EE6303 Electrical Machines II

5.0 General Engineering Aspects

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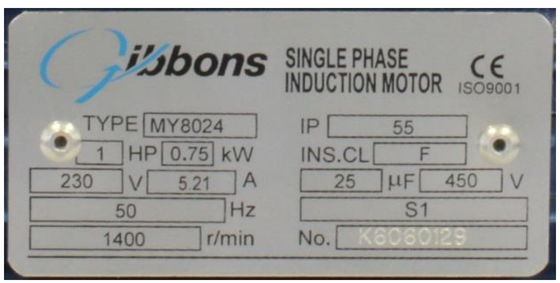
Content

General Engineering Aspects

5.1 Rating and Nameplate Data of Motors

Reading a motor nameplate

- What is a motor nameplate?
  - Means which provide the overview of structural and operational characteristics of a given motor



Reading a motor nameplate

- Why important to extract information out of a motor nameplate?
  - Connect a motor to a supply
  - Replace a motor
  - Design a power factor correction system for a motor drive system
  - Connect a drive system along with a motor
  - Repair a motor
  - Purchase parts for a motor
  - Operate a motor safely

Motor standards

- Data which should be put in a nameplate is standardized by different organizations

- Two main motor standards

1. **NEMA Standards**
   - ✓ Set by **N**ational **E**lectric **M**anufacturers **A**ssociation
   - ✓ Used mostly in North America
2. **IEC Standards**
   - ✓ Set by **I**nternational **E**lectro-technical **C**ommission
   - ✓ Used mostly in rest of the world (Original version or derivatives)
   - ✓ Examples for IEC derivatives :

     VDE 0530 standards in Germany,

     BS 2613 standard in Great Britain

Motor standards

- NEMA vs IEC Standards
  - Sometimes use different terms
  - But similar ratings and interchangeable ratings are used for most common applications
  - NEMA Standards are more conservative
  - IEC standards are more specific and categorized

Tips to Identify the motor standard

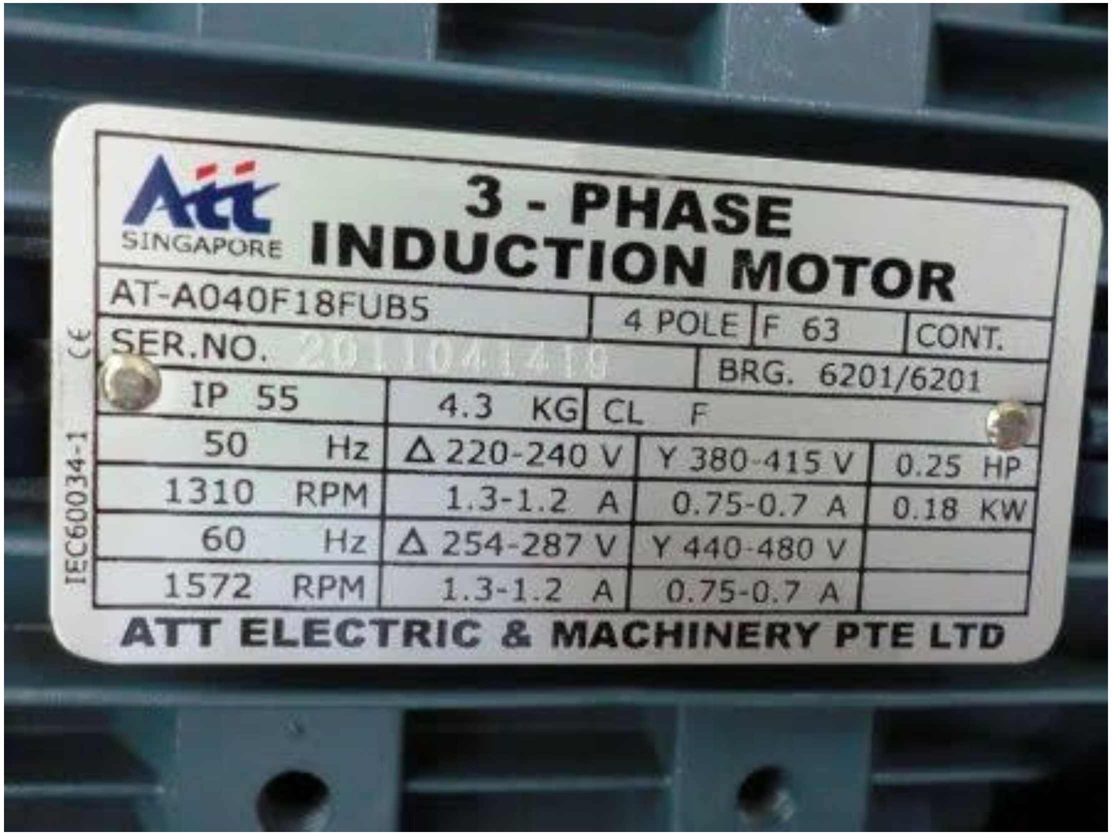
- NEMA or IEC word printed in the nameplate itself
- Unit of the Output power: IEC uses kW and NEMA uses horsepower (hp)
- Duty or time rating (DUTY/RATING) – IEC uses S1 to S8, and NEMA uses CONT. or a time in minutes.
- Efficiency labels (EFF1, EFF2 or EFF3) – Only used by IEC
- Efficiency (EFF.) – IEC gives efficiencies at full load and 75% of full load, NEMA gives nominal and guaranteed efficiency values
- Service Factor (S.F.), letter code (CODE) and deign letter (DES.) - only used by NEMA

0.75

Nameplate 01

NEMA or IEC ?

Nameplate 02

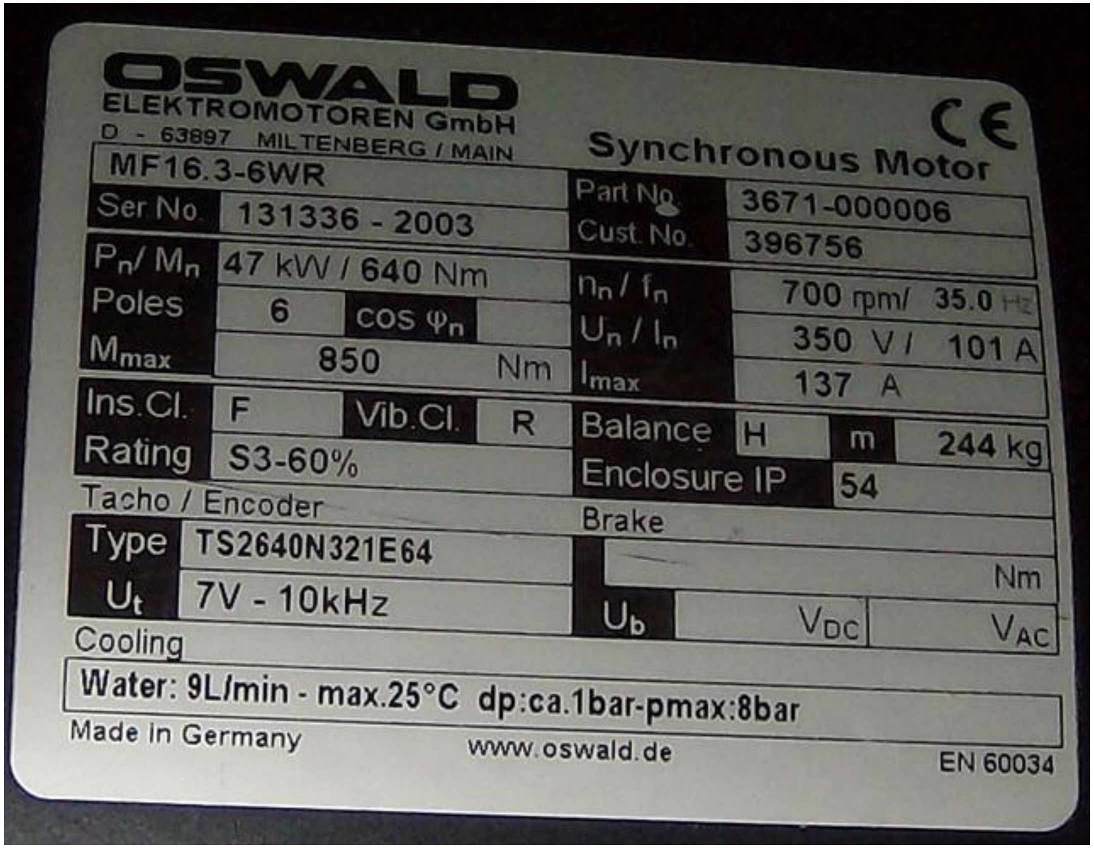


NEMA or IEC ?

Nameplate 03

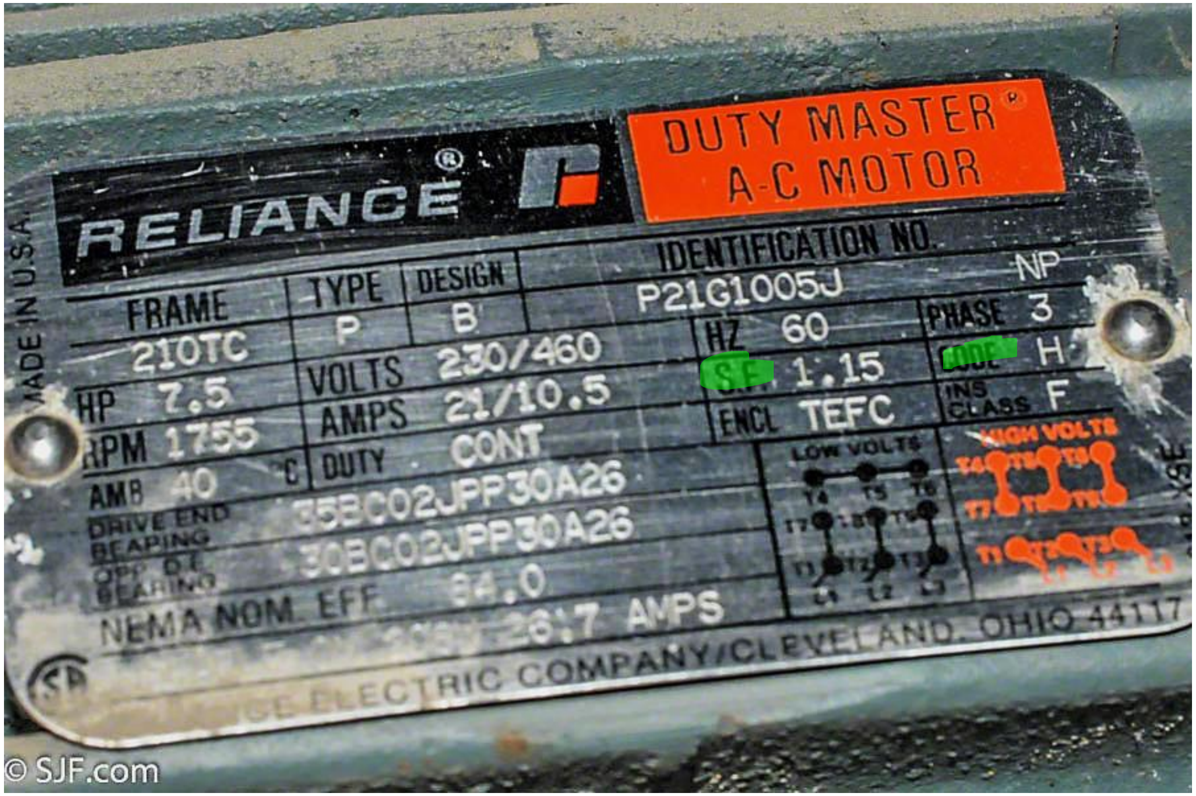
NEMA or IEC ?

