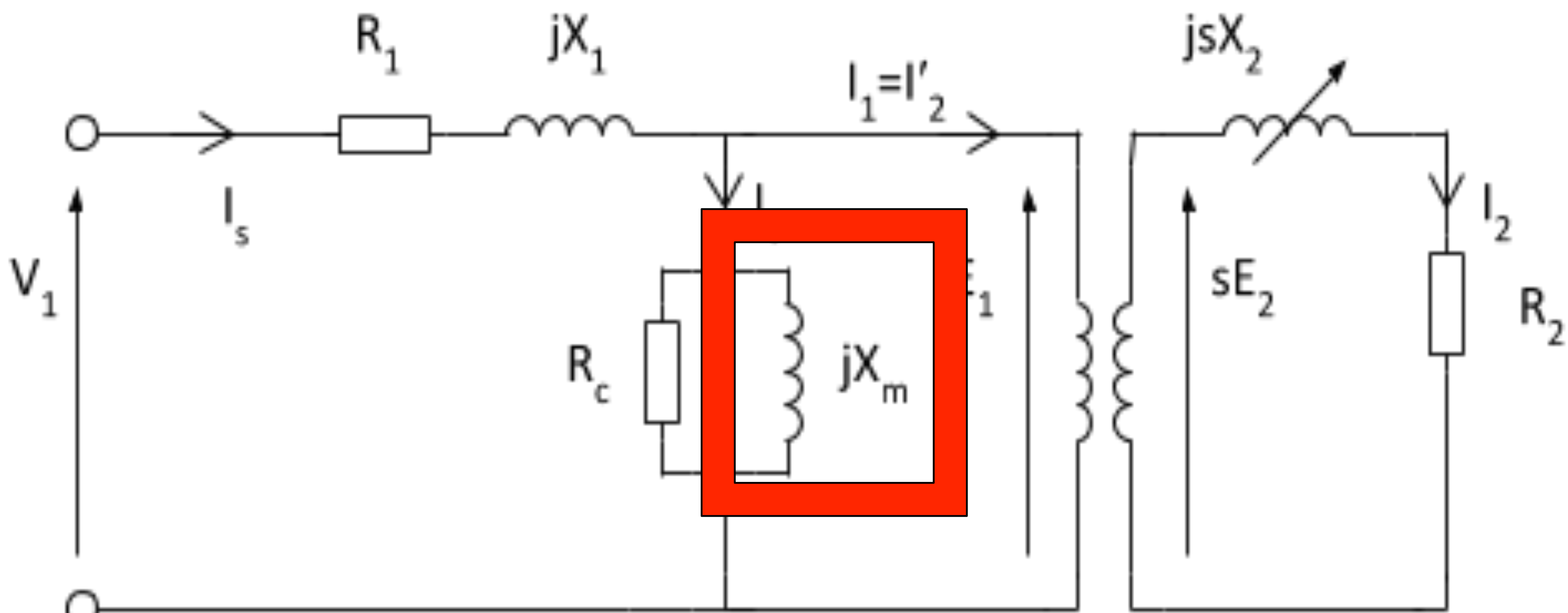
Induction motor equivalent circuit



In the equivalent circuit

- R_1 represents, the resistance of the stator winding
- X_1 the stator leakage reactance (flux that does not link with the air gap and rotor)

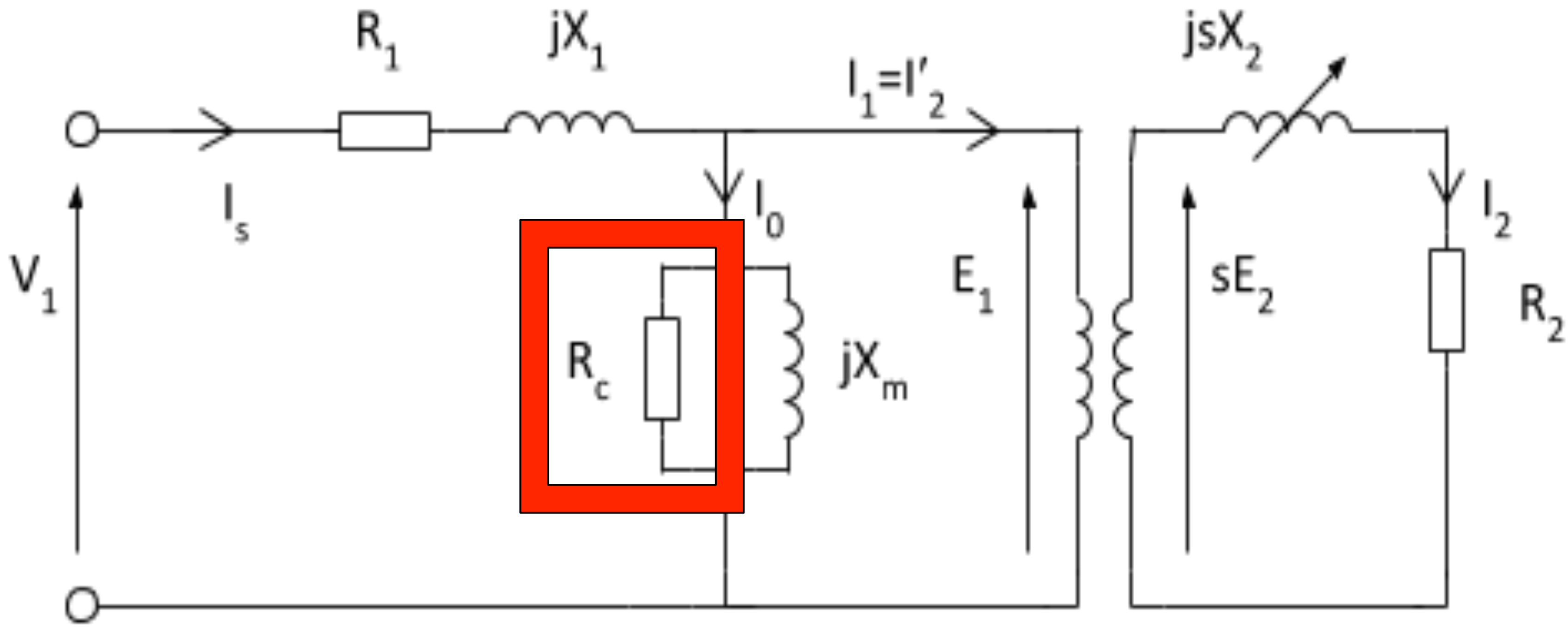
Induction motor equivalent circuit



In the equivalent circuit

- R_1 represents, the resistance of the stator winding
- X_1 the stator leakage reactance (flux that does not link with the air gap and rotor)
- Magnetizing reactance required to cross the air gap is represented by X_m

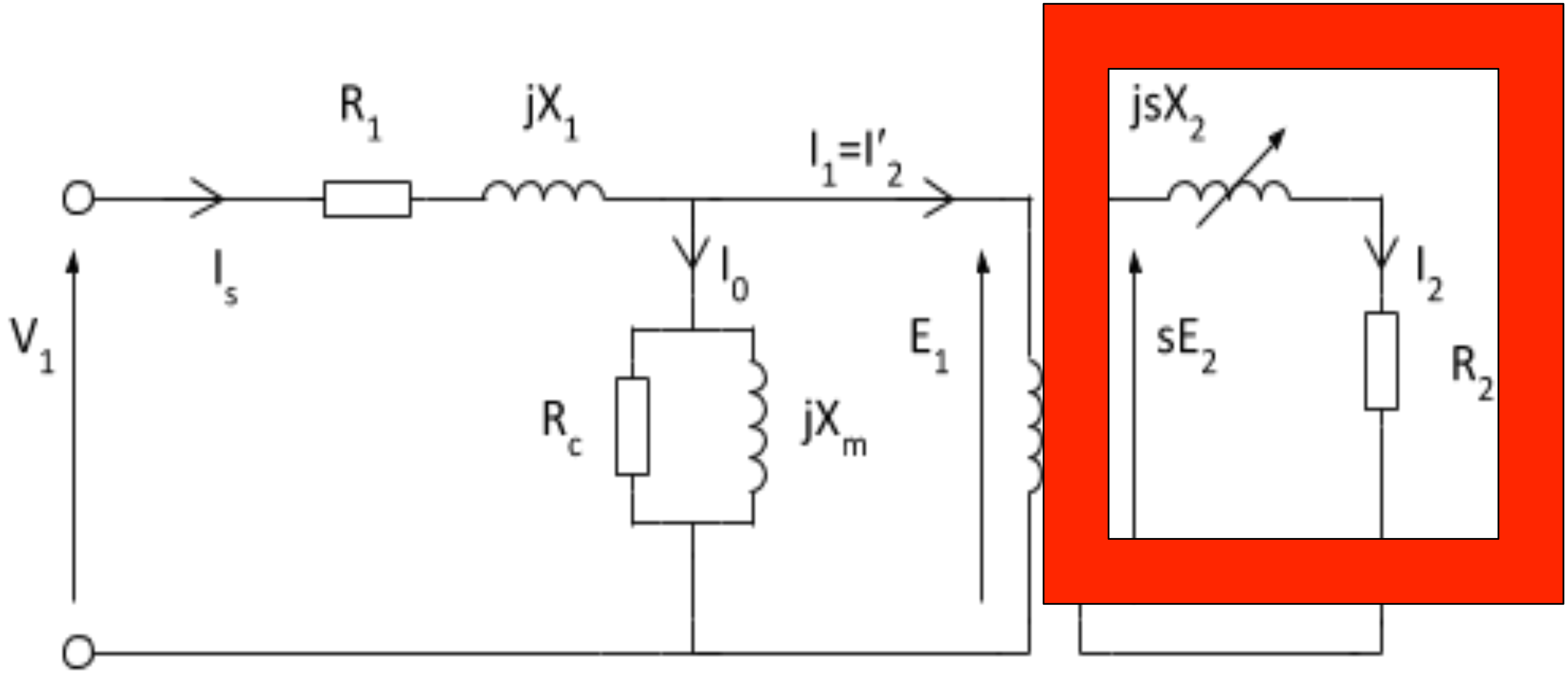
Induction motor equivalent circuit



In the equivalent circuit

- R_1 represents, the resistance of the stator winding
- X_1 the stator leakage reactance (flux that does not link with the air gap and rotor)
- Magnetizing reactance required to cross the air gap is represented by X_m
- Core losses (hysteresis and eddy current) by R_c

