Industrial Motor Control

ECET 4530

1

3Φ Squirrel Cage Induction Motors

†

An Introduction

2

Three-Phase Induction Motors

The (**3Φ**) **Three-Phase Induction Motor,** also referred to as an **Asynchronous Motor**, is the most commonly used motor in an industrial setting, for which its operating characteristics and its availability in a variety of both configurations and standard sizes ranging from fractional horsepowers up to 50,000hp, make it suitable for a wide variety of applications.

This presentation covers the **Squirrel-Cage** Induction Motor, which is the considered to be the workhorse of industry due to its extreme durability and reliability*.

* – Unlike other (larger-sized) motors, the **squirrel-cage** induction motor requires **no external electrical connection to its rotor**, simplifying its construction and decreasing its overall maintenance requirements.

3

This Presentation

Note that this presentation is **not intended** to provide the audience with either a comprehensive view of the underlying theory upon which the design of an induction motor is based or an in-depth analysis the induction motor's operational characteristics, as would be suitable for a course that focuses on machine design.

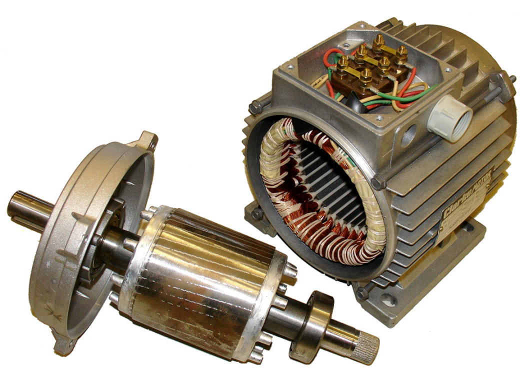
Instead, this presentation **is** meant to provide the audience with an "**overview**" **of the induction motor's design and operational characteristics**, along with a spattering of both electromagnetic theory and practical considerations, in order to make sure that everyone entering this course has at least a base set of knowledge from which we can begin our investigation into the operation and control of these motors in an industrial setting.

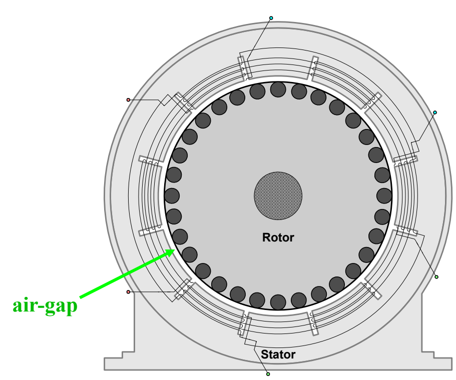
4

Basic Construction
of the
3Φ Squirrel Cage
Induction Motor

5

3Φ Induction Motor Construction

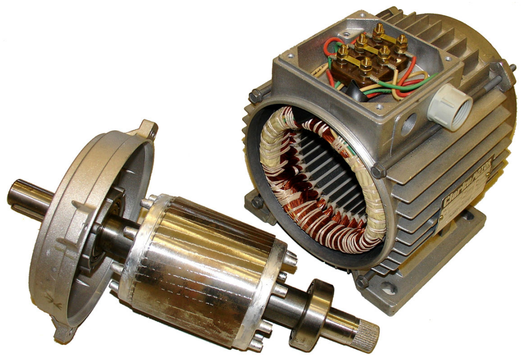


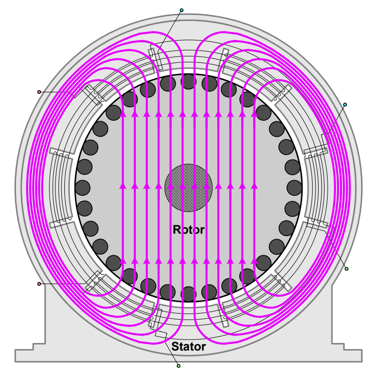


A 3Φ Induction Machine has two primary components:
a **stator** (stationary portion) and a **rotor** (rotational portion),
that are separated by a small **air-gap** when combined together,
allowing for the rotor to rotate freely within the stator region.

6

3Φ Induction Motor Construction

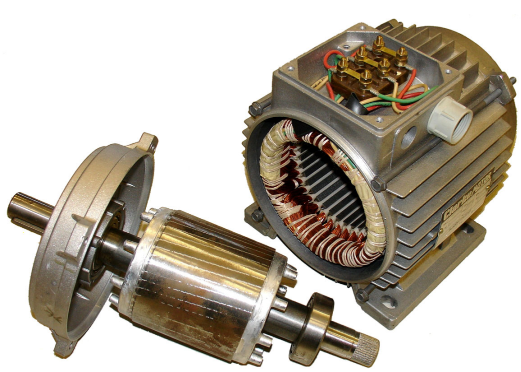


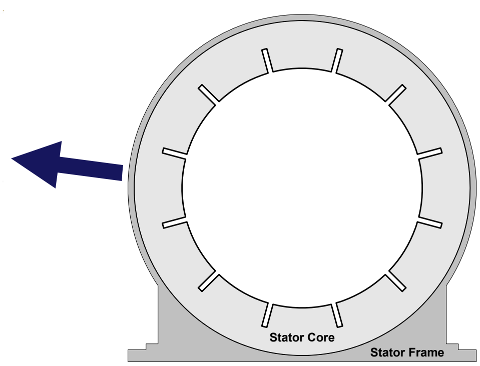


Although the stator and the rotor are electrically isolated from each other, their operation is linked together by means of a mutually-linked **magnetic field** that passes through both regions.