Nameplate 04



NEMA or IEC ?

Nameplate 05



NEMA or IEC ?

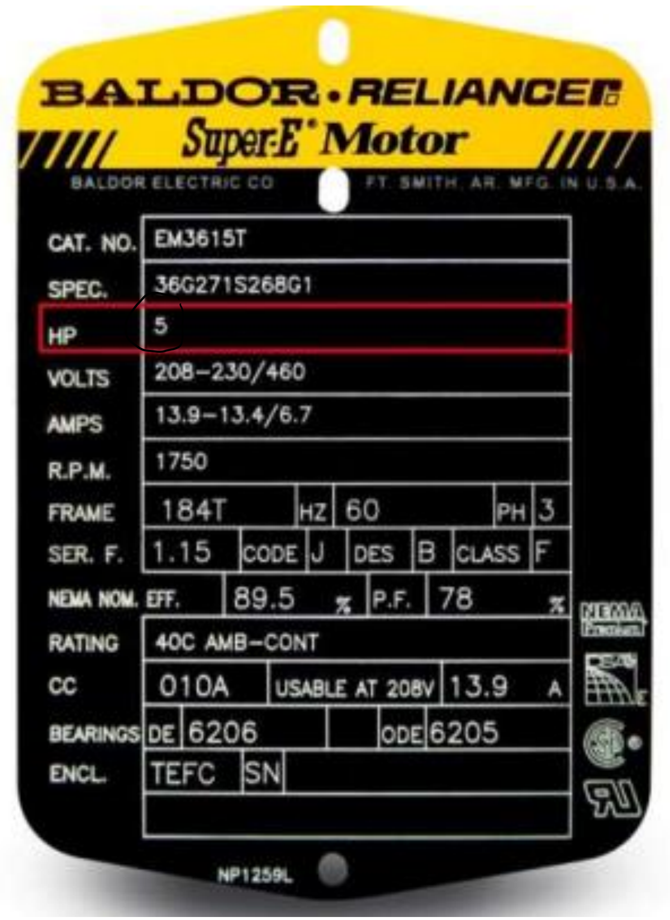
Nameplate 06

NEMA or IEC ?

Motor Nameplate data

Rated Mechanical Output (HP, KW)

- Maximum **continuous** output power the motor delivers without exceeding its internal thermal limits when operating under rated voltage and frequency.
- Defined for 40ºC and sea level conditions
- Outside of North America the output rating is commonly expressed in watts or kilowatts.
- Derated might be required based on
  - Ambient temperature
  - Altitude
  - Mounting arrangement
  - Motor drive switching frequency



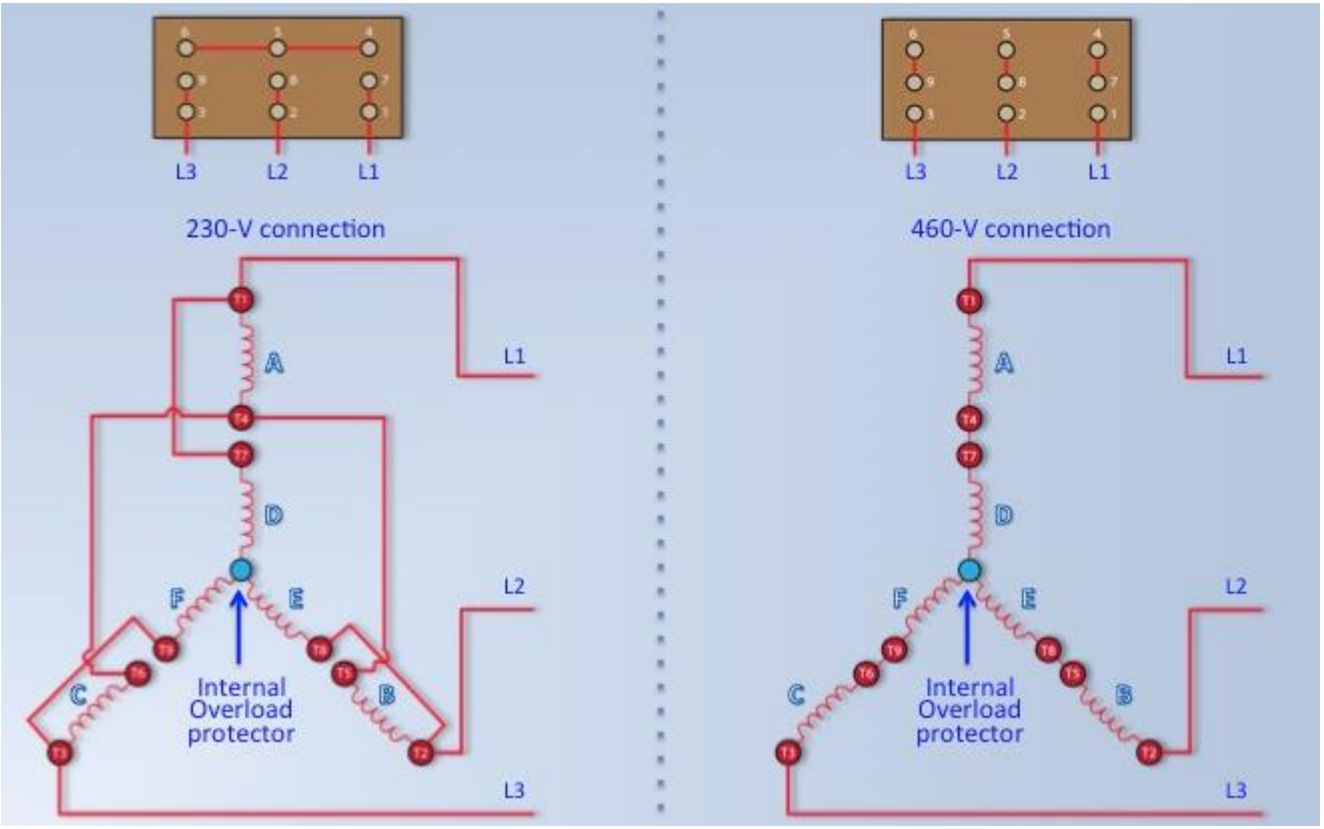
Motor Nameplate data

Rated Voltage (VOLTS, V)

- Voltage at which the motor is designed to operate most efficiently (L-L for 3 phase, L-N for single phase)
- NEMA has 10% tolerance while IEC allows 5%
- P.f, efficiency, torque and current ratings are given for the rated voltage
- Dual voltage motors
  - In North America – e.g. 230 V/460 V
  - Rest in the world – e.g. 230V/400V

Motor Nameplate data

Rated Voltage (VOLTS, V)

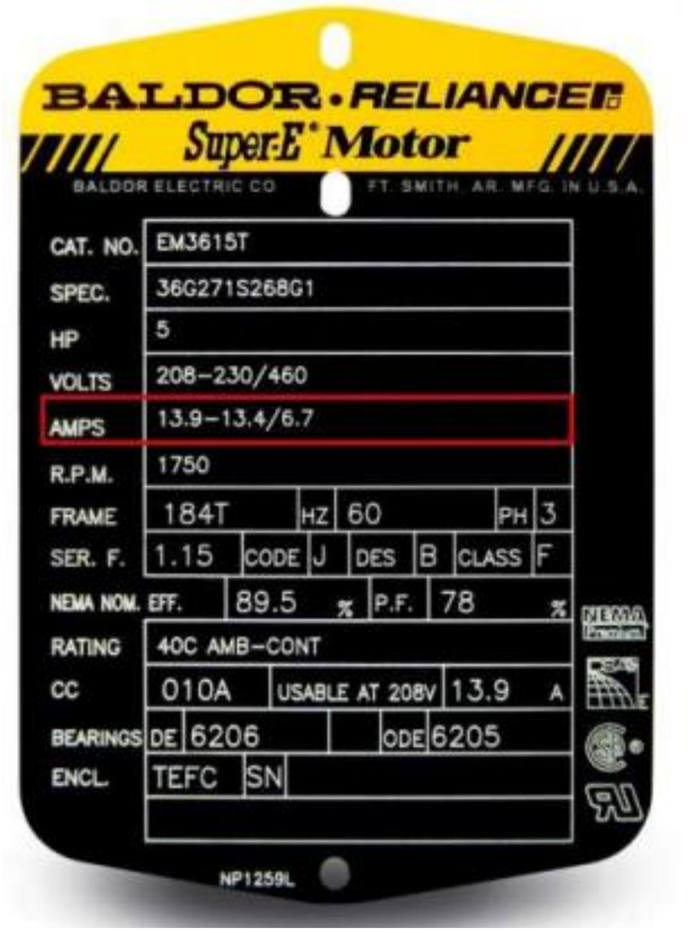


Winding arrangement in 230/460 V dual voltage motor

Motor Nameplate data

Full Load Amps (F.L.A, AMPS)

- The current at full torque and rated output power
- Determined through laboratory tests
- Important in selecting
  - Wire size
  - Motor starters
  - Overload protection