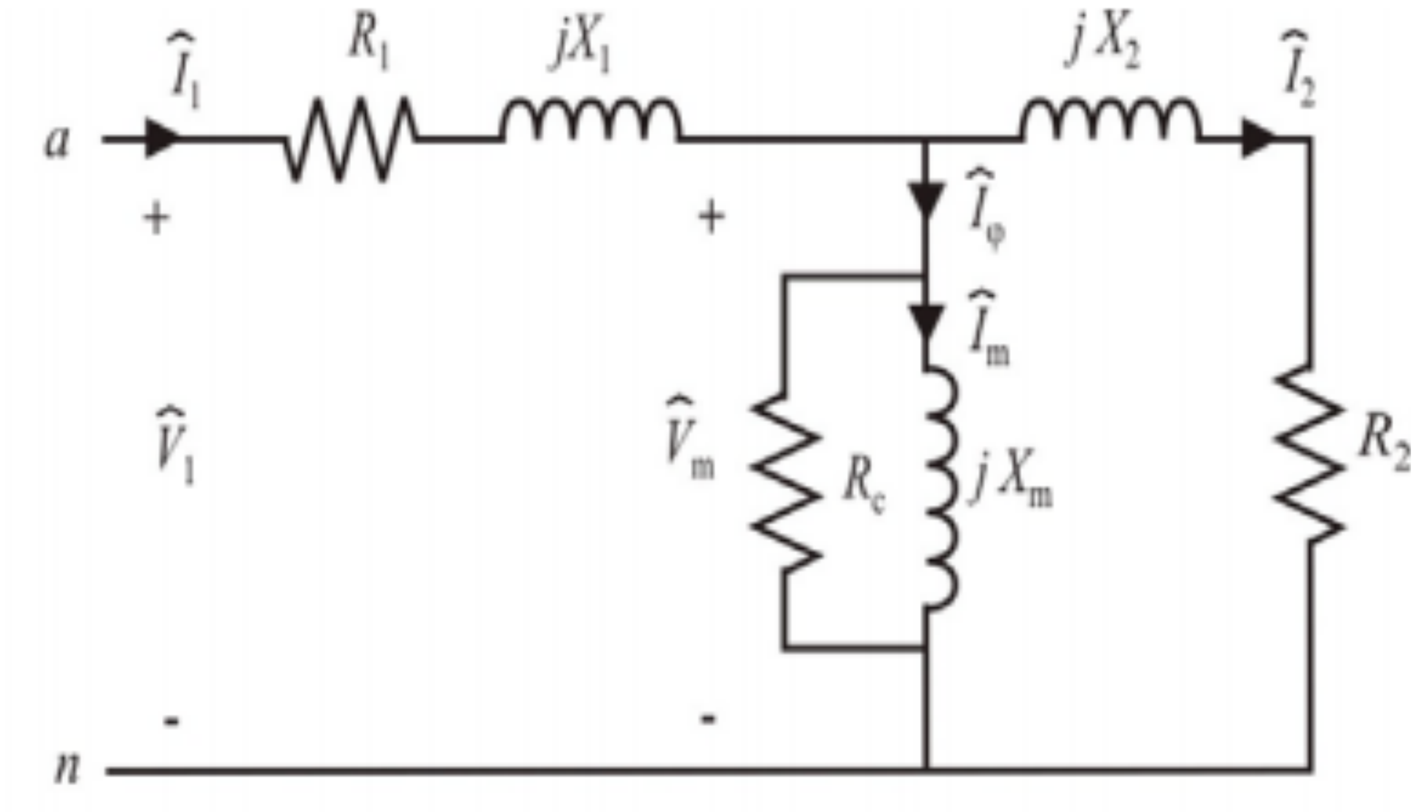
Induction motor equivalent circuit



- An ideal transformer of N_1 and N_2 turns respectively represents the air gap
- For the rotor side, the induced EMF is affected by the slip
- As the rotor gains speed, slip reduces and less EMF is induced
- The rotor resistance and reactance are represented by R_2 and X_2; with X_2 being dependent on the frequency of the inductor rotor EMF

Induction motor equivalent circuit

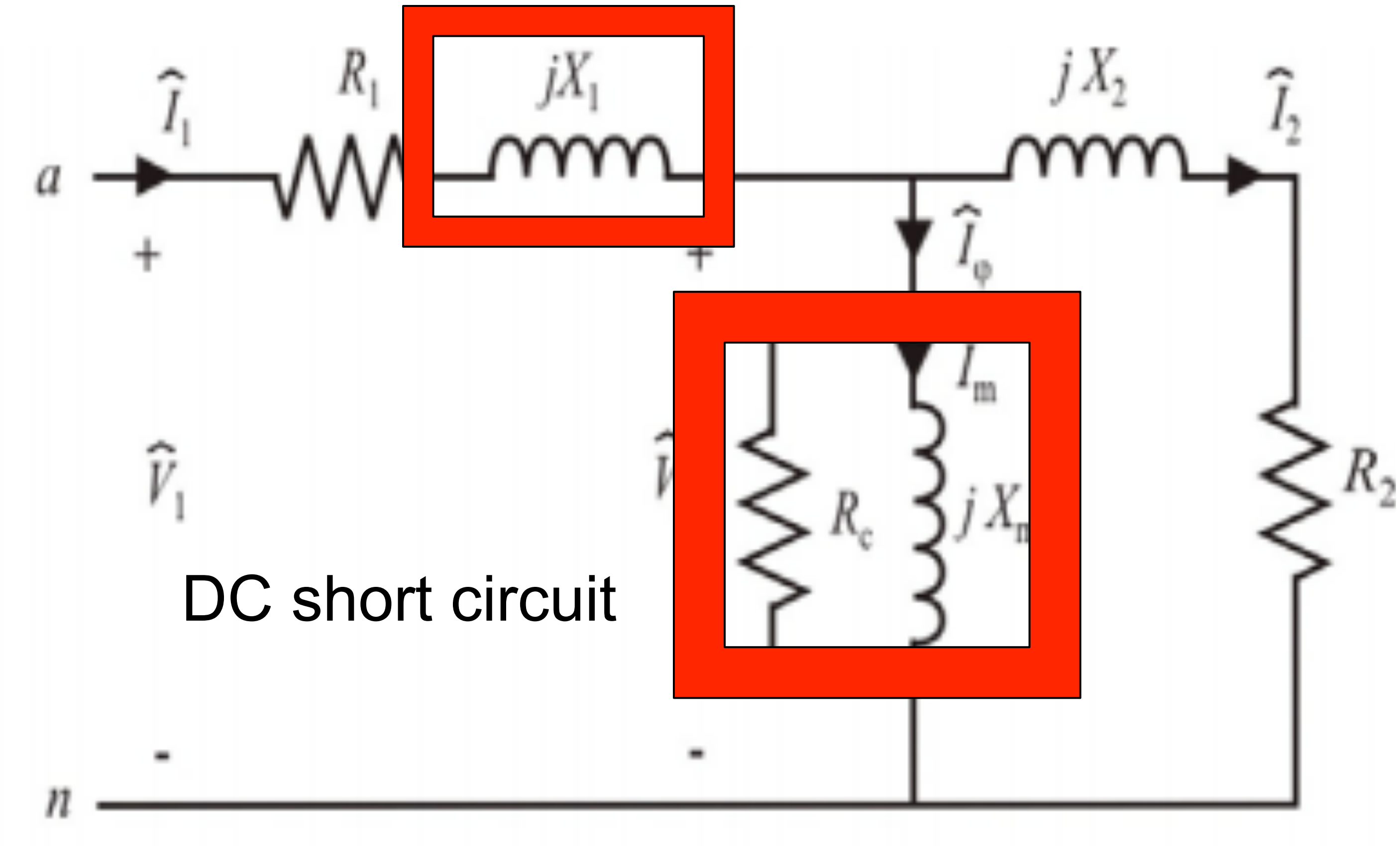
- Circuit can be drawn without transformer as shown below
- How can we determine parameters?



DC resistance measurement

- With DC measurements:

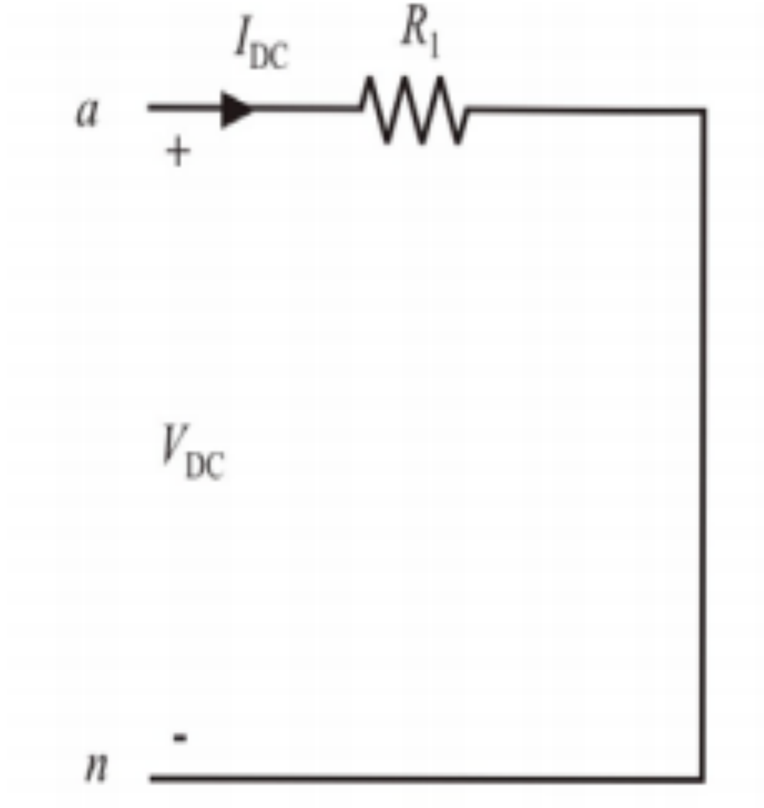
DC short circuit



DC short circuit

DC resistance measurement

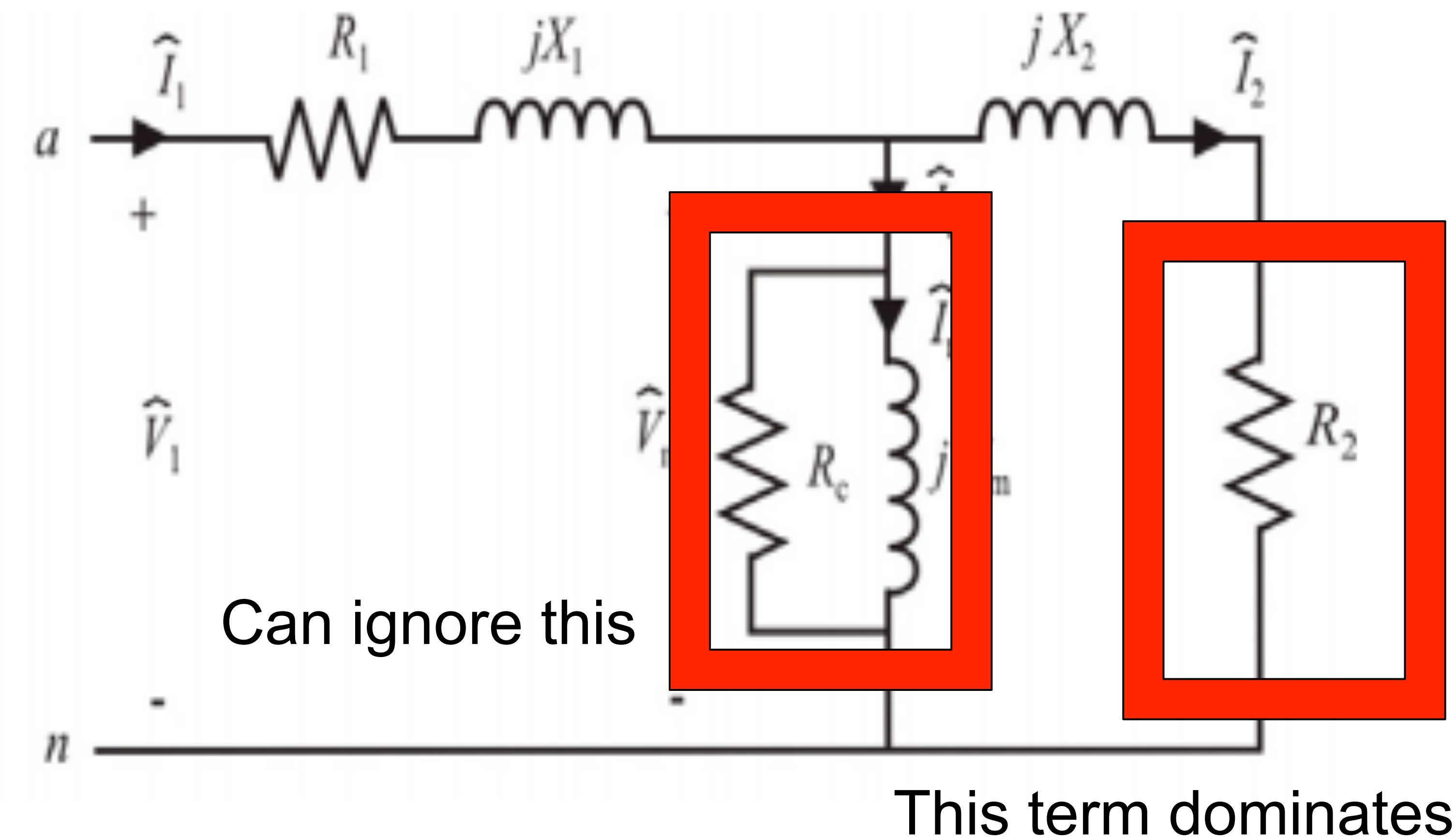
- So DC circuit simplified to



- Can directly measure the stator DC resistance R_1

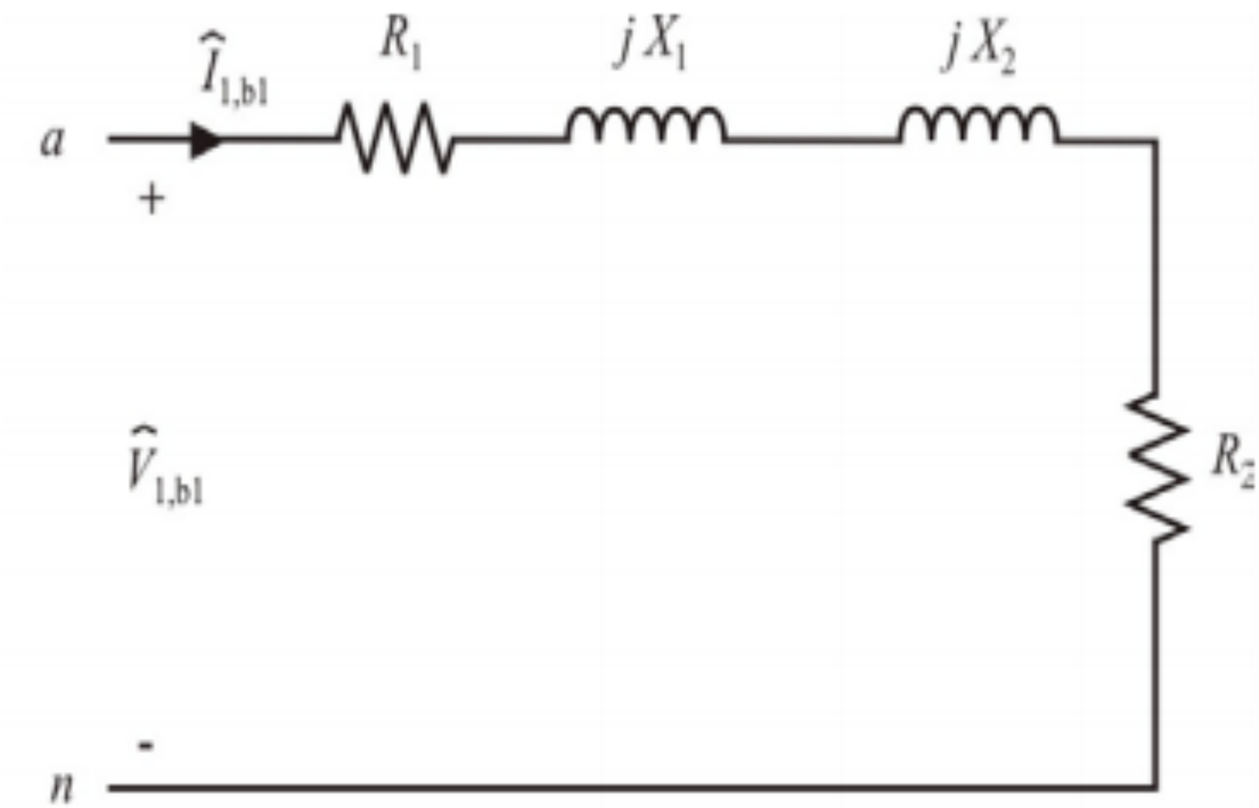
Blocked rotor condition

- Clamp rotor to prevent rotation
- Mechanical speed ω_m is then zero so slip is unity.
- Rotor impedance Z_2 now much smaller than magnetizing impedance Z_m.
- Magnetizing impedance can be neglected



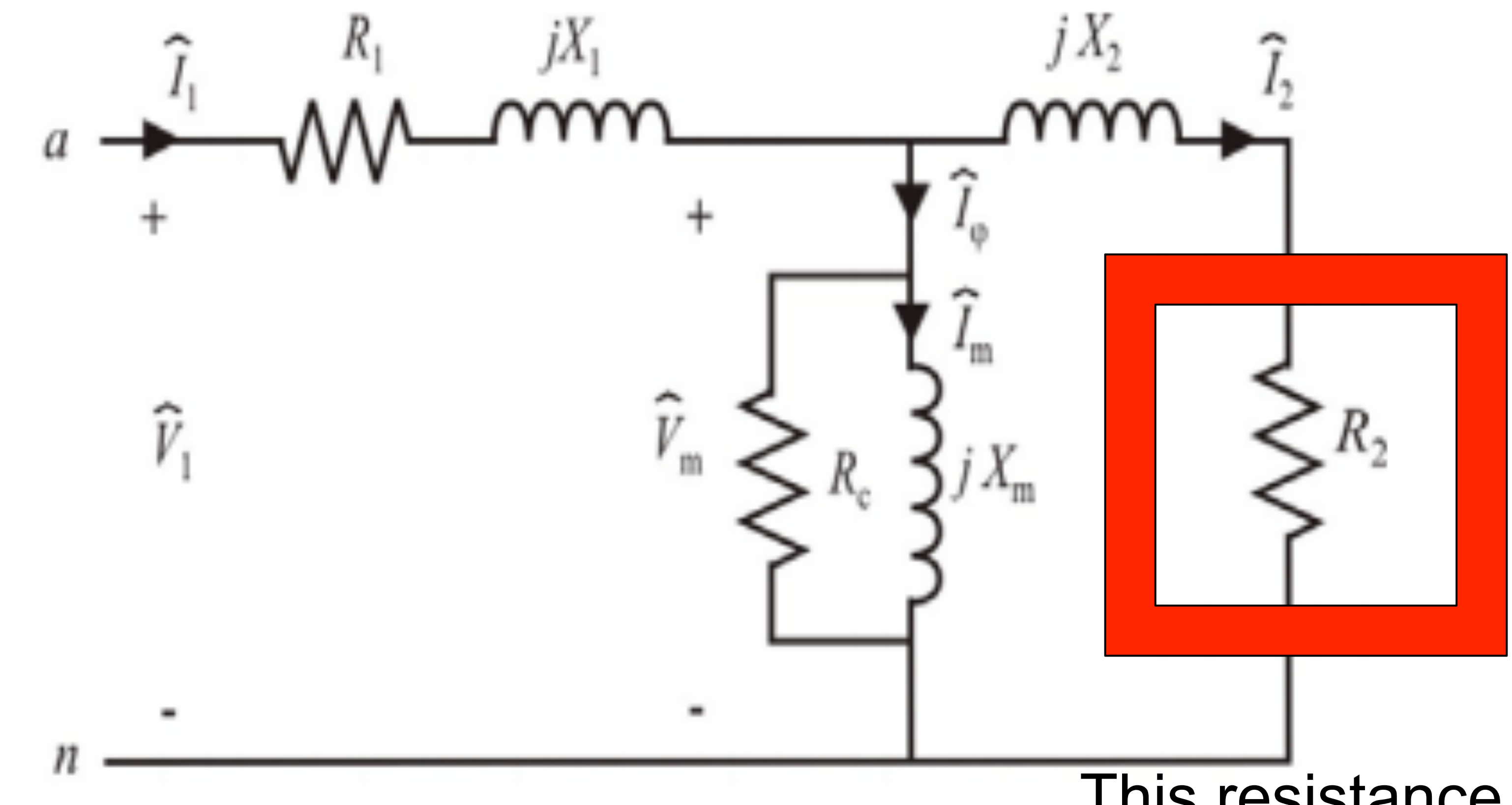
Blocked rotor condition

- So blocked rotor circuit simplified to:



No load condition

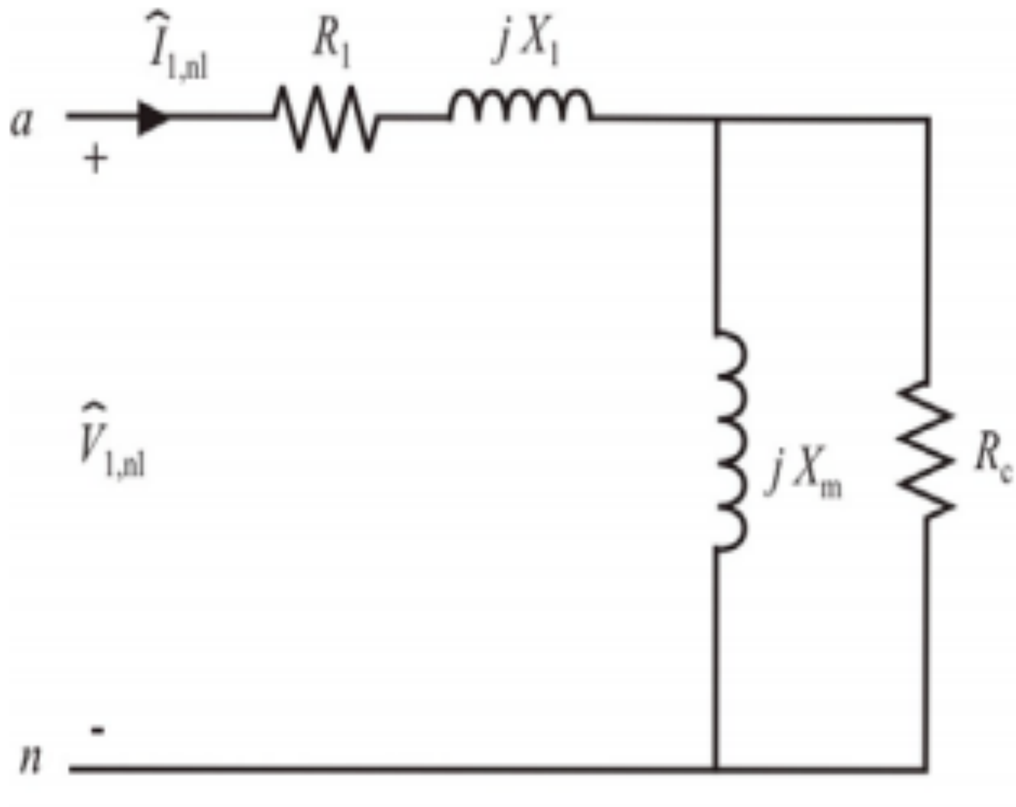
- Motor is operating at rated voltage without a load
- Mechanical speed is close to synchronous and the slip goes towards zero
- Rotor impedance goes towards infinity