7

3Φ Induction Motor Construction – Stator



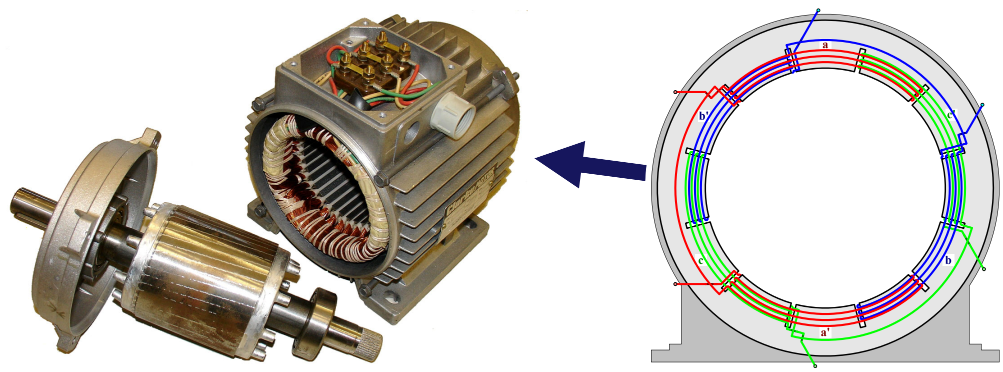


The **stator** consists of a **frame**, a **core**, and a set of **windings**.

The **core**, a hollow cylinder with slots cut lengthwise down its inner surface, is mounted within the support structure of the **frame**.

8

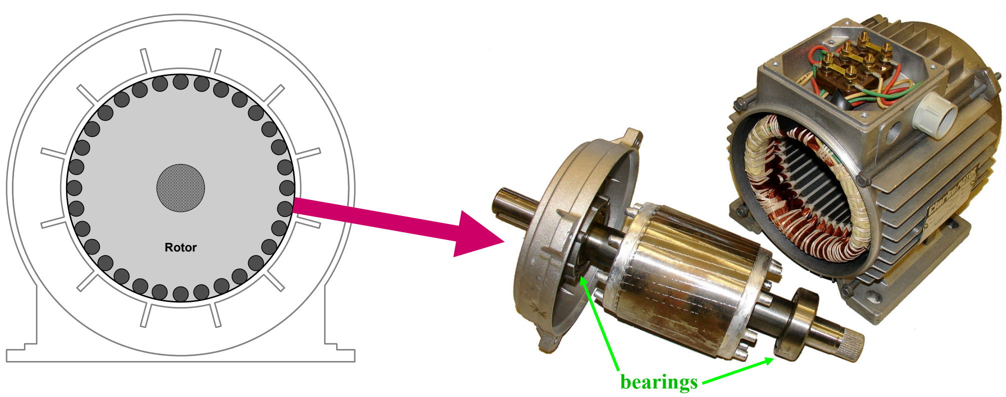
3Φ Induction Motor Construction – Stator



A set of **stator windings** are placed within the slots that are cut into the core, forming an overall magnetic circuit that, when energized, produces the **primary magnetic field** that links with the rotor in order to develop a torque upon the rotor and induce rotation.

9

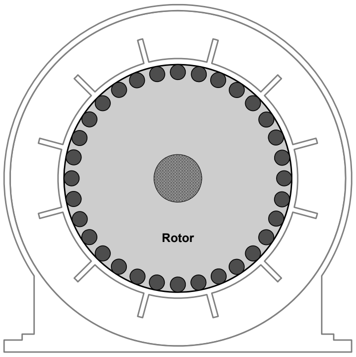
3Φ Induction Motor Construction – Rotor

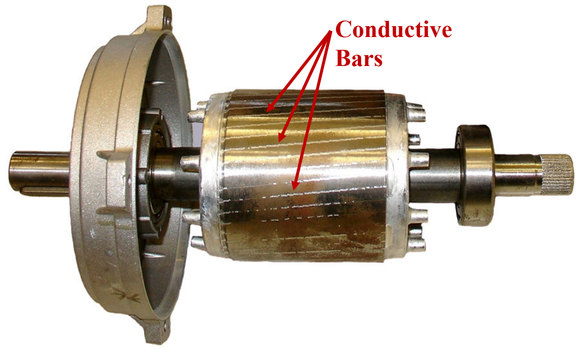


The **rotor** consists of a cylindrical structure that is mounted axially on a central shaft, the ends of which are held in place by a set of bearings that allow the entire structure to rotate freely when placed within hollow center of the stator core.

10

3Φ Induction Motor Construction – Rotor

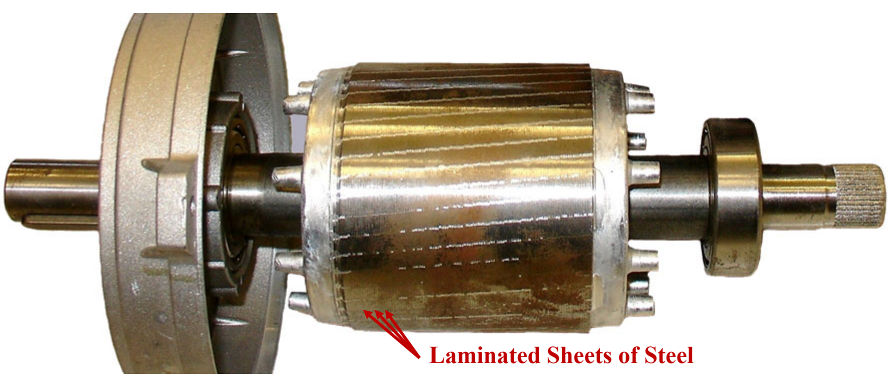




A "**Squirrel-Cage**" rotor is constructed using laminated sheets of steel, through which holes are cut in order to provide openings that span the entire length of the rotor, within which a set of **conductive bars** are embedded.