Motor Nameplate data

Rated Rotational Speed (RPM, MIN^{-1})

– Rotational Speed when delivering rated output power at rated frequency and rated voltage

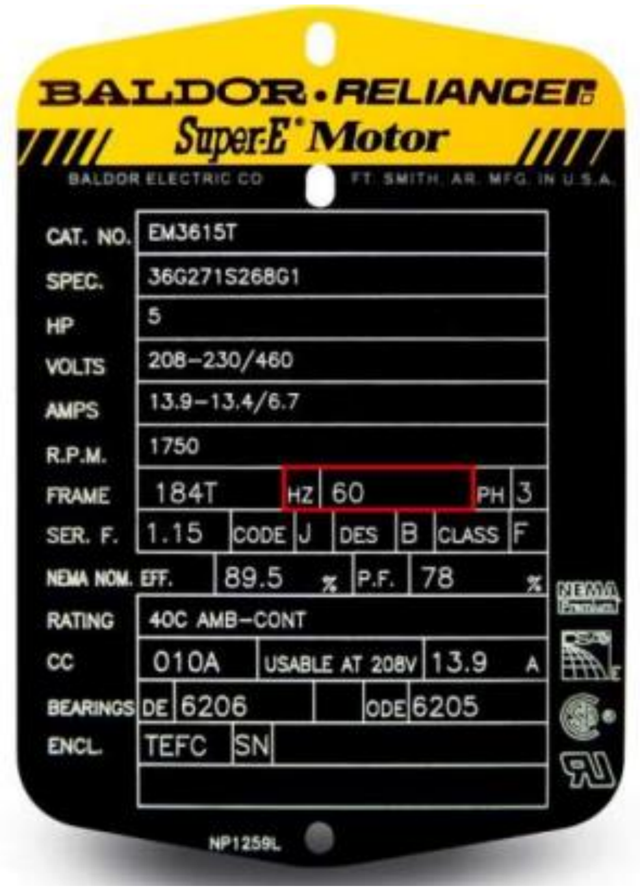
– Number of poles of the motor can be determined using this value.

– For induction motors RPM is around 5% less than the synchronous speed depending on the slip under rated condtions.

Motor Nameplate data

Frequency (HZ, FREQ)

- The frequency for which the motor is designed
- Two mains supply frequencies
  - 50 Hz in Europe, most of Africa, most of Asia, most of South America and Australia
  - 60 Hz in North America and few other regions
- Motors specially designed to run with VFDs has a maximum allowable frequency or a frequency range



Motor Nameplate data

No of Phases (PH, PHASE)

- Indicates the type of power supply for which the motor is designed (Only for AC motors)
- Usually rated for single phase or three phase AC supply.

Motor Nameplate data

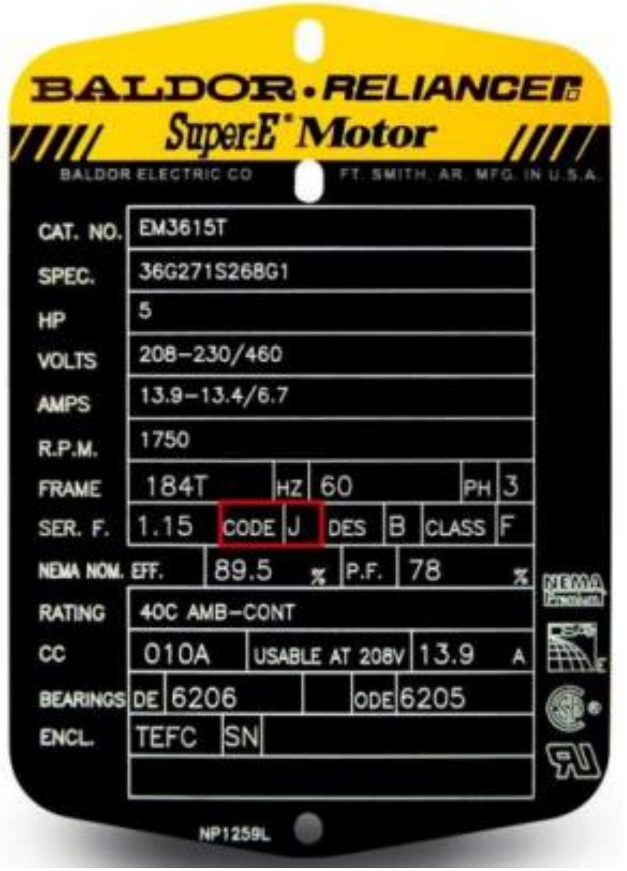
Service Factor (SF, SER F.)

- Indicates the amount of overload a motor can be expected to handle for a short period of time
- An insurance policy designed for changes in
  - Ambient temperatures
  - Altitude
  - Line voltage and Voltage imbalances
- Should never used as a method of increasing motor output power for regular use.
- Typically ranges from 1 to 1.15.
- Fraction horsepower sometimes have higher S.F. such as 1.25, 1.35 and even 1.50.

Motor Nameplate data

NEMA letter code/ Locked rotor KVA code (CODE, LRA, KVA CODE)

- Higher starting current of AC motors (200% to 600% greater than their full load running current)
- Sometimes referred as the inrush current or the locked rotor current.
- Code letter indicates the amount of inrush current of the motor. (Uses standard tables)
- Important in sizing starters and to determine circuit protection ratings.



Motor Nameplate data

Exercise 5.1

Calculate the approximate inrush (locked rotor) current for a 3-phase induction motor with a rated voltage of 230 V, output power of 5 hp and code letter of K.

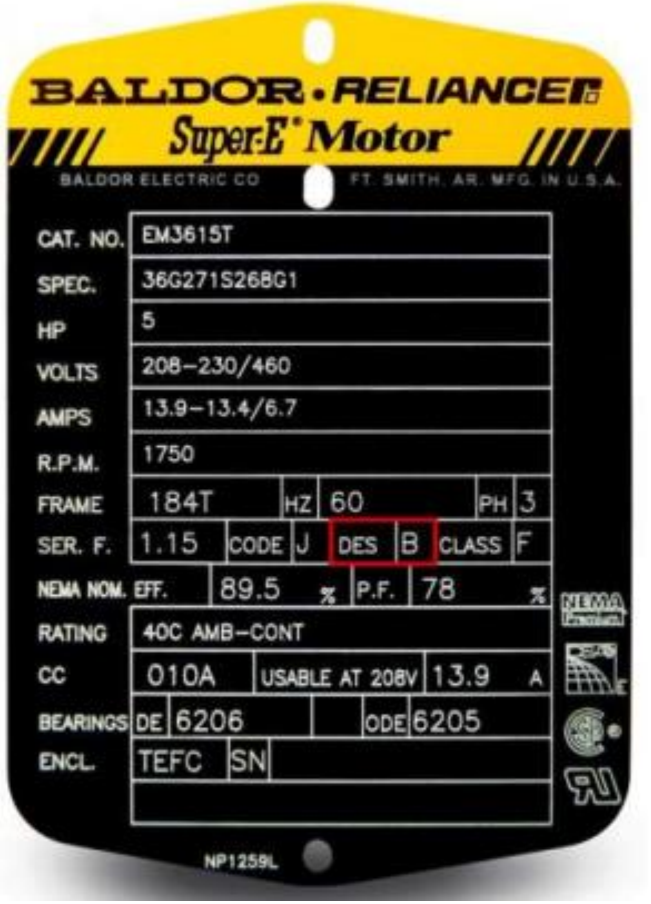
(Anz: 106.684 A)

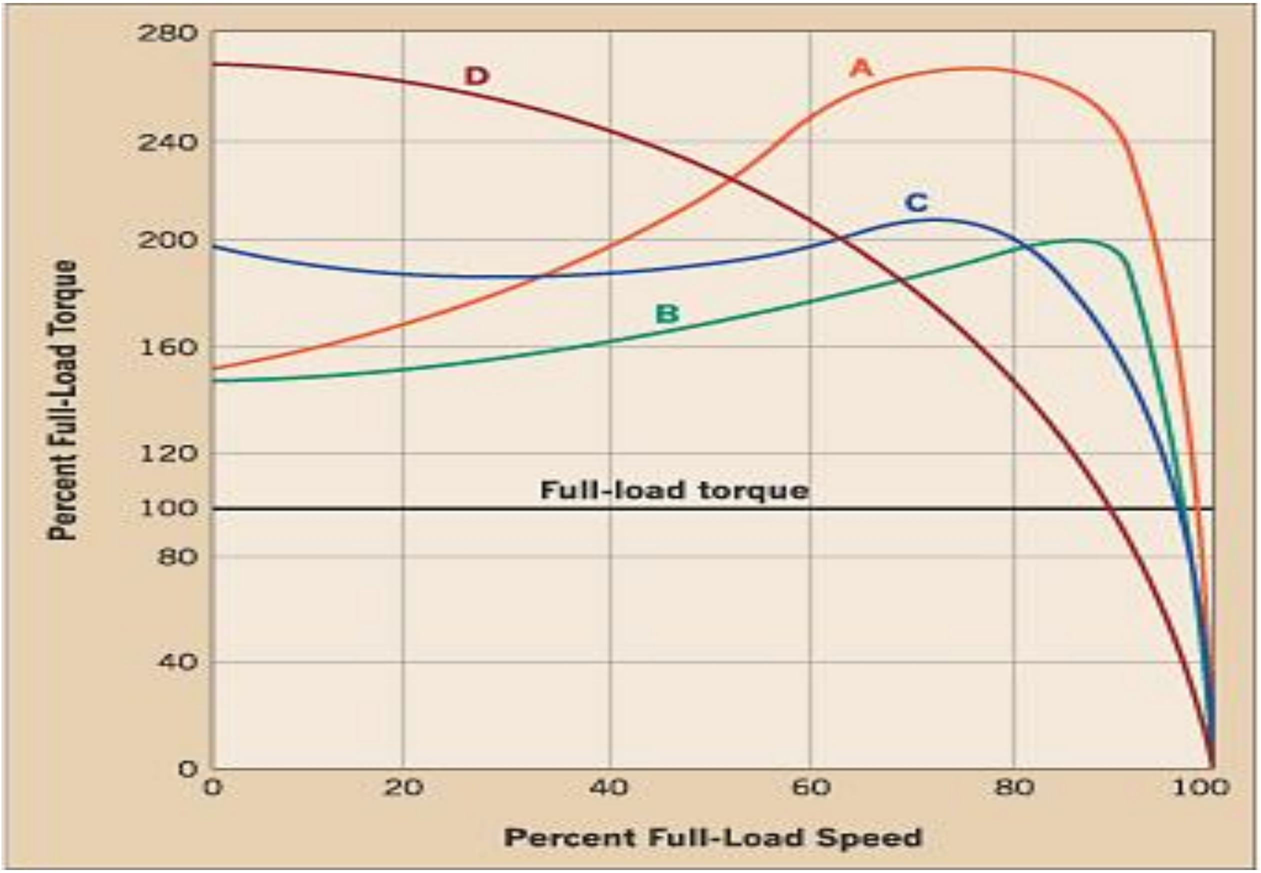
NEMA Code Letter	KVA/HP with locked rotor	Approximate Mid-Range Value
A	0-3.14	1.6
B	3.15-3.55	3.3
C	3.55-3.99	3.8
D	4.0-4.49	4.3
E	4.5-4.99	4.7
F	5.0-5.59	5.3
G	5.6-6.29	5.9
H	6.3-7.09	6.7
J	7.1-7.99	7.5
K	8.0-8.99	8.5
L	9.0-9.99	9.5
M	10.0-11.19	10.6
N	11.2-12.49	11.8
P	12.5-13.99	13.2
R	14.0-15.99	15.0
S	16.0-17.99	-
T	18.0-19.99	-
U	20.0-22.39	-
V	22.4-and up	-