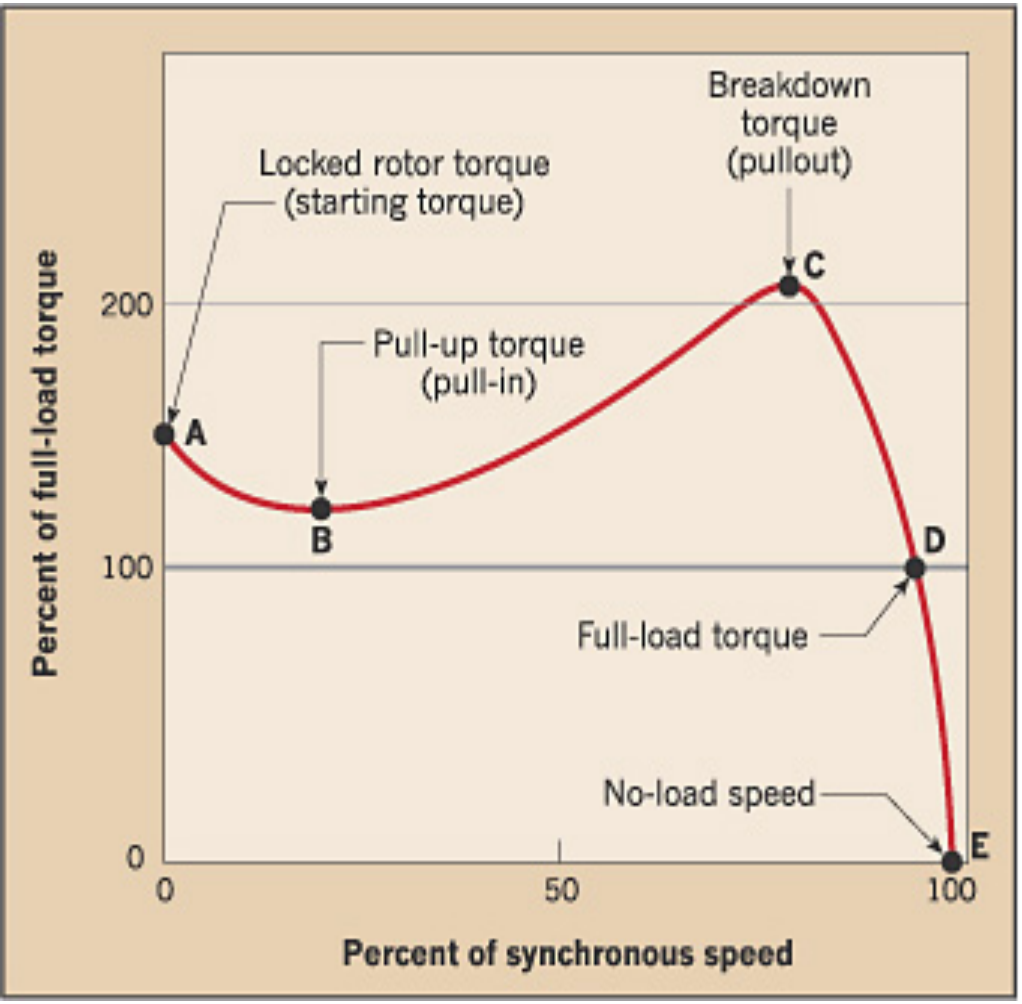
This resistance goes to infinity

No load condition

- So no load rotor circuit simplified to:



Induction motor torque



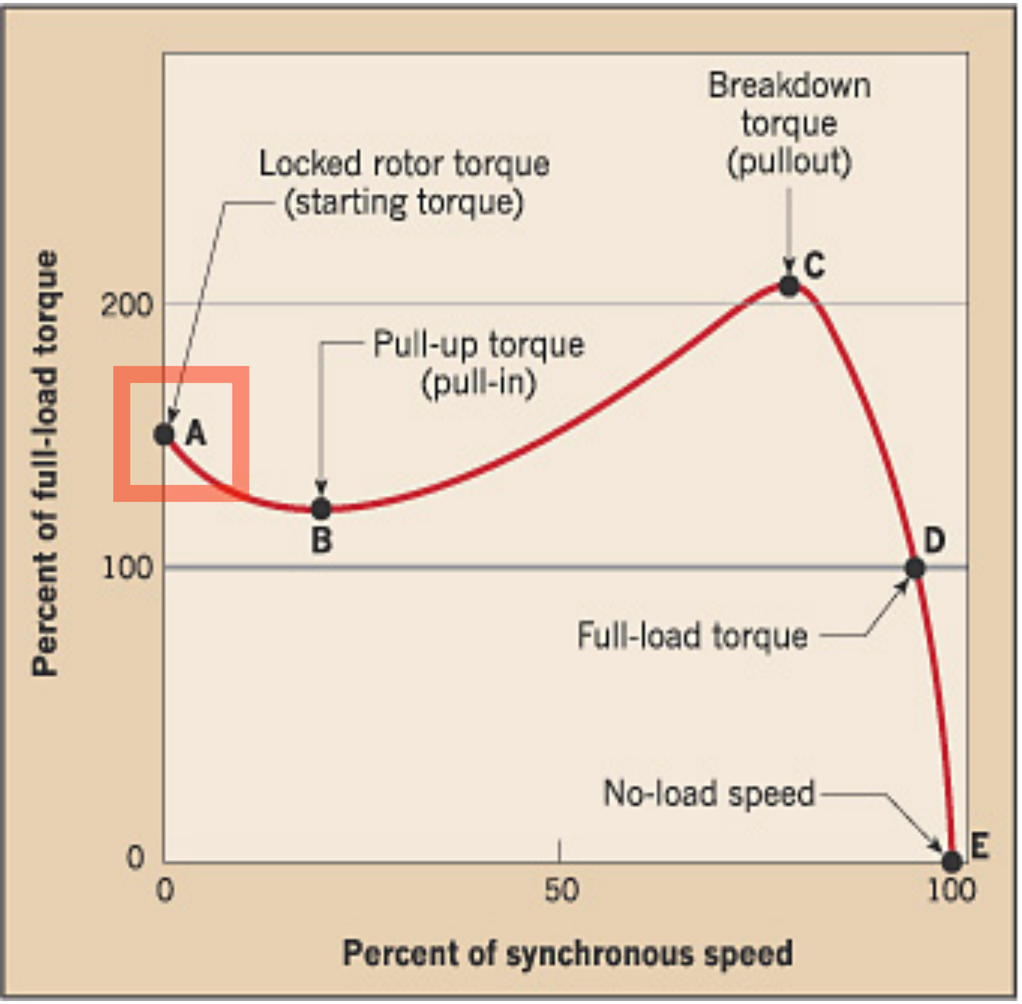
Asynchronous motor characteristic

- The torque characteristic of induction motor is quite complex compared to that of DC motor

Plot shows:

- Percent of synchronous speed on the x-axis
- Percent of full load torque on the y-axis
- We now consider some important points on the characteristic curve

Induction motor torque

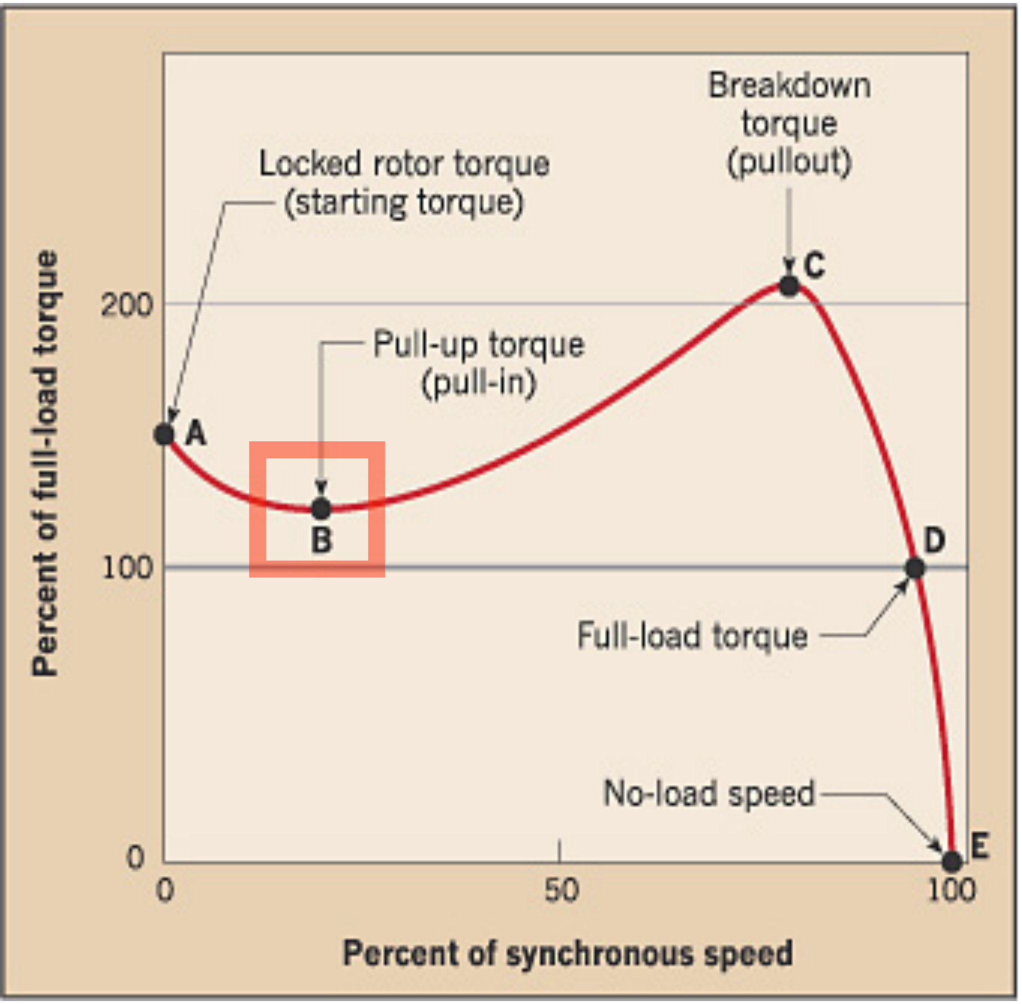


Asynchronous motor characteristic

A. Locked Rotor or Starting Torque

- The torque the electrical motor develop when its starts at rest or zero speed.
- A high Starting Torque is more important for application or machines that are hard to start
- E.g. good for positive displacement pumps, cranes etc.
- A lower Starting Torque can be accepted in applications as centrifugal fans or pumps where the start load is low or close to zero