11

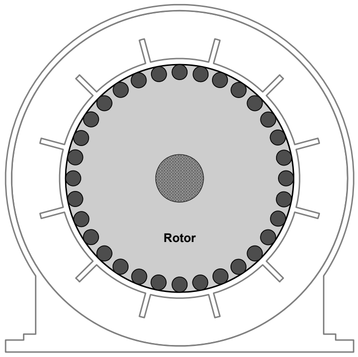
3Φ Induction Motor Construction – Rotor

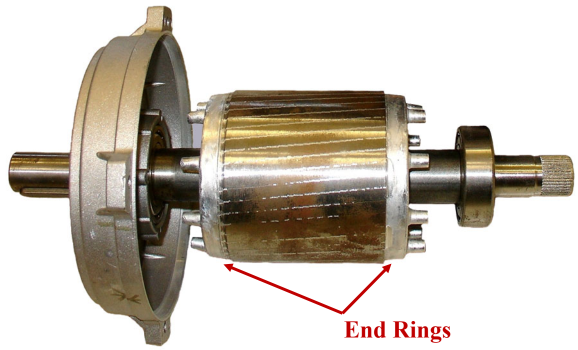


The **laminations** provide insulation between the sheets that form the rotor, thus preventing currents from flowing length-wise through the rotor unless they travel within the embedded bars.

12

3Φ Induction Motor Construction – Rotor





The ends of the **conductive bars** are **shorted** together by a pair of **conductive rings**, forming the “Squirrel-Cage” aspect of the rotor while, more importantly, providing the **closed-loop paths** that are required for current flow within the rotor conductors.

13

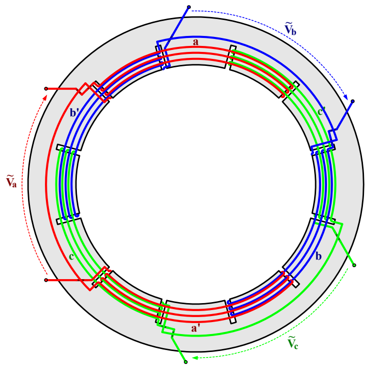
A Closer Look at the Construction

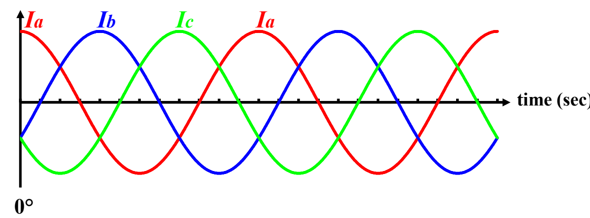
of the

3Φ Squirrel Cage
Induction Motor

14

3Φ Induction Machine Stator

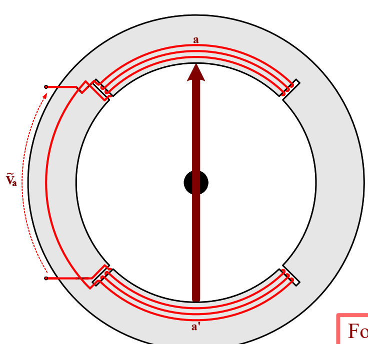


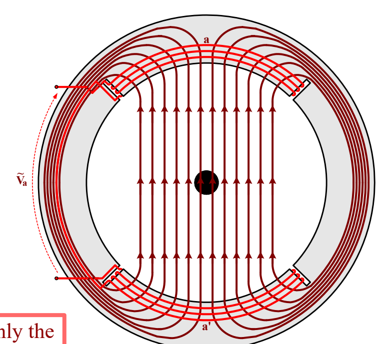


The **stator** contains **three stator windings**, each of which are split into two halves. The half-windings are placed symmetrically around the interior of the stator core, and then wired together to form either a **Y** or **Δ** load for a 3Φ source.

15

3Φ Stator Windings



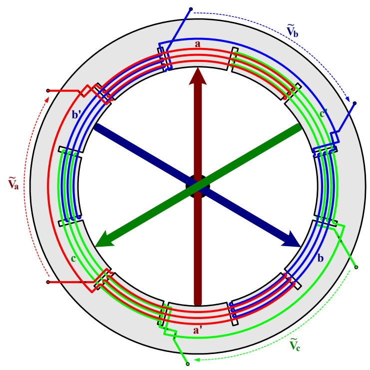


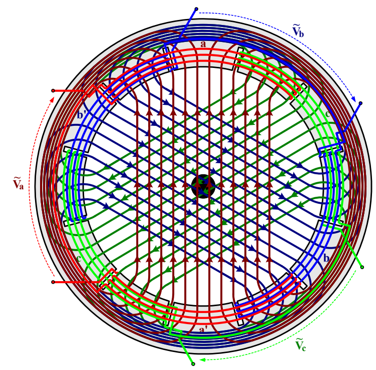
For simplicity, only the "**a**" winding is shown.

When **current** flows through a winding, the winding creates a **magnetic field** that is proportional in magnitude to the current and has closed-loop field lines that pass through "rotor region" and back around through the outer portion of the stator.

16

3Φ Stator Windings

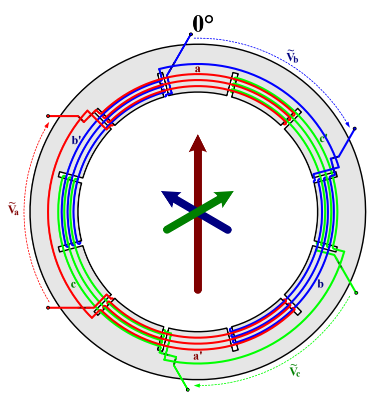


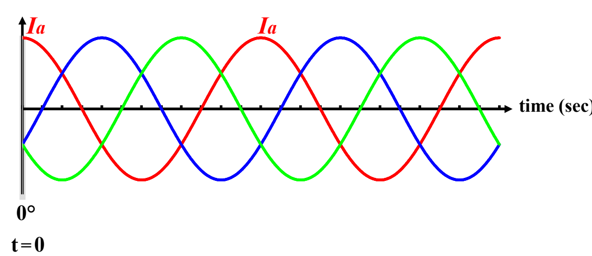


Since the **windings** are placed symmetrically around the stator, the fields created by each of the windings are oriented such that they pass through the rotor region at angles the differ by 120°.