Motor Nameplate data

NEMA Design Letter (DES, DESIGN)

- Based on the diversity of
  - starting torque
  - Break down torque
  - Starting current
  - slip
- Basically indicates the shape of the torque current characteristics (Can be altered with winding and rotor design)
- Four main design letters for general purpose motors
  - Design A
  - Design B
  - Design C
  - Design D



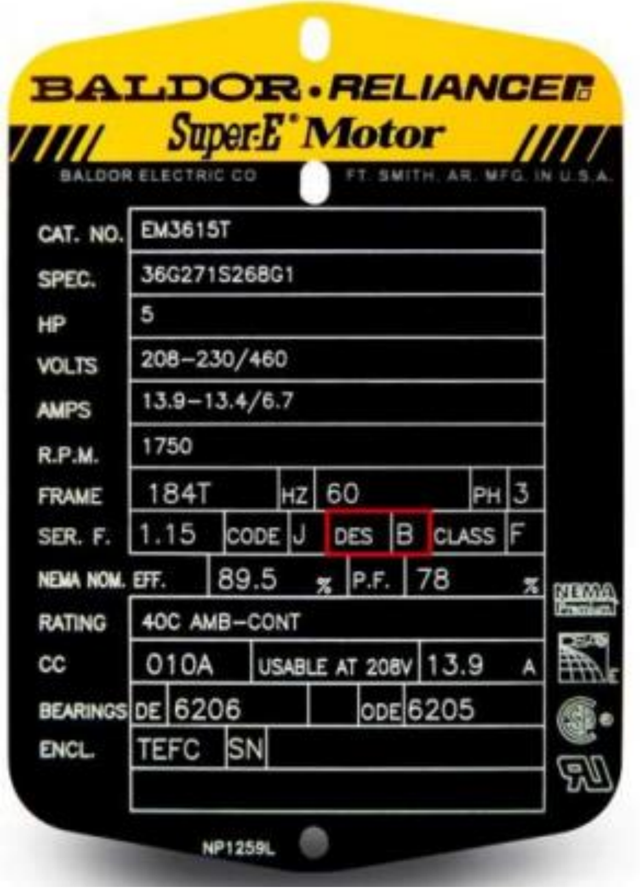


Percent Full-Load Torque
280
240
200
160
120
100
80
40
0
0
20
40
60
80
100
Percent Full-Load Speed
D
A
C
B
Full-load torque

Motor Nameplate data

NEMA Design Letter (DES, DESIGN)

- Design A
  - Normal starting torque and High starting current
  - Suits for brief heavy loads – machine tools, fans, pumps
- Design B (Most common design)
  - Similar to A with lower starting current and torque
  - Uses for same applications as A where less starting current is preferred
- Design C
  - High starting torque and low starting current
  - For starting heavy loads – compressors, conveyors
- Design D
  - Very high starting torque with desirable starting current
  - For equipment with very high inertia starts– Cranes, Hoists, mechanical punches

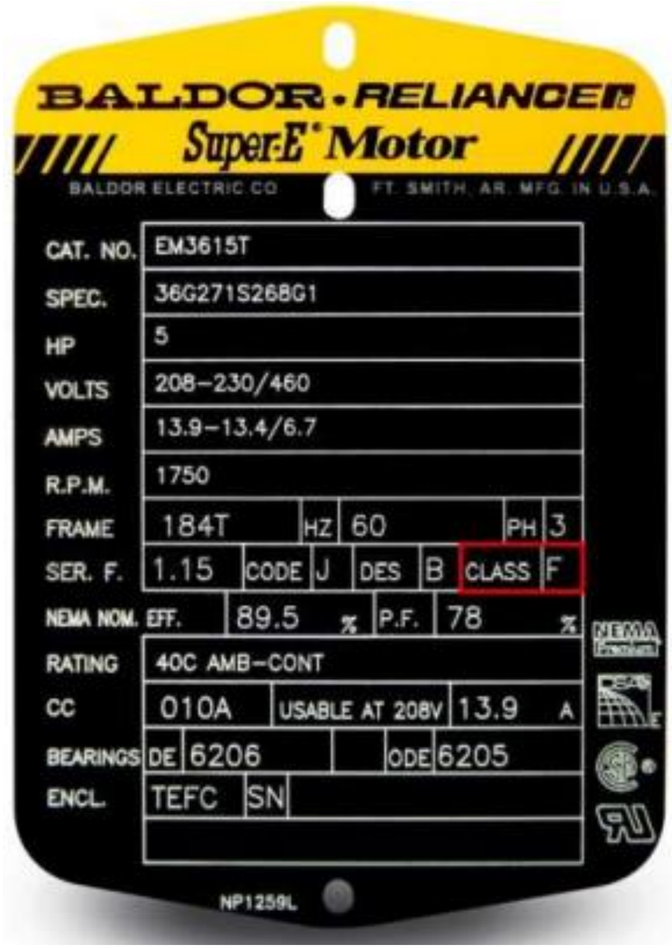


Motor Nameplate data

Insulation/Thermal Class(CLASS, INSUL CLASS, Th Cl)

- Indicates the thermal tolerance of the motor winding
- NEMA classifies motor insulation materials into four thermal classes – A, B, F and H.
- IEC standards has and additional class E with a allowable hotspot temperature of 120 ^{0}C.

Class	Maximum hot spot temperature allowed (^{0}C)
A	105
B	130
F	155
H	180



Motor Nameplate data

Nominal Efficiency (NOM EFF, EFF)

- Average efficiency of large number of motors of the same design under rated conditions
- Actual efficiency should be within a 20% band of this value
- Guaranteed efficiency is the minimum efficiency to be expected for a certain motor design under nameplate values.

Motor Nameplate data

Power Factor(PF, Cosϕ)

- Measure of a motors requirement for magnetizing amperage under rated condtions
- P.F. is minimum at no load and peaks near the rated load.
- Sometimes nameplate indicates maximum allowable
  - VAR compensation or
  - Capacitor rating

  for power factor improvement.

Motor Nameplate data

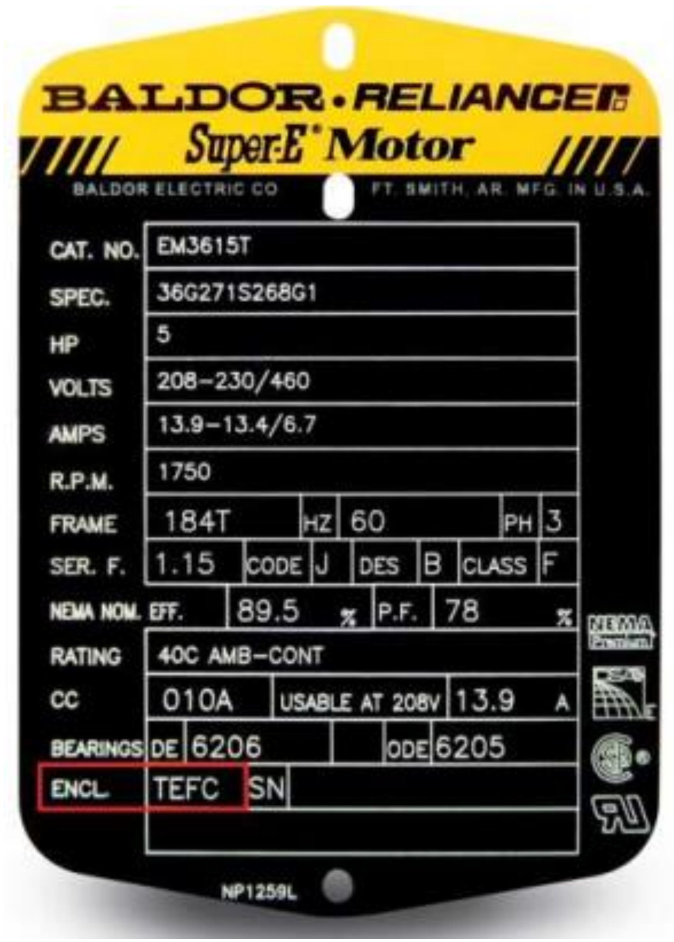
Time Rating/Duty (RATING, DUTY)

- Indicates the length of time a motor can operate at its rated load safely
- Typically maximum allowable ambient temperature for the given duty is mentioned under **AMB**
- With NEMA standards
  - For continuous duty **CONT** (Most common)
  - Some motors used for cranes, hoses, valve actuators and etc. have short-time duty with values 5 min to 60 min.
- With IEC
  - For continuous duty **S1** (Most Common)
  - Categorized from S1 to S8

Motor Nameplate data

Enclosure Type (ENCL, ENC)