Induction motor torque

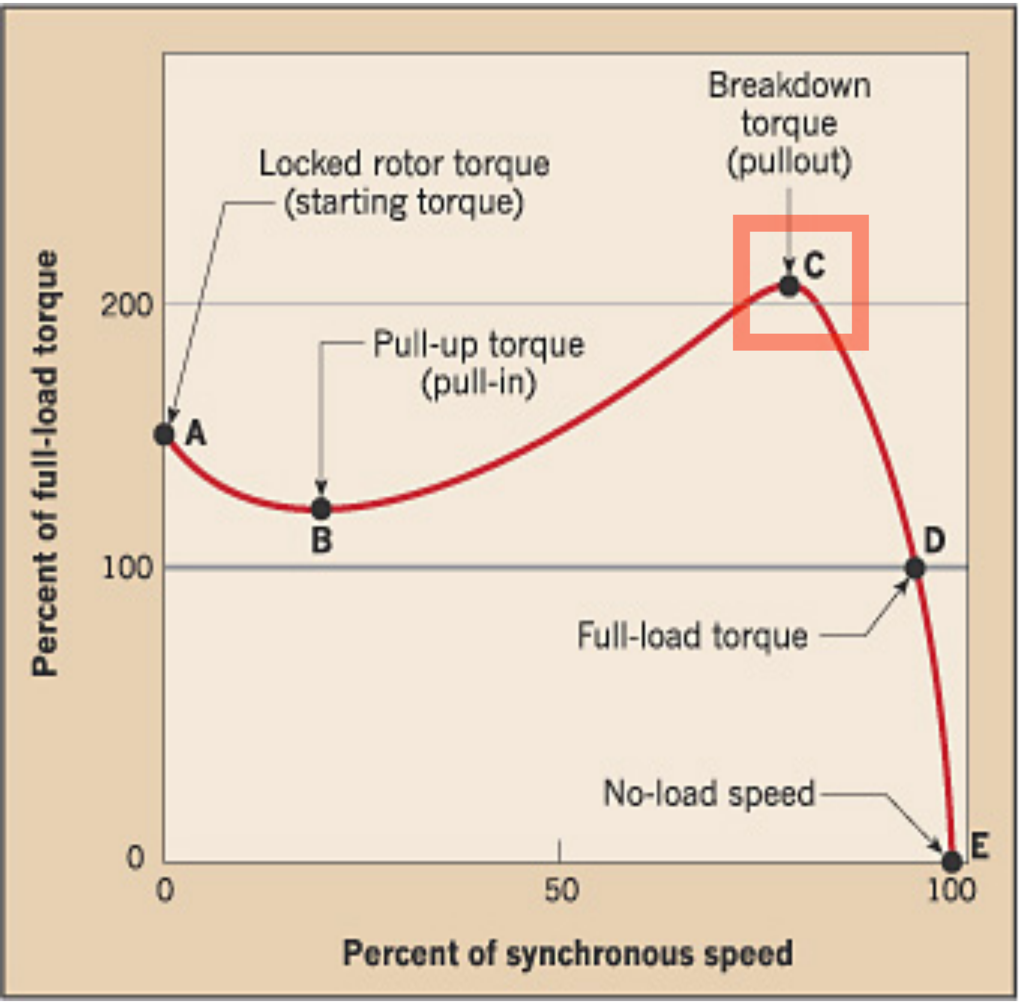


Asynchronous motor characteristic

B. Pull-up torque

- The minimum torque developed by the electrical motor when it runs from zero to full-load speed (before it reaches the break-down torque point)
- When the motor starts and begins to accelerate the torque in general decrease until it reach a low point at a certain speed - the pull-up torque - before the torque increases again
- The pull-up torque may be critical for applications that needs power to go through some temporary barriers achieving the working conditions

Induction motor torque

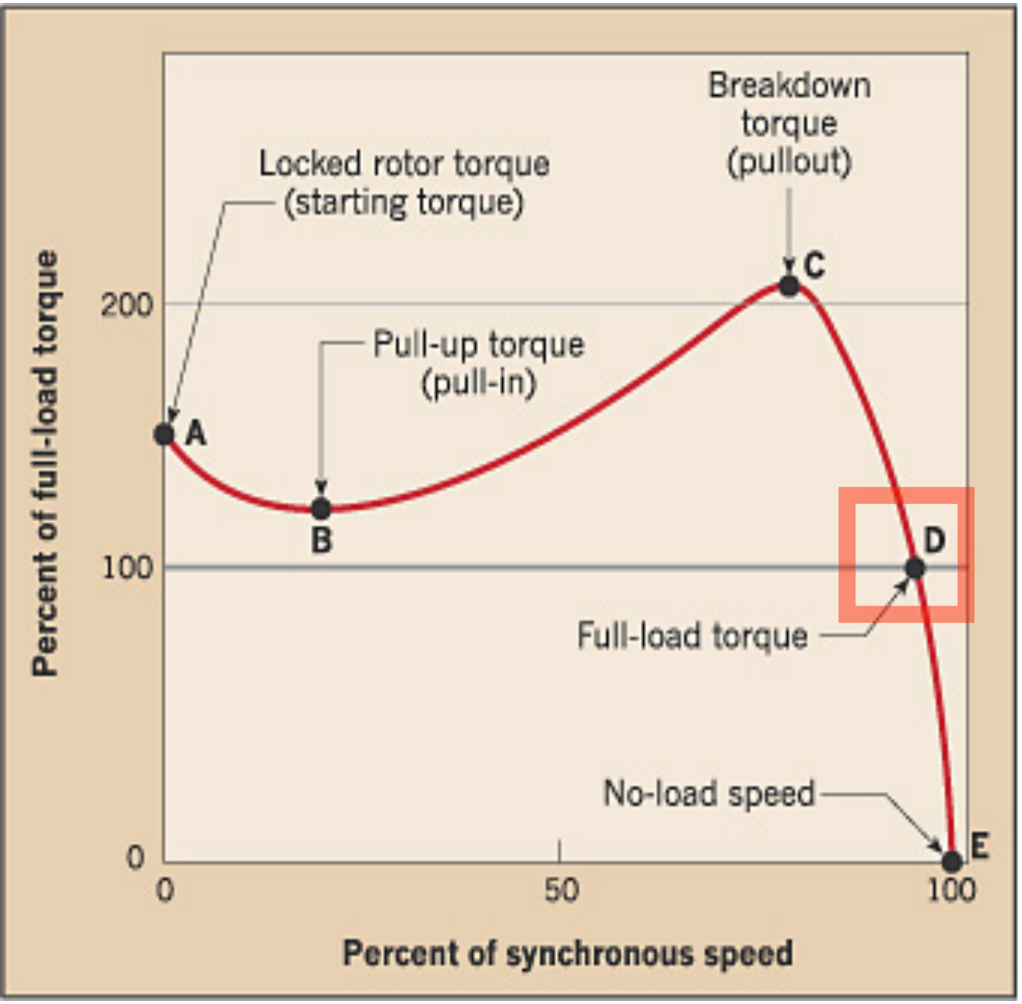


Asynchronous motor characteristic

C. Break-down torque

- Highest torque available as the torque decreases when the machine continues to accelerate to the working conditions.

Induction motor torque

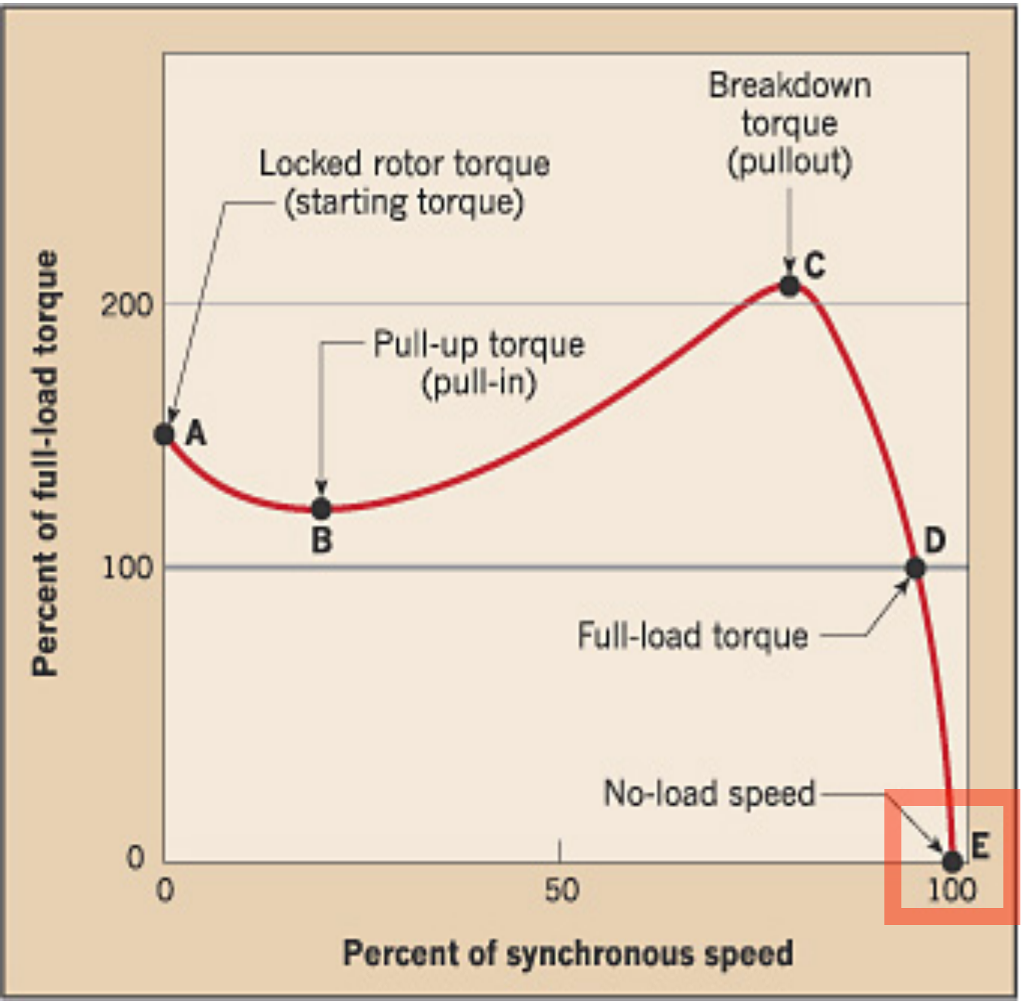


Asynchronous motor characteristic

D. Full-load (Rated) Torque or Braking Torque

- The Full-load Torque is the torque required to produce the rated power of the electrical motor at full-load speed.

Induction motor torque



Asynchronous motor characteristic

E. No-load speed

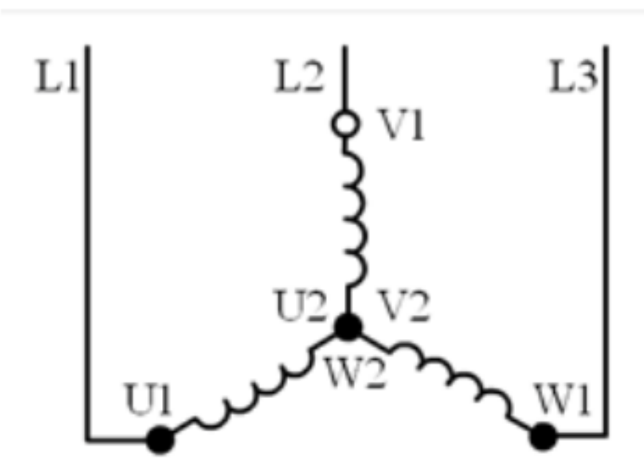
- Speed reached when no load is present
- Essentially reaches synchronous speed

Starting 3 phase induction motors

Induction motor staring currents can be very high.
Solution is to:

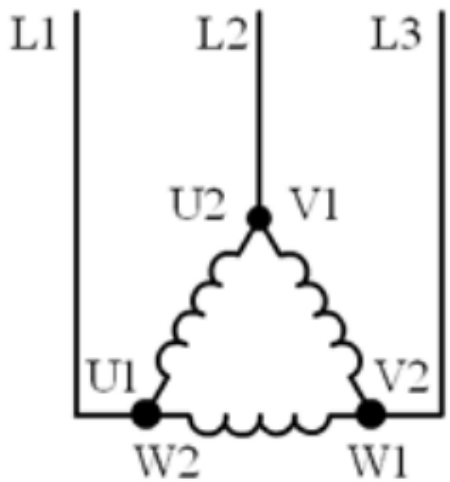
- Start the motor in star connection
- When the motor has gained sufficient speed the change connections to delta connection!

STAR



- Start connection leads to full supply voltage across two coils

DELTA



- Delta connection leads to full supply voltage across each coil

Starter devices are commercially available

Choosing an induction motor

- Decide on
- 1 or 3 phase
- Power output
- Rotational speed (2 or 4 pole)
- Continuous or intermittent
- Physical motor size
- Etc.

Our top quality range of single and 3 phase motors are ideal for reliable long term use.

- Full range of single and 3 phase up to 20hp
- Manufactured to the latest electrical and mechanical standards including IEC34-1, BS5000, CEN, HD231 & IEC72.
- All models are totally enclosed fan ventilated cage pattern metric type.

Technical Features

- Standard Keyway shaft.
- Foot mounting (B3).
- Permanent capacitors on single phase.
- Precision balanced rotor for vibration-free operation and extra long bearing life.
- Double shielded self-lubricating radial ball bearings.
- Stator windings have Class F insulation and are impregnated with Class H resin.