17

3Φ Stator Windings

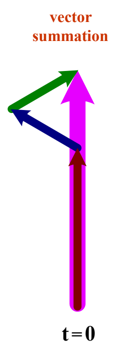


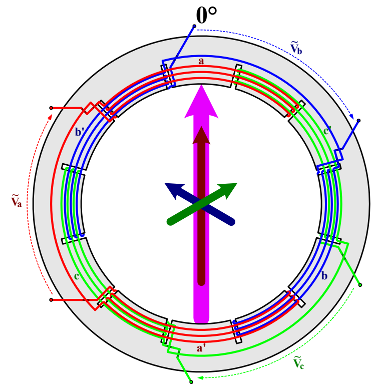


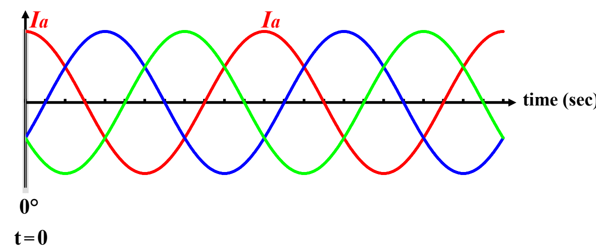
Furthermore, since the windings are supplied with a balanced set of 3Φ currents that differ in phase by 120°, the magnitudes of the individual **fields** created by the windings also vary sinusoidally and differ in phase by 120°.

18

Net Stator Field







The **net stator field** induced within the rotor region by the currents flowing in the stator windings is the **vector sum** of the three individual magnetic fields.

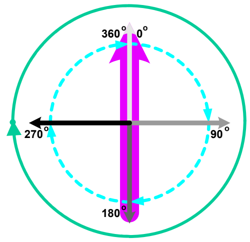
19

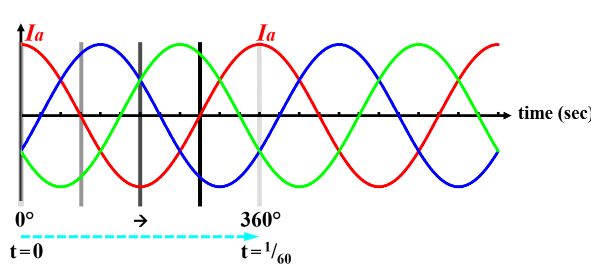
Rotating Stator Field

It turns out that, **during one cycle** of progression (**0°→360°**) in the phase currents, the vector sum of the three individual fields results in a **net stator field, Φ_s,** within the rotor region that:

- has a **magnitude** that remains **constant**, and
- has a **direction** that **rotates** 360° clockwise.

(i.e. – one complete revolution)





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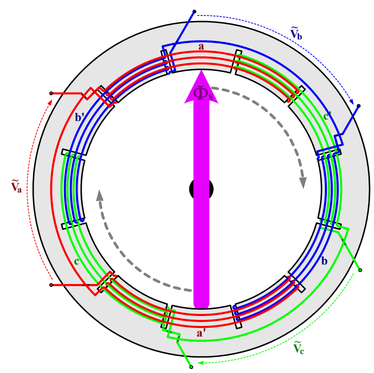
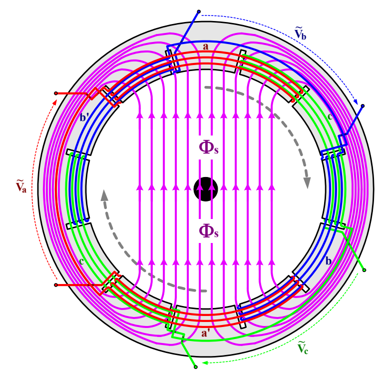
Rotating Stator Field



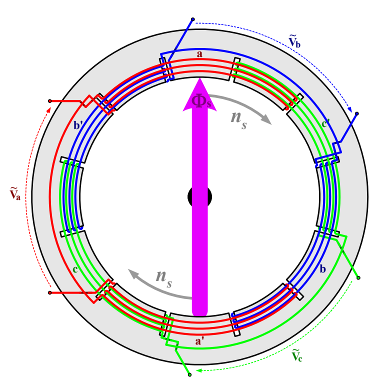


And it is **rotational speed** of the constant magnitude, directionally-rotating stator field, $\mathbf{\Phi_s}$, that fundamentally governs the overall operation of the Squirrel-Cage Induction Motor.

21

Synchronous Speed

Remember that the previously-described stator field completes one rotation for each cycle of progression in the stator currents.



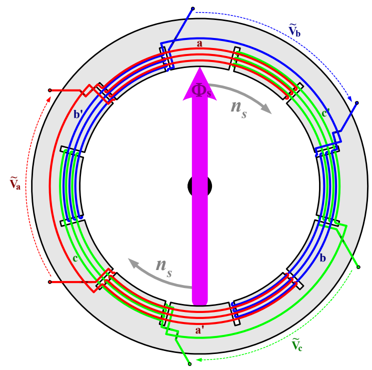
The **synchronous speed**, $\boldsymbol{n_s}$, of an induction motor is defined to be the **rotational speed** of the **stator field**.

(It is referred to as "**synchronous speed**" because the rotor conductors will be synchronized in time with the stator field when rotating at this speed.)

22

Synchronous Speed

Given a $f = 60$ Hz electrical supply, the rotational speed of the previously-described stator field is 60 $^{rev}/_{sec}$ or 3600 RPM.



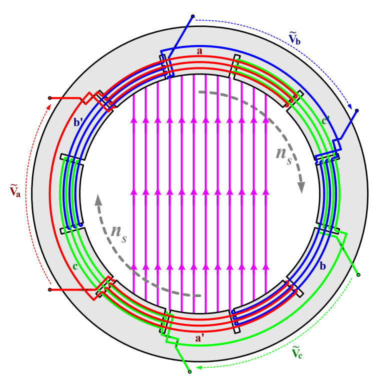
$$n_s = \frac{120 \cdot f_{elec}}{\# \, poles}$$

The **synchronous speed**, $\boldsymbol{n_s}$, is a function of both the **frequency** of the source and the **number of poles*** of the machine.