- Indicates how motor is protected from the environment and heat transferring method.
- Most common types- TEFC, ODP ,TENV, XP
- Totally Enclosed Fan Cooled (TEFC)
  - Prevents air from flowing freely into the motor
  - Motor is cooled by a fan than blows air on the outside of the enclosure
  - Not fully air or water proof
- Open Drip-Proof (ODP)
  - Open enclosure that allows air to flow freely inside around the windings
  - Protects the motor from drops of liquid falling downward from 0 to 15 degrees
  - Not suitable for outdoor use

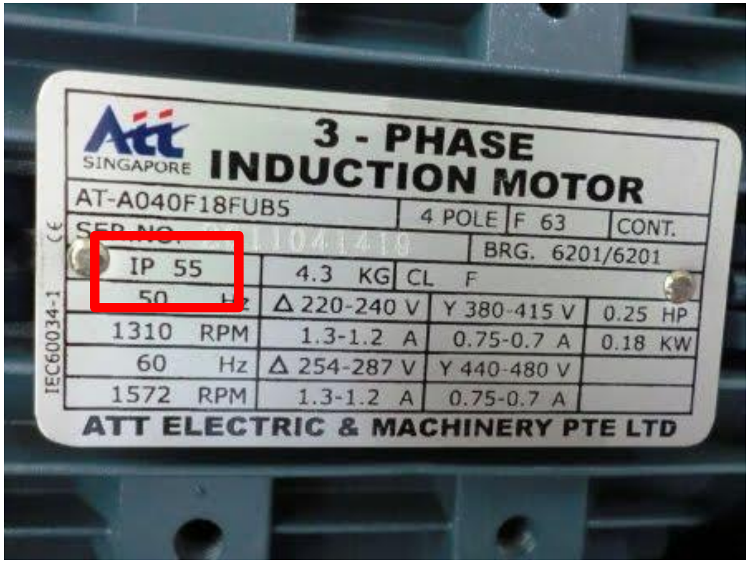


Motor Nameplate data

Motor Nameplate data

IP Rating (Ingress Protection)

- Used in IEC nameplates to define the levels of sealing effectiveness of electrical enclosures against intrusion from foreign bodies
- Use two numbers to express , e.g.: **IPxy**
- x indicates the intrusion protection. Ranges from 0 to 6.
- y indicates the moisture protection. Ranges from 0 to 8.
- Higher the number, better the protection.



Motor Nameplate data

INGRESS PROTECTION (IP) RATINGS			
FIRST NUMBER	PROTECTION AGAINST SOLIDS	SECOND NUMBER	PROTECTION AGAINST LIQUIDS
0	No protection	0	No protection
1	Objects over 50 mm (hand)	1	Vertically falling drops of water
2	Objects over 12 mm (finger)	2	Direct sprays up to 15º from vertical
3	Objects over 2.5 mm (tools and wires)	3	Direct sprays up to 60º from vertical
4	Objects over 1 mm (small tools and wires)	4	Sprays from all directions, limited ingress
5	Dust-limited ingress (no harmful deposit)	5	Low pressure jets of water from all directions, limited ingress
6	Totally protected against dust	6	Strong jets of water from all directions, limited ingress
		7	Temporary immersion (30 minutes) between 15 centimeters and 1 meter
		8	Long periods of immersion under pressure

Revising Nameplate data for a Different frequency

- Consider following parameters

Parameter	With $f_{original}$ (original data)	With f_{new} (revised data)
Rated voltage	$V_{original}$	V_{new}
Rated current	$I_{original}$	I_{new}
Apparent power	$VA_{original}$	VA_{new}
Rated power	$P_{original}$	P_{new}
Rated rotational speed	$N_{original}$	N_{new}

- ***For V_{new}***
  - Original air gap flux should not change
  - Hence v/f ratio should kept the same

$$\frac{V_{original}}{f_{original}} = \frac{V_{new}}{f_{new}} \Rightarrow V_{new} = \frac{V_{original}}{f_{original}} f_{new}$$

Revising Nameplate data for a Different frequency

- ***For*** $\boldsymbol{I_{new}}$
  - As air gap flux does not change, no-load losses remain the same
  - Other background factors such as cooling remain the same
  - Hence ohmic loss can be permitted to be the same

$$I_{new} = I_{original}$$

- ***For*** $\boldsymbol{N_{new}}$
  - Total current does not change as stator current and air gap flux is the same
  - Hence rotor results in the same slip speed

$$N_{S,new} - N_{new} = N_{S,original} - N_{original}$$

$$N_{new} = N_{S,new} + N_{original} - N_{S,original}$$

Revising Nameplate data for a Different frequency

- ***For P_{new}***
  - Output power of the motor equals to the product of rotational speed in rad/s and torque is Nm.

$$P = \tau\,\omega$$

  - The torque of the motors will be the same as air gap flux and currents are same

$$P_{new} = \frac{P_{original}\ \omega_{new}}{\omega_{original}}$$

Exercise 5.2 : A 60 Hz, 480 V, 25 A, 820 rpm, 20 kW motor is to be operated on 50 Hz. Compute the set of revised ratings by giving reasons. ***(400 V, 25 A, 670 rpm, 16.341 kW)***

5.2 Estimation of Motor Rating for a given Duty Cycle

Motor Sizing

Motor is loaded

↓

Heat generated

↓

Temperature Rise

↓

Motor Rating

As the supply voltage for the motor does not change much, current drawn by the motor is proportional to the load.

The heat generated inside the motor is proportional to the square of the current

Hence required **motor rating for a operation should be higher than the RMS loading** for a given duty cycle.

Motor Sizing

In general this can be expressed as

$$size\ of\ the\ motor \geq \sqrt{\frac{\sum_{i=1}^{n} L_i^2 t_i}{\sum_{i=1}^{n} t_i}}$$

Exercise 5.3: An electric motor operates at full-load of 100 kW for 10 minutes, at 50 kW for the next 10 minutes and at no-load for the next 5 minutes. Estimate the continuous rating of the suitable motor if the same cycle repeats continuously.

(Anz: Should be higher than 70.72 kW = 75 kW)

Motor Sizing

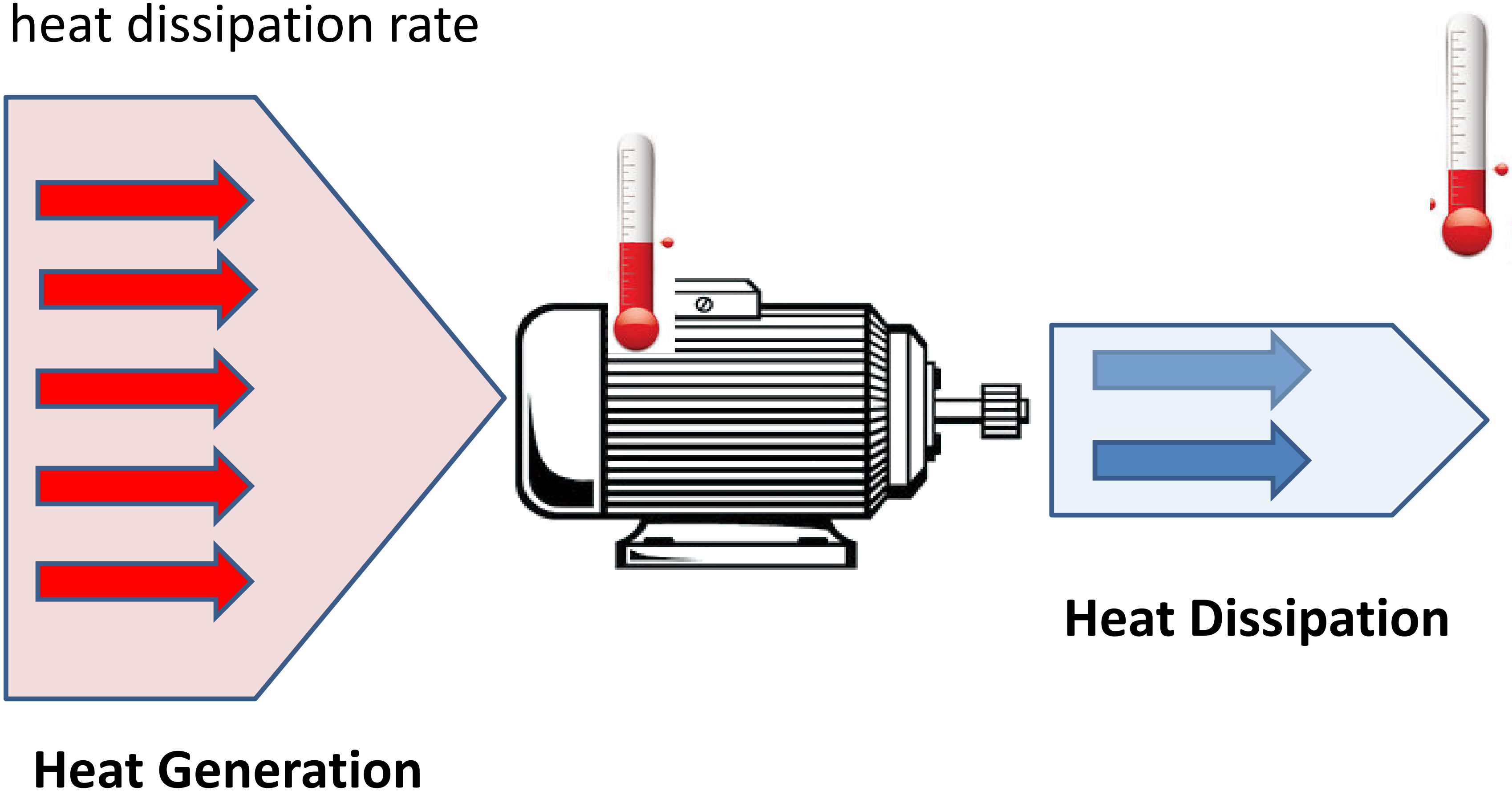
Exercise 5.4: A motor working on a coal mine has to exert power starting from zero and rising uniformly to 100 hp in 5 minutes after which it works at a constant load of 50 hp for 10 minutes. Then, the motor operate at no-load for 3 minutes. Estimate the suitable size of motor if the same cycle repeats continuously.