Available to Order

- Larger Sizes
- Other Voltages/Frequencies (HZ)
- 6/8 pole available in bulk only (minimum of 10)

Accessories

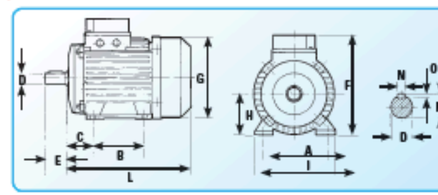
- Direct on line & automatic Star Delta starters
- Pulleys & belts

Great as replacement on Lathes, Drills, Woodworking Machinery, Air Compressors and a huge variety of Electric Driven Machines where performance and reliability are essential

Dimensions (mm) - 1 and 3 Phase

Frame Size	A	B	C	D	E	F	F**	G	H	I	L	L**	M	N	O
63	100	80	40	11	23	155	176	124	63	120	183	185	12.5	4	4
71	112	90	45	14	30	171	192	142	71	134	215	213	16	5	5
80	125	100	50	19	40	200	222	158	80	152	240	238	21.5	6	6
90 S	140	180	56	24	50	216	216	178	90	170	255	255	27	8	7
90 L	140	125	56	24	50	216	243	178	90	170	280	282	27	8	7
100 L	160	140	63	28	68	238	268	194	100	192	305	308	31	8	7
112 M	190	140	70	28	68	267	-	220	112	220	332	-	31	8	7
132 S	216	140	89	38	80	308	-	262	132	260	382	-	41	10	8
132 M	216	178	89	38	80	308	-	262	132	260	420	-	41	10	8

1 phase machines only **



Specification - 1 Phase

Hp	kW	Pole (speed)	Frame	Volts	Wt (kg)	Part No.
0.33	0.25	2 (3000)	63	230	4.6	6310203
0.75	0.55	2 (3000)	71	230	7.2	6310208
1.50	1.10	2 (3000)	80	230	10.3	6310214
2.00	1.50	2 (3000)	80	110	11.9	6310226
3.00	2.20	2 (3000)	90	110	16.8	6320228

Specification - 3 Phase

† 2 Pole = 3000 rpm & 4 Pole = 1500 rpm

Hp	kW	Pole (speed)†	Frame	Volts	Wt (kg)	Part No.
1.00	0.75	2 (3000)	80	400	8.3	6330210
1.00	0.75	4 (1500)	80	400	9.9	6330410
1.50	1.10	2 (3000)	80	400	9.6	6330215
1.50	1.10	4 (1500)	90	400	13.0	6330416
2.00	1.50	4 (1500)	90	400	15.0	6330420
3.00	2.20	4 (1500)	100	400	19.2	6330440
4.00	3.00	4 (1500)	100	400	21.5	6330450
5.50	4.00	4 (1500)	112	400	27.4	6330455
7.50	5.50	4 (1500)	112	400	32.0	6330475
10.0	7.50	4 (1500)	132	400	51.0	6340410
12.5	9.20	2 (3000)	132	400	47.0	6340300
12.5	9.20	4 (1500)	132	400	57.0	6340350
15.0	11.0	2 (3000)	132	400	53.0	6340216
20.0	15.0	2 (3000)	132	400	62.0	6340230

Star Delta, Direct On Line and Combined Pressure Switch/Starters Available See Page 22

ROCO222: Intro to sensors and actuators

Lecture 9

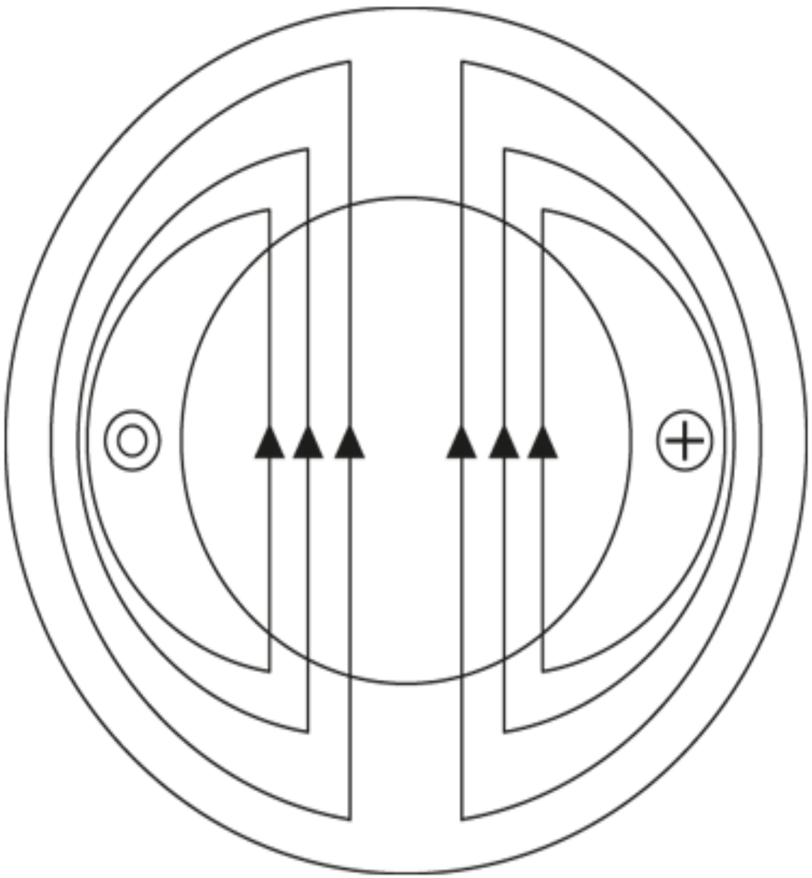
Single phase induction motors

Single phase induction motors

- Single-phase motors are used mostly to operate home appliances
- E.g air conditioners, refrigerators, pumps, and fans

- Designed to operate on 120 V or 240 V
- They range in capacity from fractional horsepower to several horsepower depending on the application

Single phase induction motor magnetic field

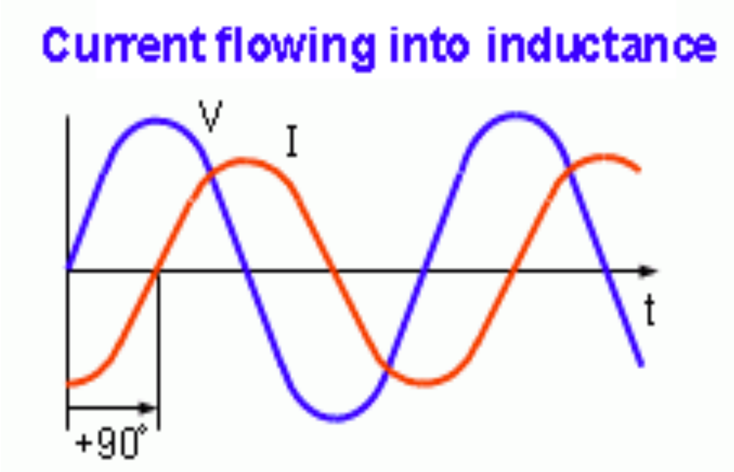


- A single phase field does not rotate
- However the field still changes sinusoidally with time
- Such a field can be considered as two counter rotating magnetic field phasors
- It turns out if rotor rotates, one rotating phasor will exert more torque on the rotor than the other
- Therefore if rotor already moving it will develop torque can be driven by the stator field
- Therefore motor will run if we can think of a way to get it started

Split phase induction motors

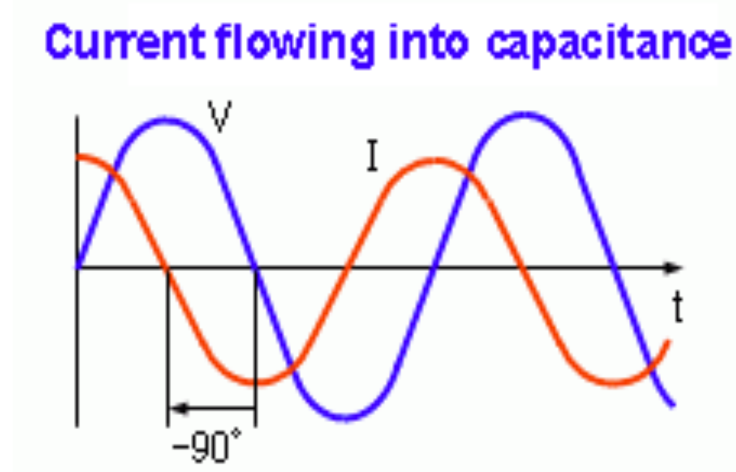
- To get an induction motor started need to setup a rotating field!
- A rotating magnetic field can be produced with a two-phase system
- Split phase induction motors split the current flow through two separate windings to simulate a two-phase power system
- Two phases can be produced by splitting a single phase
- There are two main types of split-phase motors depending on the means of starting

The resistance-start induction-run motor



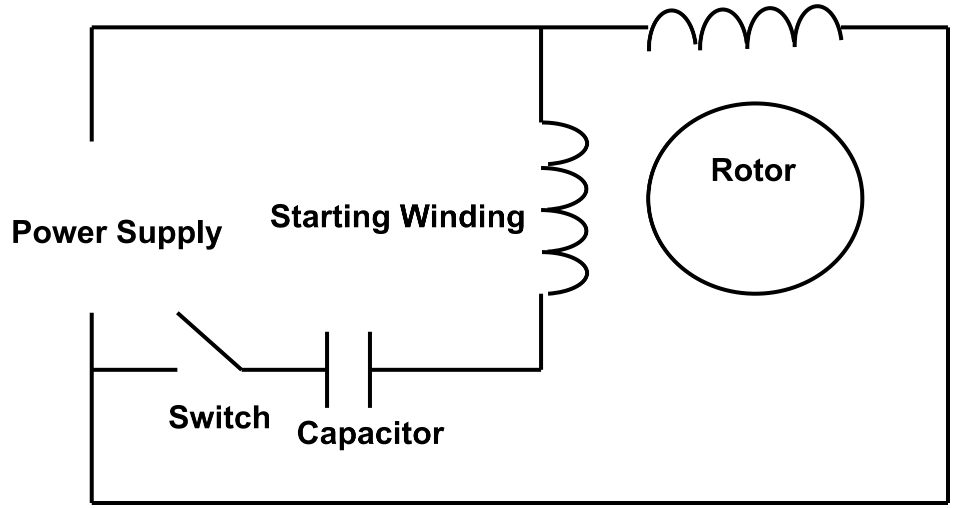
Inductance: Current lags applied voltage

The capacitor-start induction-run motor



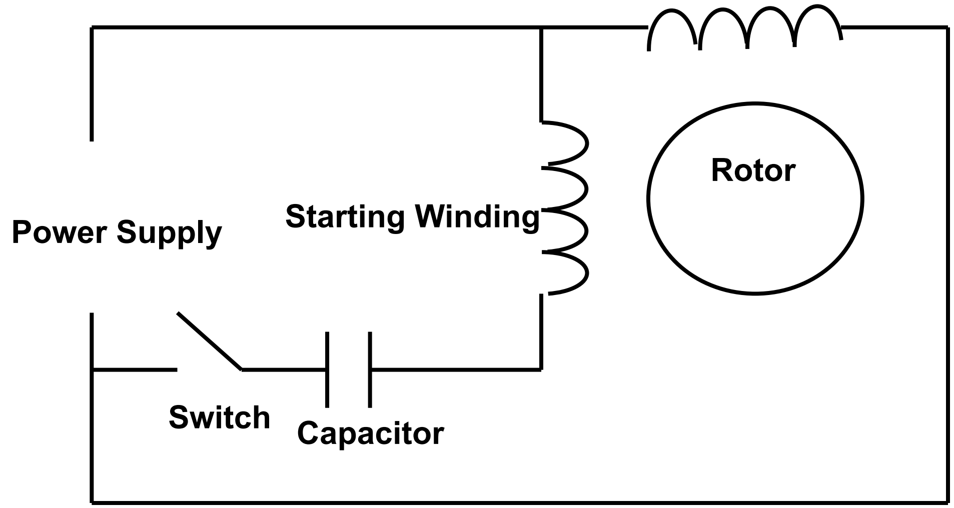
Capacitance: Current leads applied voltage