[* – the # of poles is a constructional feature of the machine]

23

Two-Pole Stator Construction

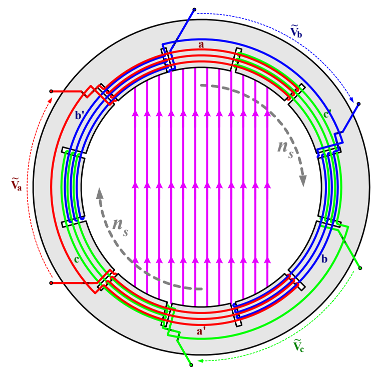


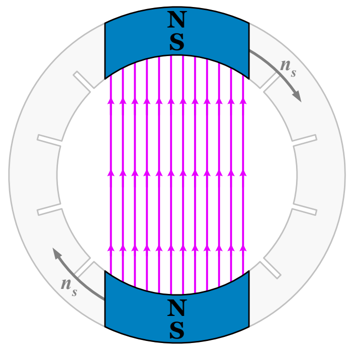
At any point in time, the net stator field induced by the set of three, symmetrically-placed, stator windings, passes through the rotor region from one side to the other in an (ideally) linear manner.

The construction of the previously-described stator is referred to as a "**two-pole**" construction due to the resultant composition or orientation of the **net stator field** within the rotor region.

24

Two-Pole Stator Construction

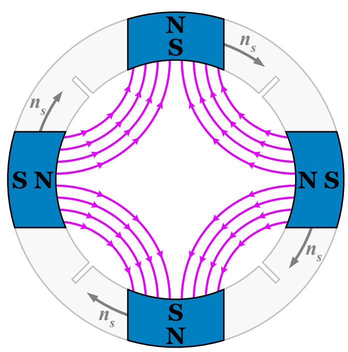




It is a "**two-pole**" construction because the resultant field within the rotor region is similar to the field that would be created by the opposing poles (one N & one S) of two permanent magnets placed on opposite sides of the stator.

25

Four-Pole Stator Construction



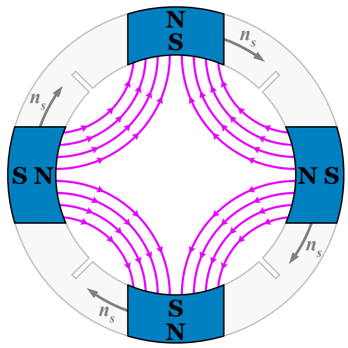
$$n_s = \frac{120 \cdot f_{elec}}{\# \, poles}$$

Other stators constructions also exist, such as a "**four-pole**" stator, that is constructed by placing two sets of symmetrically-placed, three-phase windings.

26

Four-Pole Stator Construction

f = 60 Hz	
# poles	n_s (RPM)
2	3600
4	1800



$$n_s = \frac{120 \cdot f_{elec}}{\#\,poles}$$

Compared to a 2-pole stator field, when supplied at the same frequency, a **4-pole** stator field enters and exits the rotor region at **twice as many locations** but rotates at a **half the speed**.

27

Higher-Order Stator Constructions

f = 60 Hz	
# poles	n_s (RPM)
2	3600
4	1800
6	1200
8	900
10	720

Note that the winding configurations for the 4-pole and higher-order stator designs will neither be shown nor discussed in this presentation.

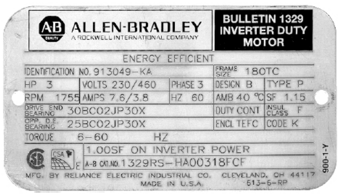
$$n_s = \frac{120 \cdot f_{elec}}{\#\,poles}$$

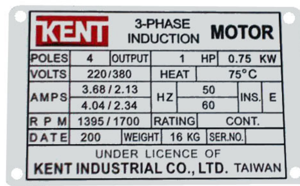
A stator with any **even #** of poles can theoretically be constructed.

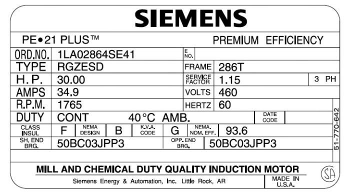
In general, a **2*n*-pole** stator, where ***n*** is an integer (***n*=1,2,3**…), is constructed using ***n***-sets of three, symmetrically-placed, stator windings.

28

Determining the "# of Poles"







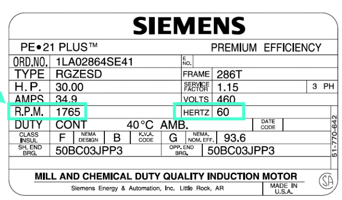
Although manufacturers provide **rated speed** and **frequency** on the nameplate of a motor, the **# of Poles** is not often displayed.

But **rated speed** is **~2–5%** less than **synchronous speed**, and thus the motor's **synchronous speed** will be the **next higher** logical value based on the frequency of operation.

29

Determining the "# of Poles"

rated speed



next higher speed value

$f = 60$ Hz	
# poles	n_s (RPM)
2	3600
4	**1800**
6	1200
8	900
10	720

$$n_s = \frac{120 \cdot f_{elec}}{\# \, poles}$$

Given a **60 Hz** motor with rated speed, $\boldsymbol{n_{rated}}$ **= 1765 rpm**,

Then the synchronous speed of the motor must be $\boldsymbol{n_s}$ **= 1800 rpm**, which relates to a **4 pole** stator construction.

30

An Initial Operational Analysis

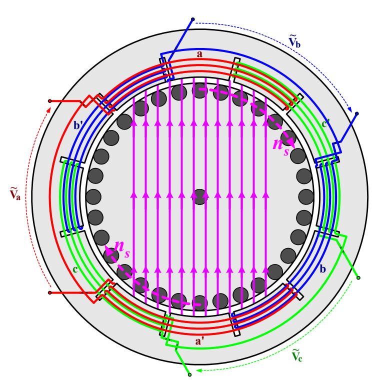
of the

3Φ Squirrel Cage

Induction Motor

31

Stator-Field / Rotor-Conductor Interaction

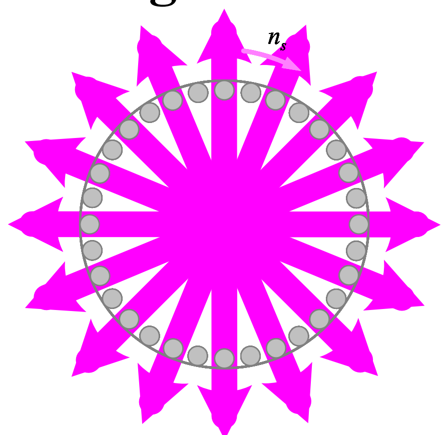


Thus far we have focused on the rotating stator field…

But, what happens when the squirrel-cage **rotor conductors** are **exposed to the rotating stator field**?