(Anz: Should be higher than 48.11 hp = 50 hp)

5.3 Heating and Cooling of Motors

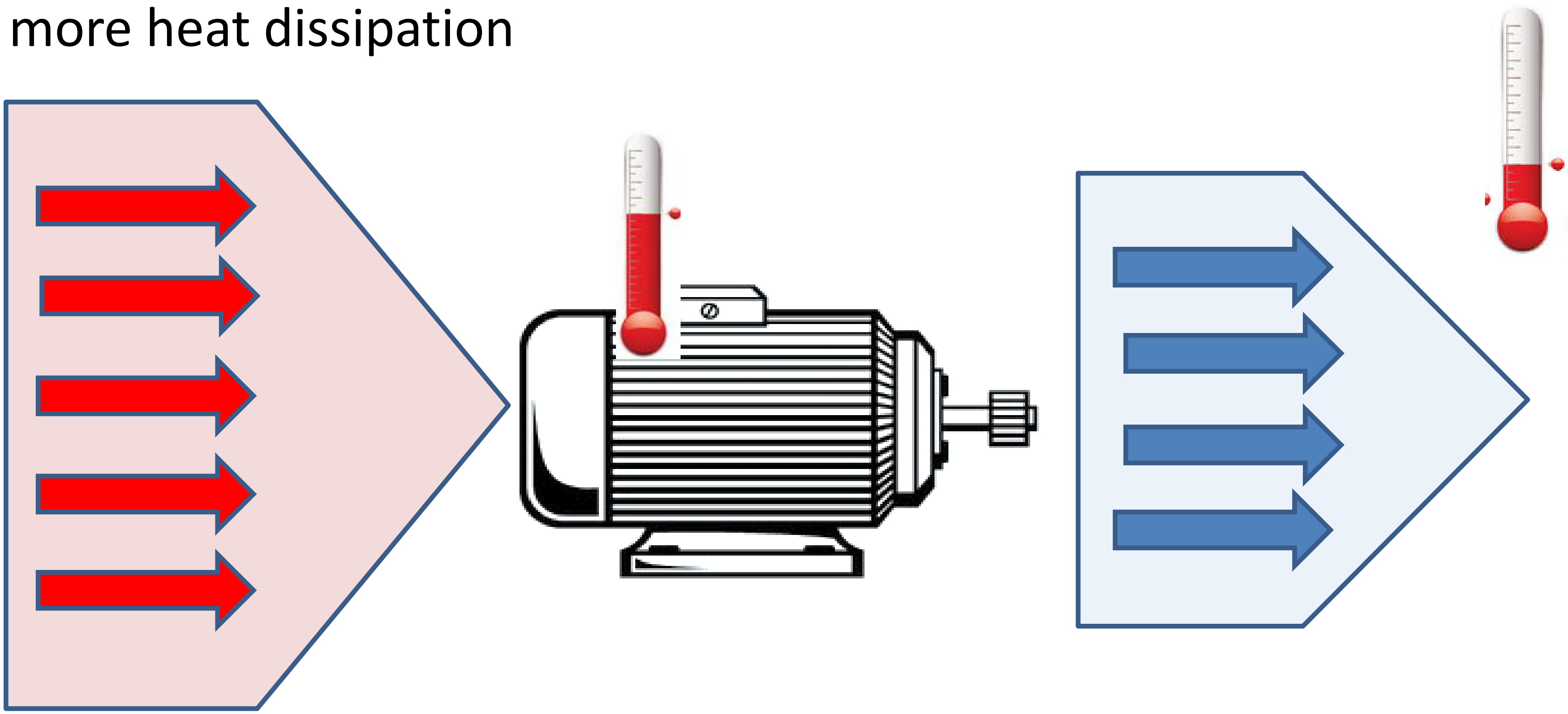
Heating of a Motor

Heating happens when heat generation rate is higher than the heat dissipation rate



Heating of a Motor

Due to the excess heat inside, motor temperature rises causing more heat dissipation

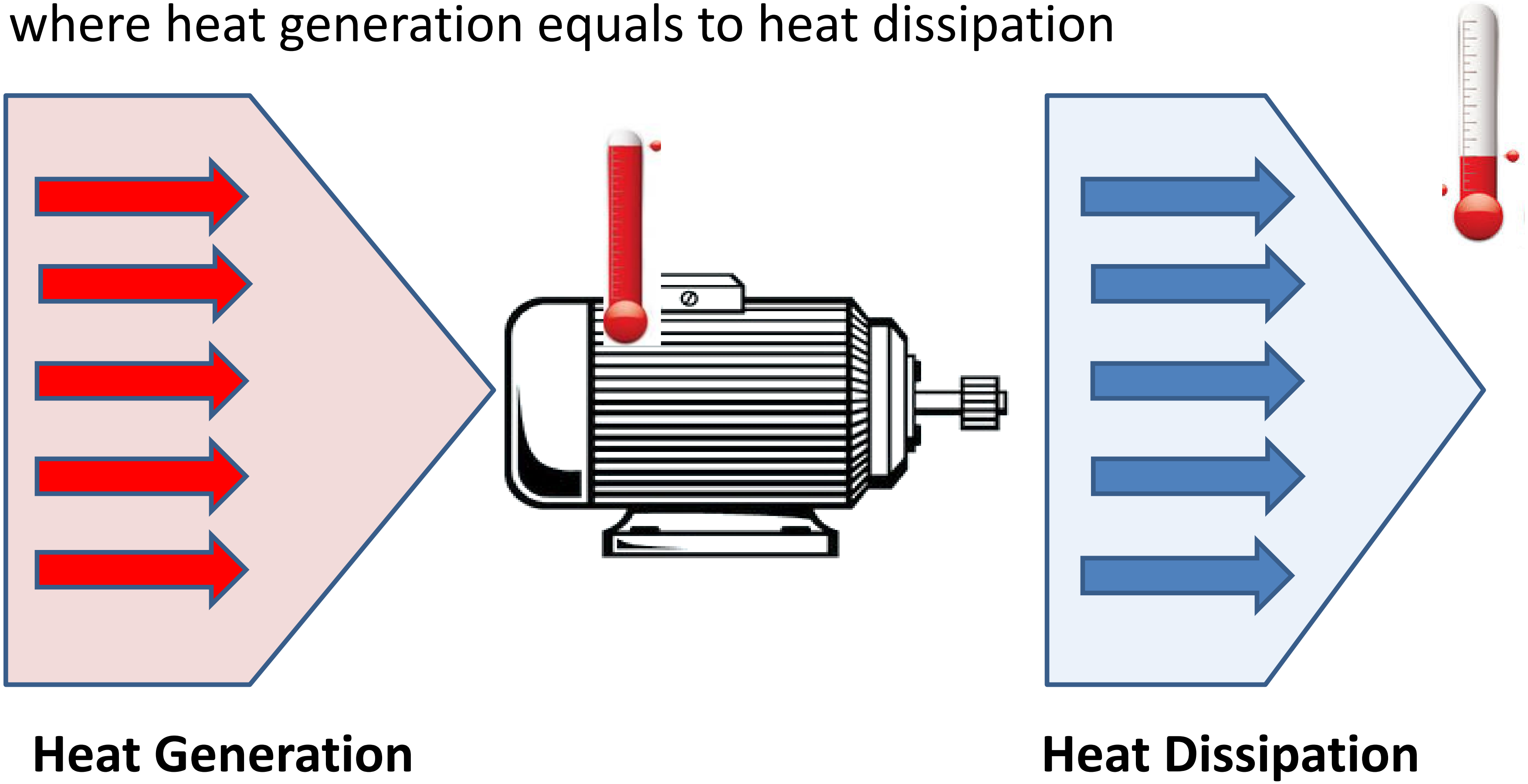


Heat Generation

Heat Dissipation

Heating of a Motor

After a while, motor will reach a steady state temperature where heat generation equals to heat dissipation



Equation for heating of motor

- If we assume,
  - ✓ Heat generation rate remains constant
  - ✓ Heat dissipation rate $\propto$ $(T_{motor} - T_{cooling\ medium})$
  - ✓ Temperature in cooling medium remains constant

$$\theta = \theta_f - (\theta_f - \theta_0) e^{-\frac{t}{T}}$$

Where

θ – Temperature rise when t = t

θ_f – Final/ maximum possible temperature rise (when heat generation= heat dissipation)

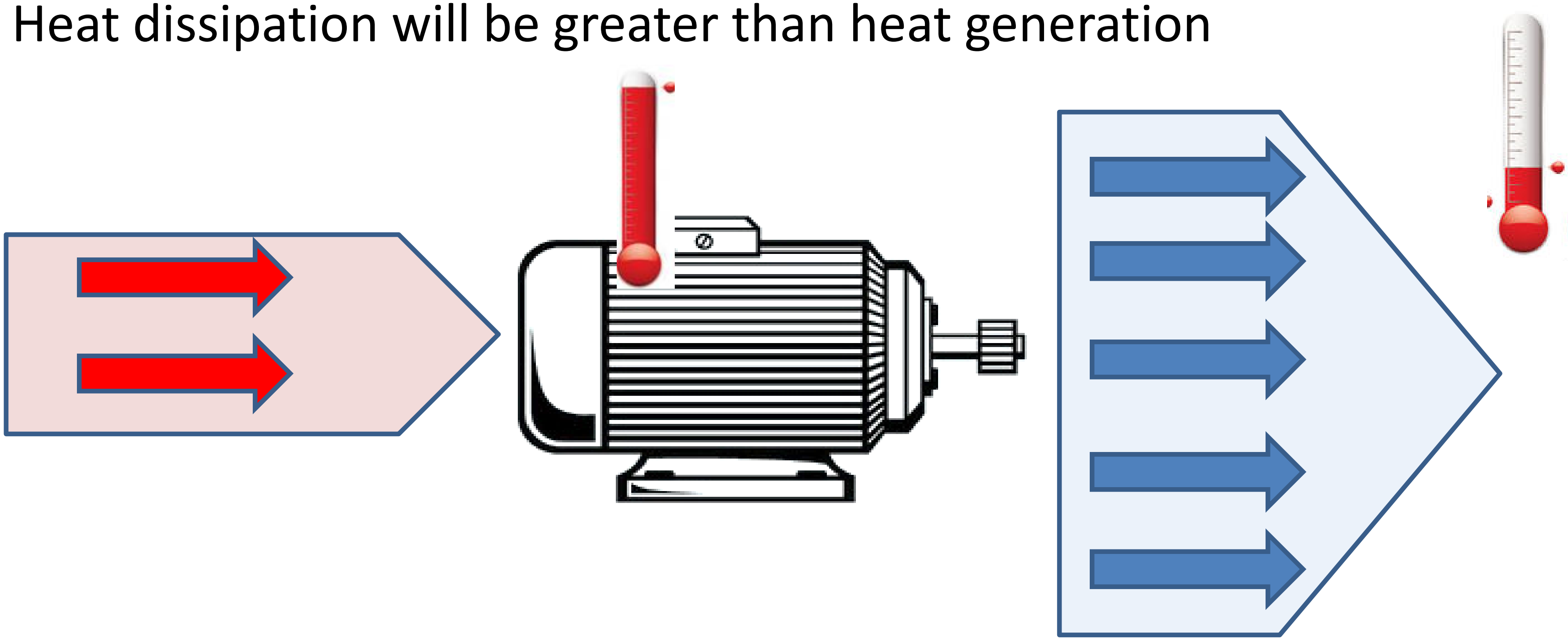
θ_0 – Initial temperature rise when t = 0