The capacitor-start induction motor



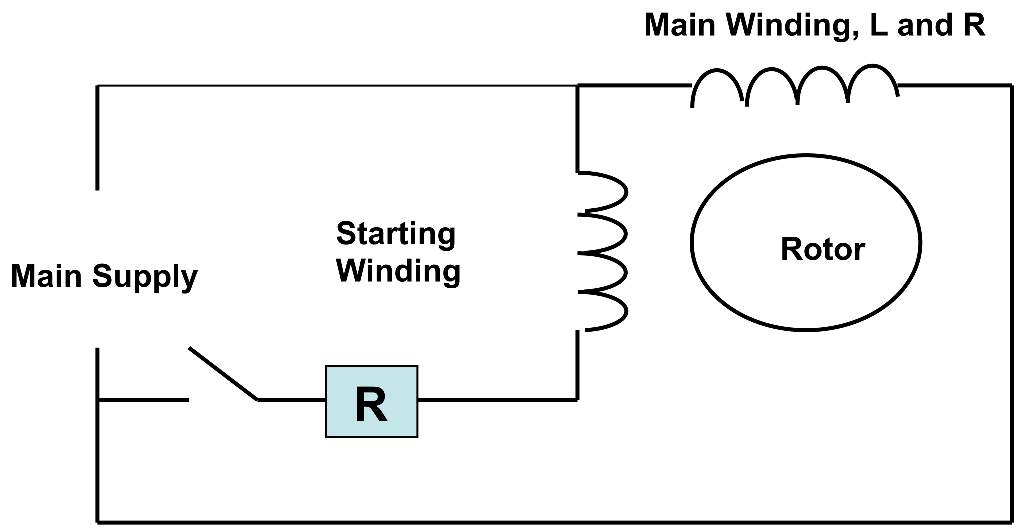
- The stator consists of the main winding and a starting winding
- The starting winding is connected in parallel with the main winding and is placed at right angles to it
- A 90-degree electrical phase difference between the two windings is obtained by connecting the auxiliary winding in series with a capacitor and a starting switch
- When the motor is energized, the starting switch is closed
- This places the capacitor in series with the auxiliary winding

The capacitor-start induction motor



- This gives an RC circuit (starting winding and the capacitor) and an RL circuit (main winding)
- The currents in each winding are therefore 90° out of phase, so are the magnetic fields that are generated
- When nearly full speed is obtained, a centrifugal device (the switch) can be used to cut-out the starting winding
- The motor then runs as a single-phase induction motor

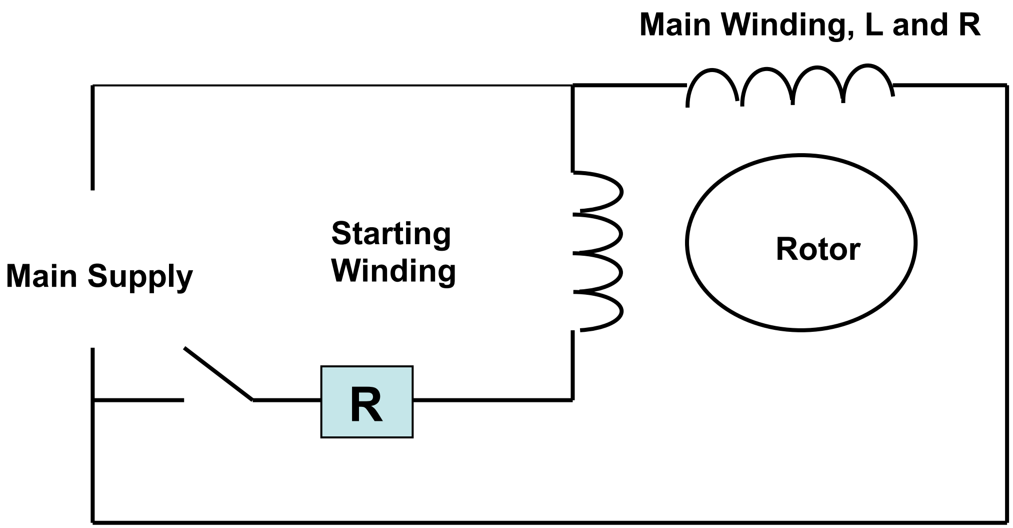
The resistance-start induction motor



The out-of-phase condition between start and run winding current is caused by the start winding having more resistance than the run winding. Specifically:

- The main winding has a high inductance and a low resistance.
- The current lags the voltage by a large angle
- The starting winding have a low inductance and a high resistance
- The current lags the voltage by a smaller angle

The resistance-start induction motor

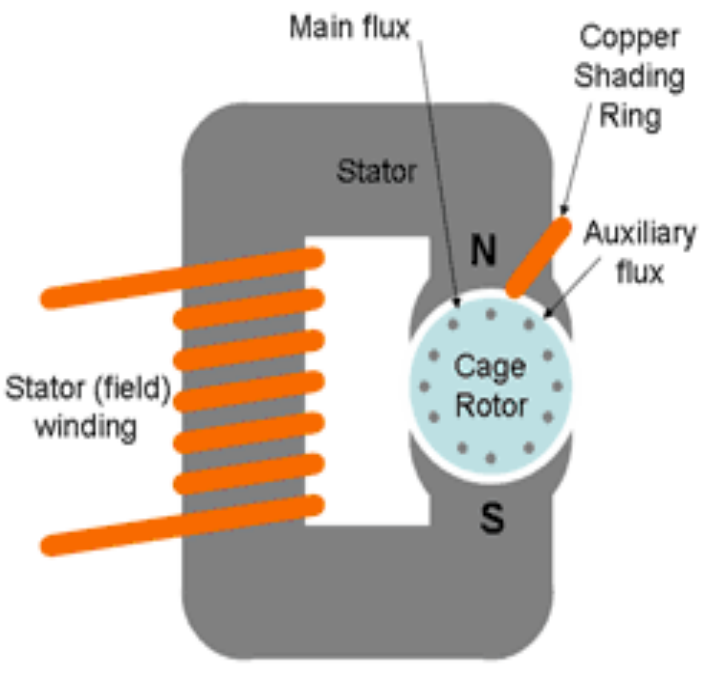


The amount of starting torque produced is determined by:

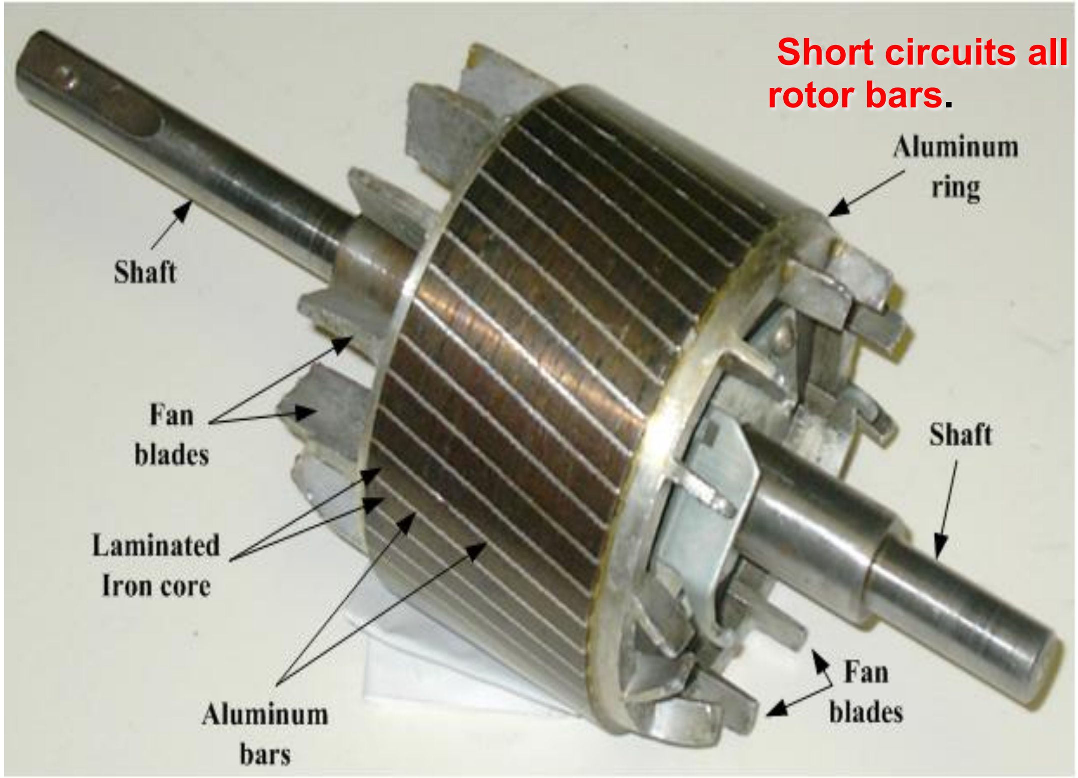
- The strength of the magnetic field of the stator
- The strength of the magnetic field of the rotor
- The phase angle difference between current in the start winding and current in the run winding (maximum torque is achieved when these two currents are 90° out of phase with each other)

Shaded pole induction motor

- Stator is made from a magnetically soft laminated core with a coil wound around it
- Rotor is generally made up of a squirrel cage rotors
- This has a magnetically soft laminated core with pure aluminum wires among its length that are shored at the ends