32

Rotating Stator Field



As the stator field rotates within the rotor region, its **field lines** cut across the conductors that are embedded under the surface of the cylindrical rotor.

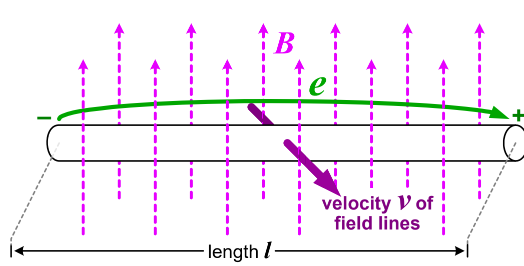
33

Faraday's Law of Induction

Applied to Linear Conductors

Faraday's Law provides that a **voltage will be induced upon a conductor if** either the conductor is moving orthogonally through a magnetic field or the **field-lines** are orthogonally **cutting across the conductor**, the magnitude of which is defined by:

$$e = B \cdot l \cdot v$$



***B* ≡ flux density of stator field**

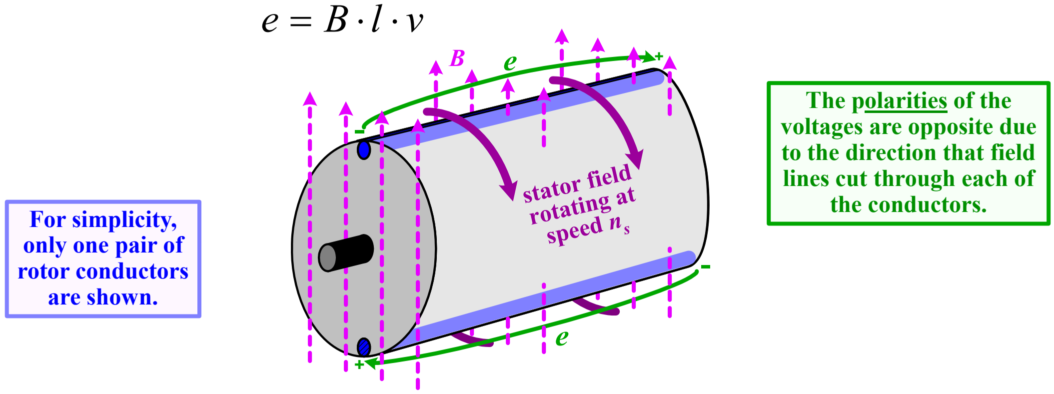
34

Faraday's Law of Induction

Rotating Stator Field & Stationary Rotor Conductors

Since the rotating field lines simultaneously cut across conductors on both sides of the rotor, **voltages** will be induced upon those conductors:

$$e = B \cdot l \cdot v$$

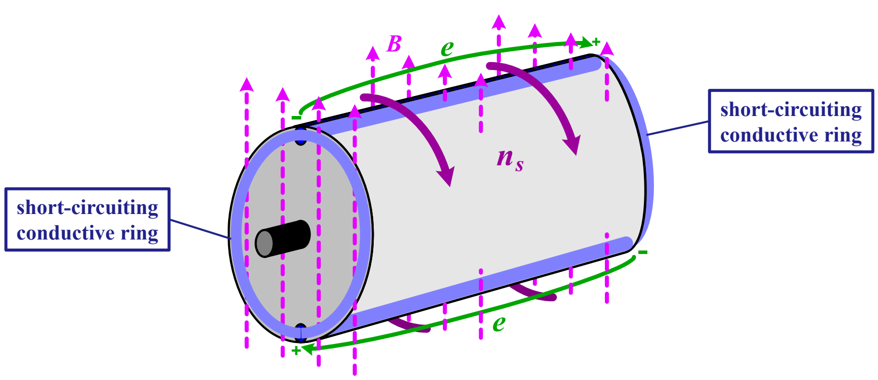


35

Stator Field – Rotor Interaction

Rotor Conductor Currents

In the case of the squirrel-cage rotor, the rotor conductor ends are shorted together by a pair of rings mounted at each end of the rotor, providing **closed-loop paths for current flow.**

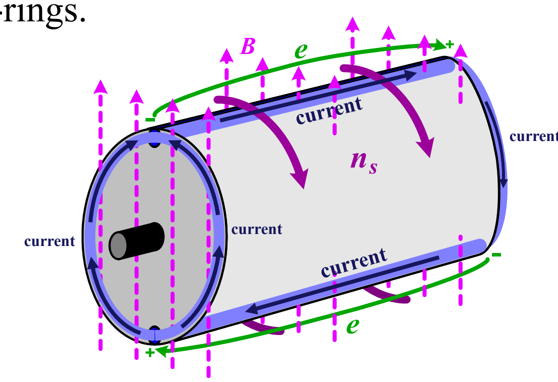


36

Stator Field – Rotor Interaction

Rotor Conductor Currents

Thus, the opposite-polarities of the opposing conductor voltages allow those voltages to work together to induce **currents** that flow in the closed-loop paths provided by the **rotor conductors** and the end-rings.