T - Heating time constant

Cooling of a Motor

If a motor at a high temperature, is suddenly disconnected or operated at a lower load

Heat dissipation will be greater than heat generation



Heat Generation **Heat Dissipation**

Equation for cooling of motor

- If we assume,
  - ✓ Heat generation rate remains constant
  - ✓ Heat dissipation rate ∝ $(T_{motor} - T_{cooling\ medium})$
  - ✓ Temperature in cooling medium remains constant

$$\theta = \theta'_f + \left(\theta_0 - \theta'_f\right) e^{-\frac{t}{T'}}$$

Where

θ – Temperature rise when t = t

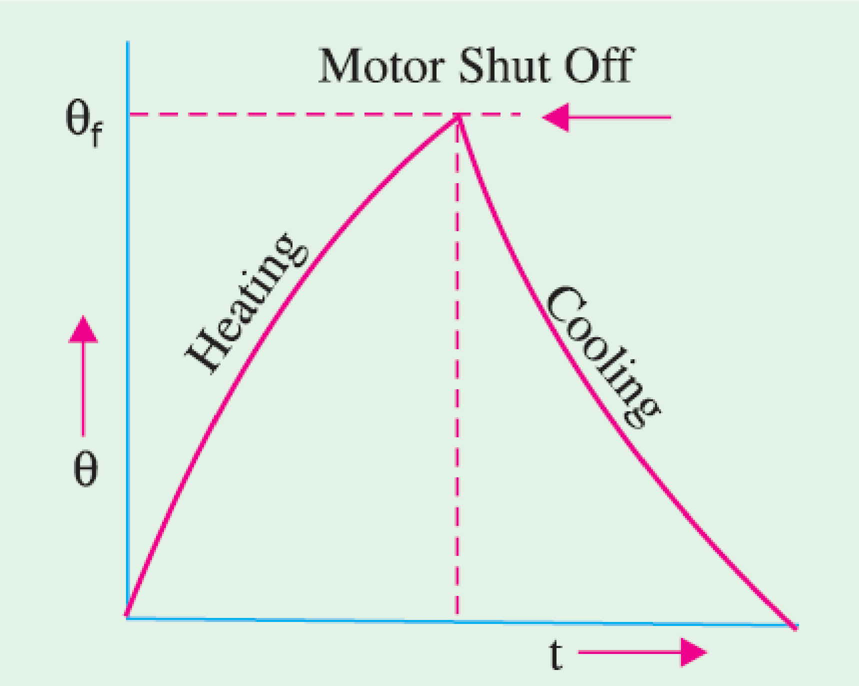
θ'_f – Final temperature rise (when heat generation= heat dissipation)

θ'_0 – Initial temperature rise when t = 0

T' - Cooling time constant

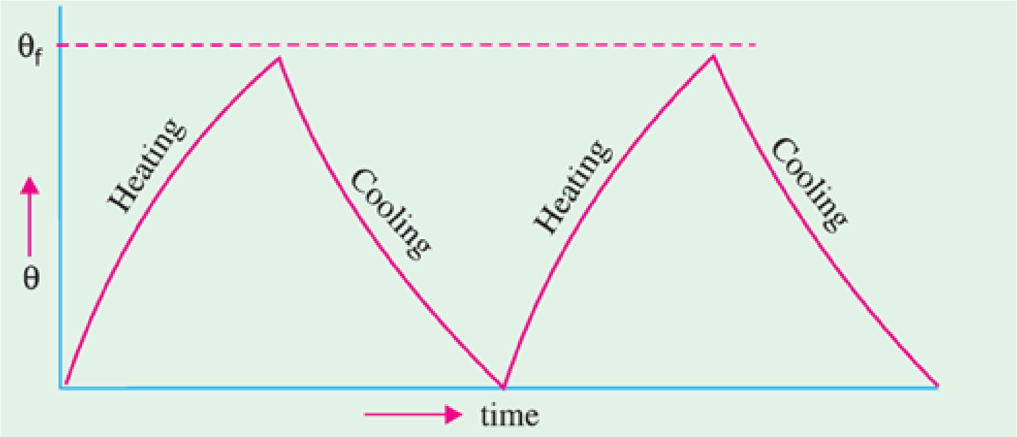
Heating and Cooling of Curves of Motor

- For a continuous duty

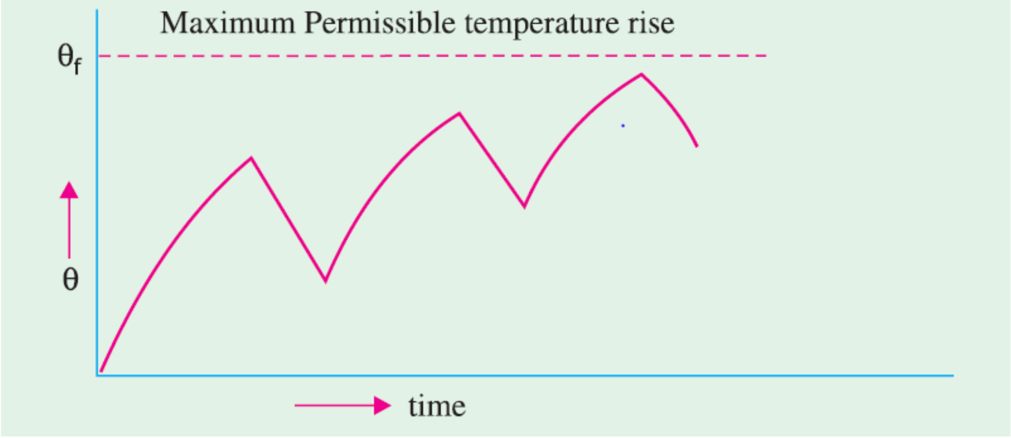


Heating and Cooling of Curves of Motor

- For a intermittent duty



When the cooling period is enough



When the cooling period is not enough

Heating and Cooling of motor

Exercise 5.5: In a motor, the temperature rise is 25 ^{0}C after 1 hour and 37.5 ^{0}C after 2 hours, starting from cold conditions. The motor is disconnected when it reaches to its final steady state temperature**.** Then its temperature falls from the final steady value to 40 ^{0}C in 1.5 hours. If the ambient temperature remains constant at 30 ^{0}C, calculate

a. the final steady temperature the motor reached due to heating ***(80 ^{0}C)***

b. heating time constant ***(1.44 hours)***

c. cooling time constant ***(0.932 hours)***

d. time it will take to cool down to 60 ^{0}C after disconnection ***(0.476 hours)***

Heating and Cooling of motor

Exercise 5.6: A 25 hp motor has a heating time constant of 90 minutes and when run continuously on full-load attains a temperature rise of 45 ^{0}C compared to ambient temperature. Calculate the 30 min rating of the motor for this temperature rise, assuming that it cools down completely between each load period and the losses are proportional to square of the load. ***(Ans: 46.96 hp)***

Equation for Heating of a Motor - Derivation

Lets take:

W – Rate of heat generated in the motor

G – Weight of the motor

S – Average specific heat of motor material

A – Cooling surface area of the motor [m^2]

λ – Rate of heat dissipation per unit area per temperature rise [$W/m^2\ {}^0C$]

θ – Temperature rise at t = t

Rate of Heat generation = Rate of heat absorbed by motor + Rate of heat dissipation

$$W = GS\frac{d\theta}{dt} + A\lambda\theta$$

$$\frac{d\theta}{\left(\frac{W}{A\lambda} - \theta\right)} = \frac{dt}{\frac{GS}{A\lambda}} \longrightarrow$$

By integrating,

$$\log_e\left(\frac{W}{A\lambda} - \theta\right) = -\frac{A\lambda}{GS}t + C$$

Equation for Heating of a Motor - Derivation

- **At thermal equilibrium** $$W = GS\frac{d\theta}{dt} + A\lambda\theta$$

$$W = A\lambda\theta_f$$

$$\frac{W}{A\lambda} = \theta_f$$

- **At t = 0** $$\log_e\left(\frac{W}{A\lambda} - \theta\right) = -\frac{A\lambda}{GS}t + C$$

$$log_e\left(\frac{W}{A\lambda} - \theta_0\right) = C$$

Derive the equation for heating by taking heating time constant T can be defined as

$$T = \frac{GS}{A\lambda}$$

Equation for Cooling of a Motor - Derivation

Lets take:

W – Rate of heat generated in the motor

G – Weight of the motor

S – Average specific heat of motor material

A – Cooling surface area of the motor [m^2]

λ' – Rate of heat dissipation per unit area per temperature drop [$W/m^2\ {}^0C$]

θ – Temperature rise at t = t

Rate of Heat generation + Rate of heat absorbed by motor = Rate of heat dissipation

$$W + GS\frac{d\theta}{dt} = A\lambda'\theta$$

$$\frac{d\theta}{\theta - \frac{W}{A\lambda'}} = \frac{dt}{\frac{GS}{A\lambda'}} \longrightarrow \log_e\left(\theta - \frac{W}{A\lambda'}\right) = -\frac{A\lambda'}{GS}t + C$$

Equation for Cooling of a Motor - Derivation

- **At thermal equilibrium** $W + GS\frac{d\theta}{dt} = A\lambda'\theta$

$$W = A\lambda'\theta_f'$$

$$\frac{W}{A\lambda'} = \theta_f'$$

- **At t = 0** $\log_e\left(\theta - \frac{W}{A\lambda'}\right) = -\frac{A\lambda'}{GS}t + C$

$$log_e\left(\frac{W}{A\lambda'} - \theta_0\right) = C$$

Derive the equation for cooling by taking cooling time constant T' can be defined as

$$T' = \frac{GS}{A\lambda'}$$

5.4 Causes of Noise Generation in Electric Machines

Causes of Noise Generation

- Vibrations due to shaft rotation in motors.
- The noise in a power transformer can be categorized into three components