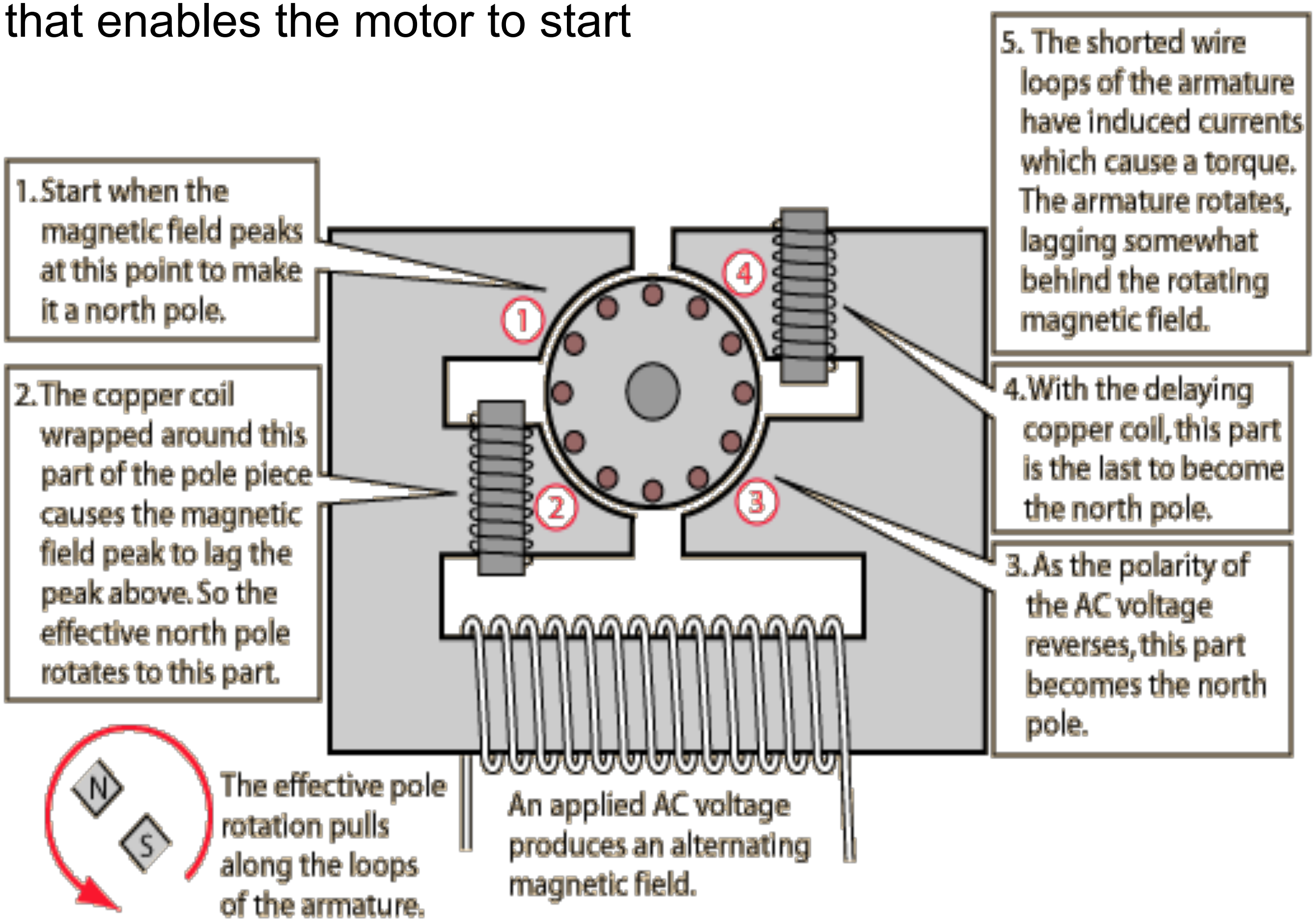


Shaded Pole Induction Motor



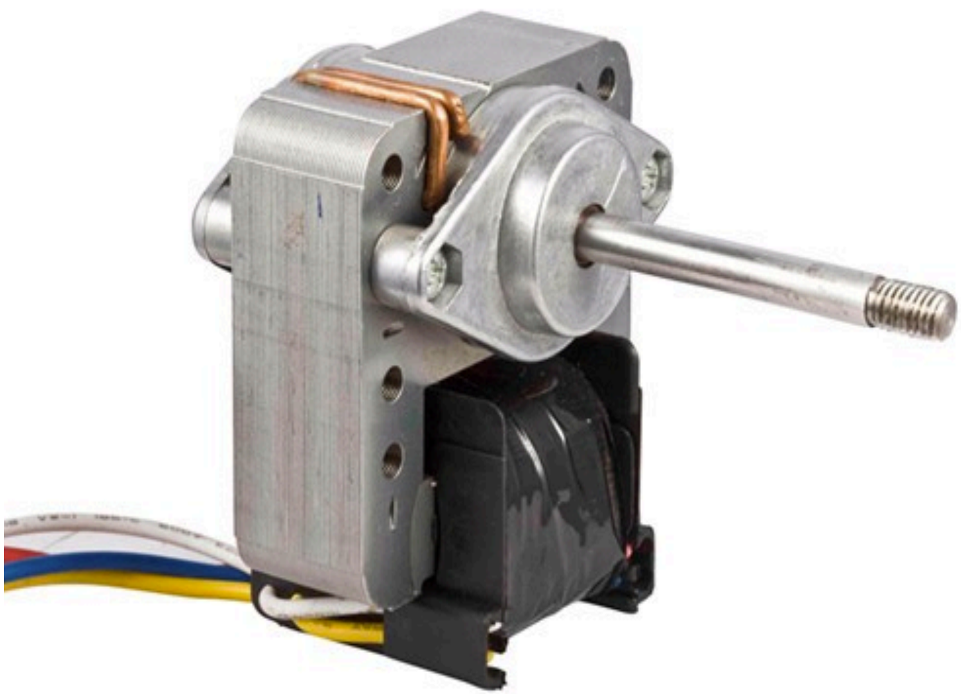
Shaded pole induction motor operation

- Induction motors need a rotating field to get them to start rotating
- AC single phase supply to coil generates a magnetic field that does not rotate but field changes sinusoidally and changes direction once per period
- Short circuit around end of pole sections (ht e shaded pole) cause a delay in build up of magnetic field at that point
- When combined with main flux path this gives rise to a weak rotating magnetic field at the poles that enables the motor to start



Shaded pole induction motor

- Motor is stable and reliable, low noise level and without electro magnetic interference
- Exhibits low starting torque due to weak field rotation
- Has low efficiency since short-circuit wastes power
- Widely used in low load starting home appliances, e.g fans, washing machine pump motors



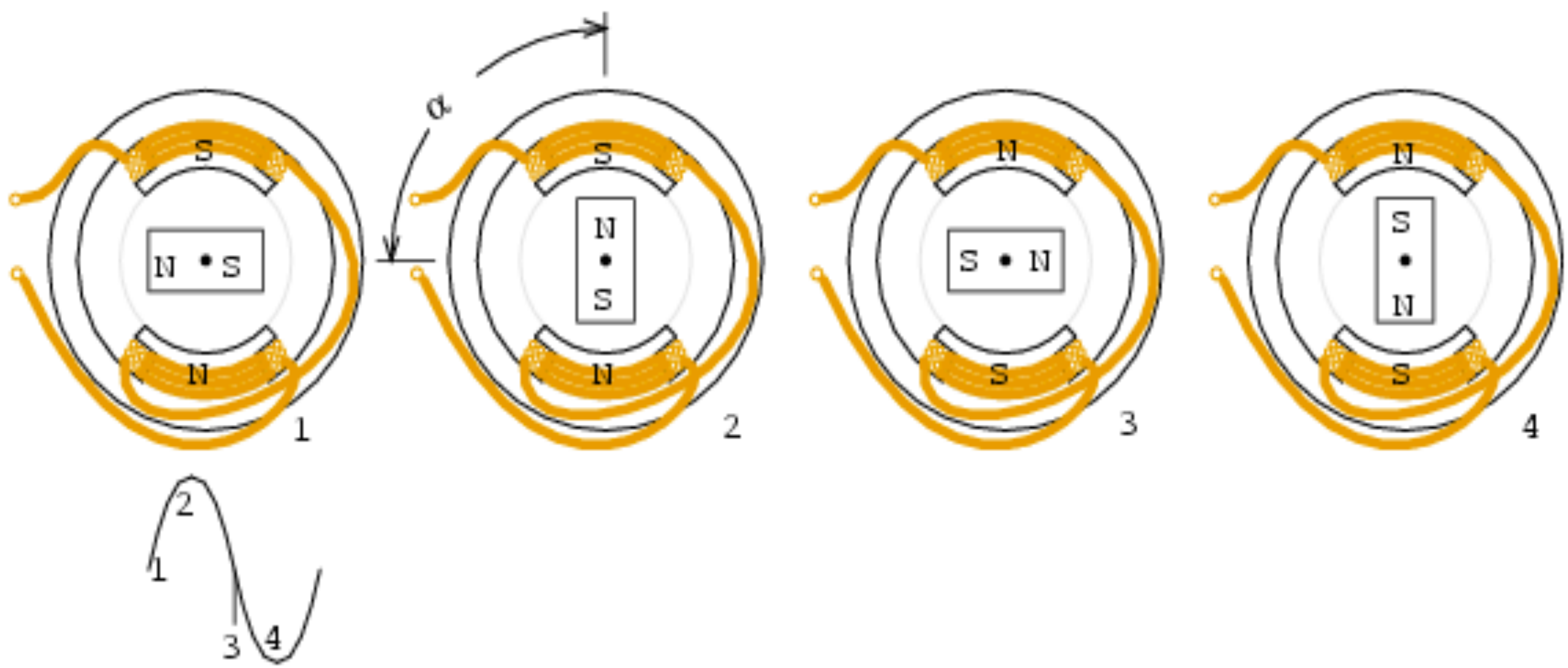
ROCO222: Intro to sensors and actuators

Lecture 9

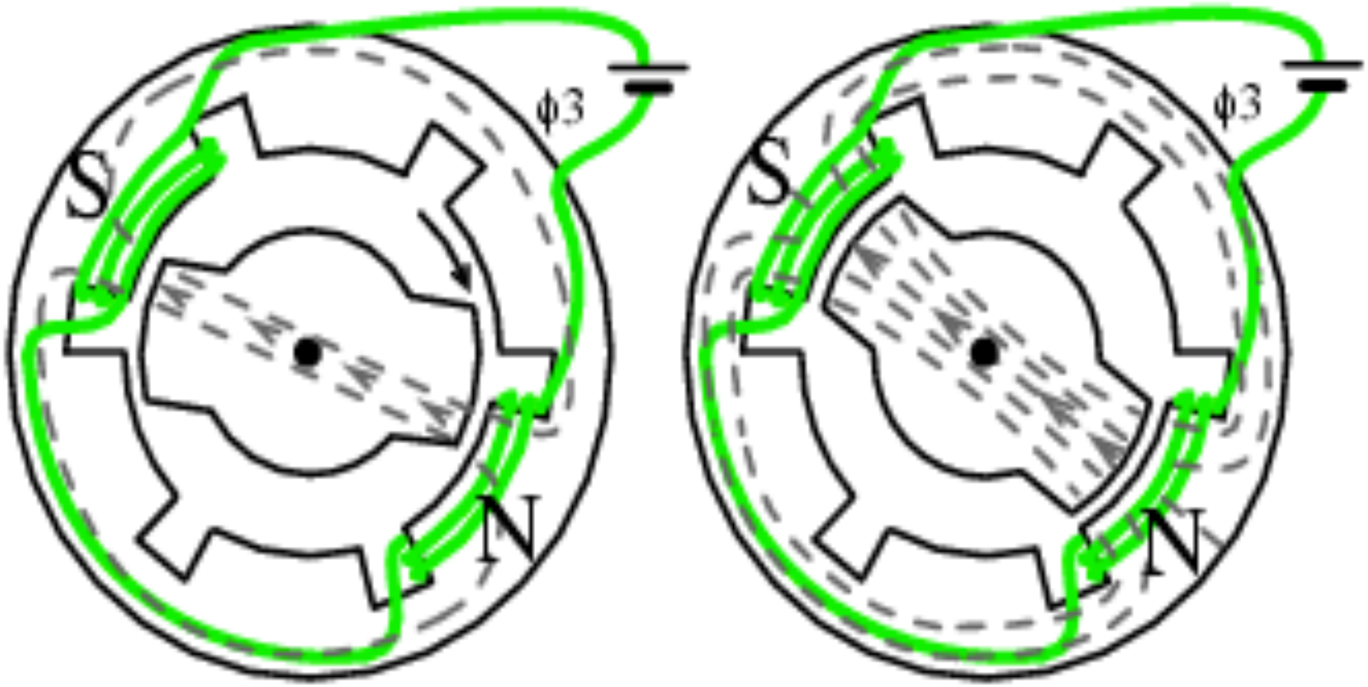
Other types of AC motors

Synchronous AC motors

- Similar to the induction motor in that it is a poly-phase machine in which the stator produces a rotating field
- A synchronous motor is also similar to an brushless DC motor, but the latter is commutated to ensure synchronous operation
- However the rotor is constructed from either
- Electromagnets energized by direct current supplied through slip ring
- Permanent magnets
- Fixed speed applications such as clocks and timers



Reluctance motor



high reluctance   low reluctance

- Magnetic flux seeks the path of least reluctance
- This is an AC motor that operates much like a reluctance stepper motor

Linear induction motor

- Like an AC induction motor that has been opened out and laid flat