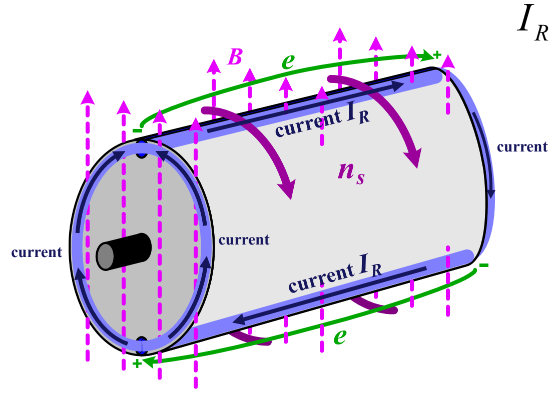
37

Stator Field – Rotor Interaction

Rotor Conductor Currents

The **rotor currents** are proportional to the rotor conductor voltages which, in-turn, are **proportional to the speed** at which the field lines **cut across the conductors**.

$$I_R \equiv e \equiv v_{\perp} \equiv n_s$$



38

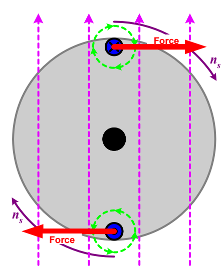
Stator Field – Rotor Interaction

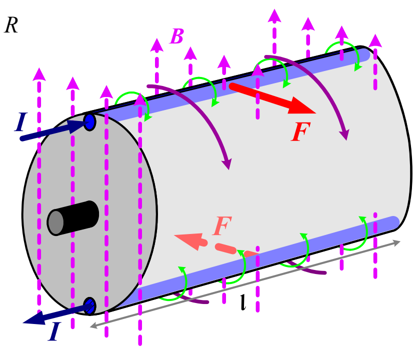
Forces Developed on the Rotor Conductors

The **rotor currents** induce **localized magnetic fields** around the rotor conductors that **interact with** the **stator field**, resulting in **forces** being developed upon the conductors, as defined by:

$$F = B \cdot l \cdot I_R$$

Note that the forces developed upon the opposing conductors point in opposite directions.





39

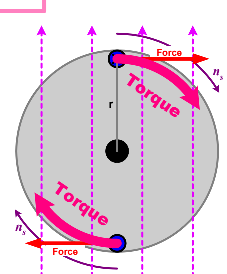
Stator Field – Rotor Interaction

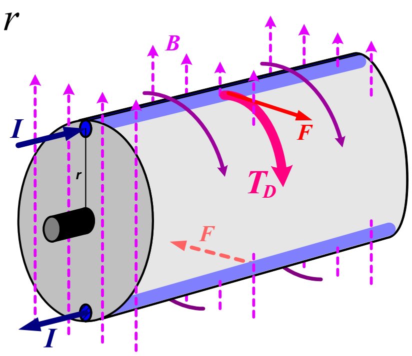
Torque Developed on the Rotor

Due to their directions, the force-pairs result in a **net torque** being **developed** upon the rotor that tries to **accelerate the rotor** in the same direction as the stator field:

$$T_D = 2 \cdot F \cdot r$$

Torque ≡ Rotational Force
Torque is the rotational equivalent of linear force.





40

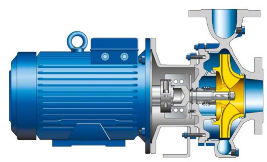
Developed Torque vs. Load Torque

Developed Torque, T_D, is the total torque (rotational force) developed by the rotor, at a specific speed and in the rotational direction of the stator field, due to the interaction between the rotor conductors and the stator field.

Developed Torque relates to an **acceleration** force that "tries" to **increase** the rotor speed.

Load Torque, T_{Load}, is the torque applied to the shaft of the rotor by an externally-coupled device, at a specific speed, that opposes the rotation of the rotor.

Load Torque relates to a **deceleration** force that "tries" to **decrease** the rotor speed.

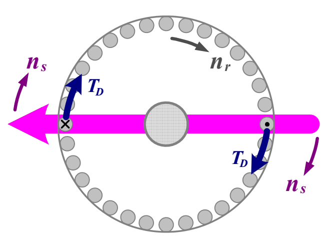


Motor coupled to a Pump

41

Rotation of the Rotor

Rotor Acceleration



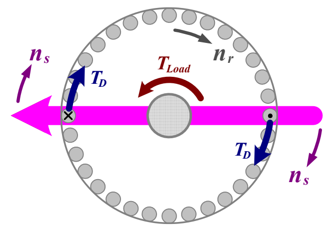
The operation of the rotor is a function of both the **torque**, T_D, **developed** by the motor, and any external forces experienced by the machine's rotor that oppose its rotation.

Note that the **developed torque**, T_D, tries to **accelerate** the rotor in the same direction as the rotating stator field.

42

Rotation of the Rotor

Load Torque



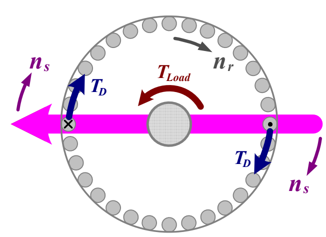
The **total load torque**, T_{Load}, experienced by the machine's rotor is the total torque, applied to its shaft, that opposes rotation.

In this case, T_{Load} includes both the stopping force provided by any mechanical load coupled to the shaft, along with any friction, windage, or other rotational loss experienced by the rotor.

43

Rotation of the Rotor

Acceleration Torque



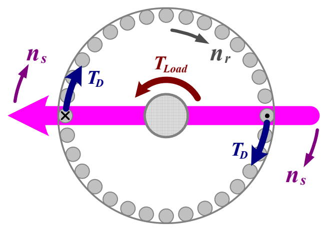
The **acceleration torque**, T_{accel}, experienced by the rotor is the difference between the amount of torque (T_D) available to accelerate the rotor and any coupled mechanical load (T_{Load}), as defined by:

$$T_{accel} = T_D - T_{Load}$$

44

Rotation of the Rotor

Acceleration Torque



And, based on the value of the **acceleration torque**, $\boldsymbol{T_{accel}}$:

If $\boldsymbol{T_{accel} > 0}$, then **rotor speed** will **increase**.

If $\boldsymbol{T_{accel} < 0}$, then **rotor speed** will **decrease**.

If $\boldsymbol{T_{accel} = 0}$, then **rotor speed** will **remain constant**.