  1. Core Noise
  - Due to Magnetostriction of the core
  - Expansion and contraction of the shape

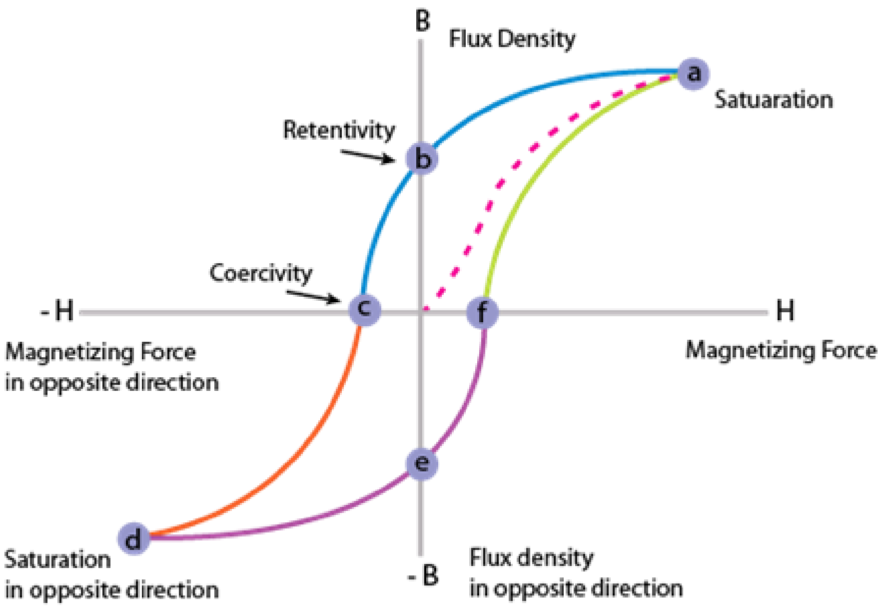
  2. Load Noise
  - Vibrations in tank walls, magnetic shields and transformer windings
  - Created by the leakage flux fields

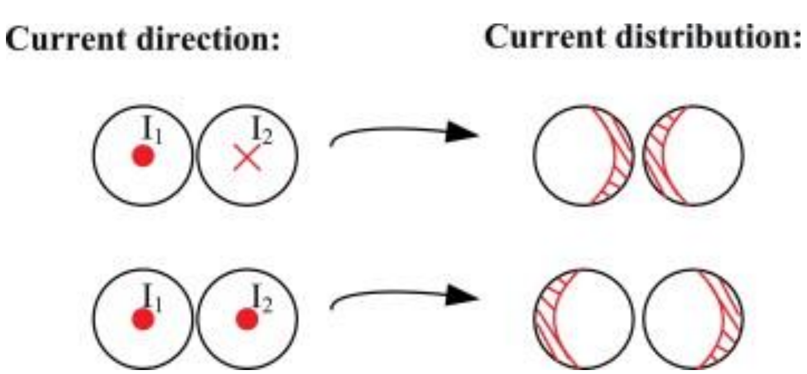
  3. Fan and Pump Sound
  - Cooling mechanisms in transformer can also generate sound

Exercise 5.7: Explain the reason behind transformer Humming.

Phenomena associated with Transformer losses

- Core Losses
  - Eddy current generation
  - Magnetic hysteresis
  - Magnetostriction
- Copper Losses
  - Skin effect
  - Proximity effect





5.5 Cooling Systems in Transformers

Cooling Systems in Transformers

- Types of transformers
  - Hermetically sealed transformers Vs. Conservator type transformers
  - Dry Type transformers Vs. Oil immersed transformers

Cooling Systems in Transformers

- ANSI/IEEE Standard C57.12.00 defines a 4 digit code to describe the cooling attributes of an oil immersed transformer.

- **The first letter designates the internal cooling medium in contact with the windings.**
  - **O** : mineral oil or synthetic insulation fluid with a fire point ≤ 300°C
  - **K** : insulating fluid with a fire point > 300°C
  - **L** : insulating liquid with no measurable fire point.

Cooling Systems in Transformers

- **The second letter designates the circulation mechanism for internal cooling medium**
  - **N** : Natural convection flow through cooling equipment and in windings
  - **F** : Forced circulation through cooling equipment and natural convention flow in the windings
  - **D** : Forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings

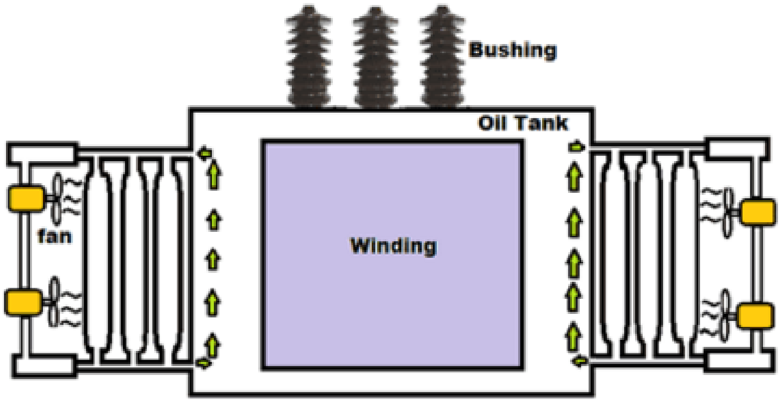
Cooling Systems in Transformers

- **The third letter designates external cooling medium**
  - **A** : Air
  - **W** : Water

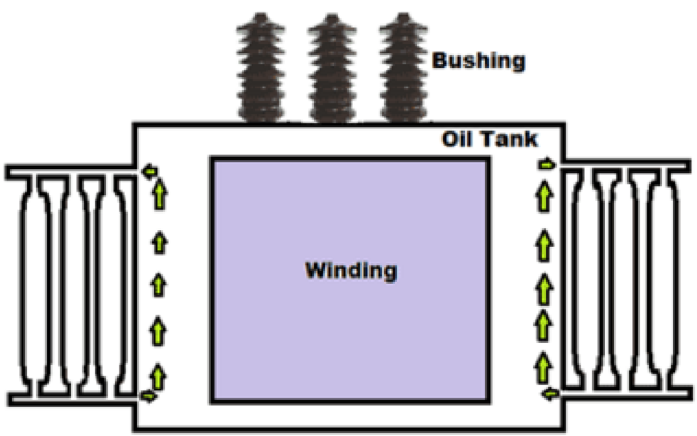
- **The fourth letter designates the circulation mechanism for the external cooling medium.**
  - **N** : Natural convection
  - **F** : Forced circulation (Fans (air cooling), pumps (water cooling))

Cooling Systems in Transformers

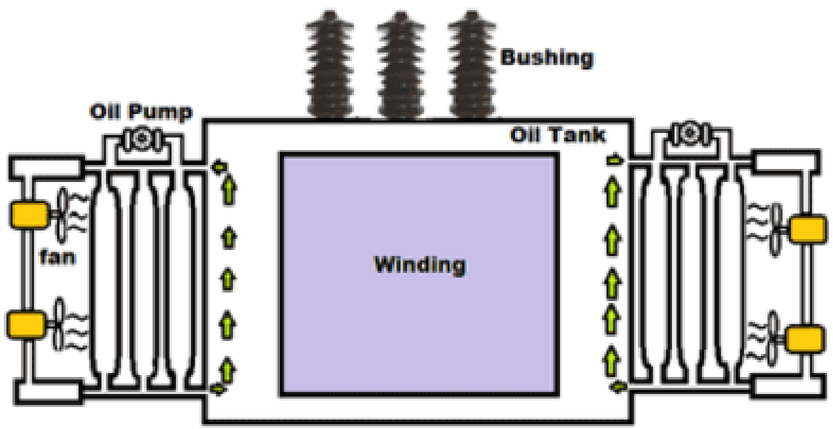
- Commonly used cooling systems in power transformers are
    1. ONAN
    2. ONAF
    3. OFAF
    4. ODAF
    5. OFWF



ONAf Cooling

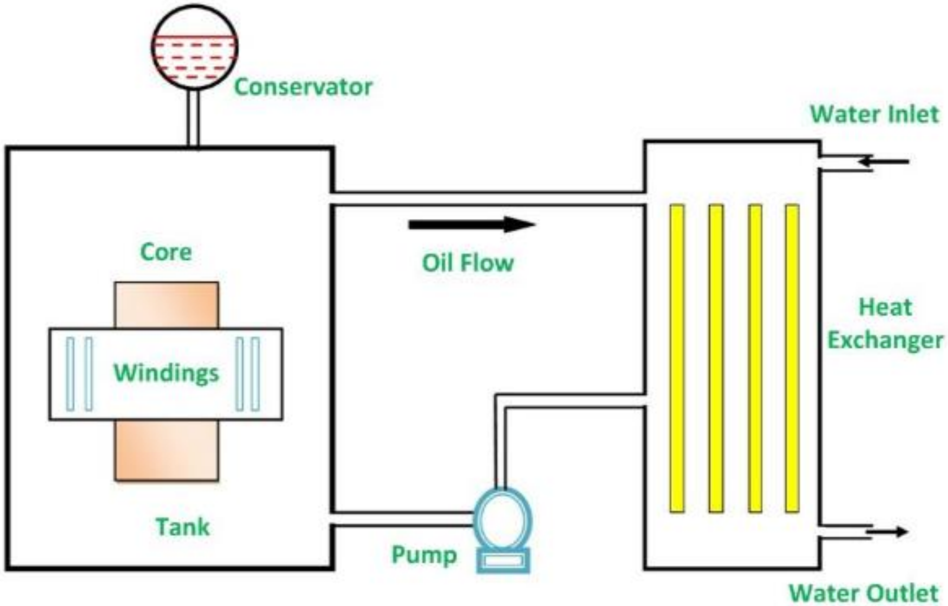


ONAN Cooling



OfAf Cooling

Cooling Systems in Transformers



Exercise 5.8: What are the common cooling systems in power transformers? Briefly explain.

End of Section 05