45

Stator Field – Rotor Interaction

Rotational Effect on Developed Torque

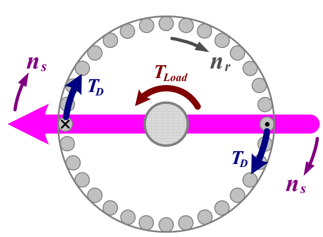
$T_D \equiv F$

$F \equiv I$

$I \equiv e$

$e \equiv v_\perp$

$v_\perp \equiv n_s$



$n_s \equiv$ sync. speed

$n_r \equiv$ rotor speed

Note that the **developed torque**, $\boldsymbol{T_D}$, is **proportional** to the **rate** at which the **stator field cuts across the rotor conductors**.

While stopped ($\boldsymbol{n_r = 0}$), the rate at which the field lines cut across the rotor conductors is **proportional** to the **synchronous speed**.

46

Stator Field – Rotor Interaction

Rotational Effect on Developed Torque

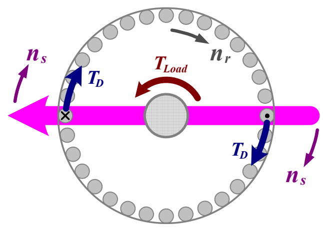
$T_D \equiv F$

$F \equiv I$

$I \equiv e$

$e \equiv v_\perp$

$v_\perp \equiv n_{effective}$



$n_s \equiv$ sync. speed

$n_r \equiv$ rotor speed

$n_{effective} = n_s - n_r$

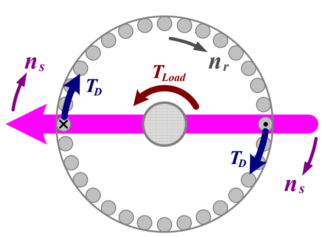
But from the **perspective** of the rotor conductors, the **rate** at which the field lines actually cut across the conductors **decreases** as the **rotational speed of the rotor increases**.

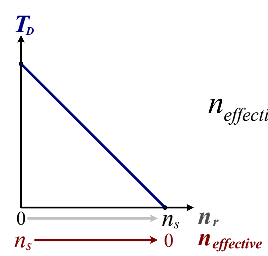
Thus, an **effective speed** at which the field-lines cut across the rotor conductors can be defined as: $\boldsymbol{n_{effective} = n_s - n_r}$.

47

Stator Field – Rotor Interaction

Effective Speed





$n_{effective} = n_s - n_r$

Effective speed, which is the difference between the rotational speeds of the stator field and the rotor:

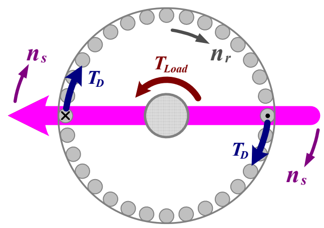
$$\boldsymbol{n_{effective} = n_s - n_r}$$

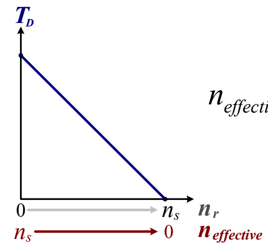
decreases linearly as rotor speed increases from zero up to synchronous speed.

48

Stator Field – Rotor Interaction

Effective Speed and Developed Torque





$$n_{effective} = n_s - n_r$$

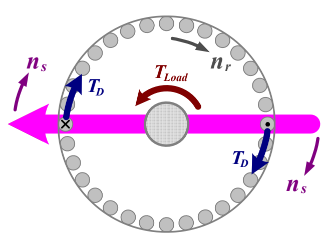
Since the **developed torque**, T_D, is **proportional** to the **effective speed**, $n_{effective}$, the developed torque will decrease linearly as the rotor speed increases, eventually decreasing to zero as the rotor reaches synchronous speed.

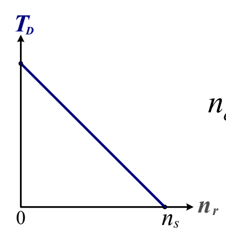
$$\text{As: } n_r \to n_s, \quad n_{effective} \to 0, \quad T_D \to 0$$

49

Ideal Motor Operation

Torque-Speed Curve





$$n_{effective} = n_s - n_r$$

Thus, based on the previous analysis, the **torque-speed curve** shown above defines the operational characteristics of an "**ideal**" **induction motor** for rotor speeds ranging from $\mathbf{0} \rightarrow \boldsymbol{n_s}$.

We will utilize this curve as we continue our investigations.

50

A Deeper Operational Analysis

of the

3Φ Squirrel Cage Induction Motor

51

Ideal Operation vs. No-Load Operation

With respect to the operation of a motor, **ideal operation** refers to the motor's internal losses, while **no-load operation** refers to any external forces (torques) being applied to its shaft.

Ideal Operation is a theoretical state of operation during which all internal "losses" are considered negligible, such that 100% of the electric energy supplied to the motor is converted to a mechanical form and delivered to the load that is coupled to the shaft.

No-Load Operation is a practical state of operation during which there is no physical load ($T_{Load} = 0$) coupled to the shaft of the motor that opposes its rotation, such that 100% of the electric energy supplied to the motor is being consumed by the motor's internal losses.

52

Ideal Operation vs. No-Load Operation

Despite their distinct separation, where **ideal operation** refers to the internal losses and **no-load operation** refers to externally applied forces, the line between the two often becomes blurred:

Along with any **electrical losses** that may exist within the stator windings and rotor conductors of a practical motor, and any **magnetic losses** (hysteresis or eddy current) that may exist within its magnetic core, **ideal operation** is also considered to include any **rotational losses** that exist within the motor's "mechanical system" (friction, windage, etc.).

The motor's **mechanical system** includes the bearings that hold the shaft in place while allowing rotation, and any components that are attached to the rotor for cooling purposes, such as fins that circulate air during rotation.

53

Ideal Operation vs. No-Load Operation

Despite their distinct separation, where **ideal operation** refers to the internal losses and **no-load operation** refers to externally applied forces, the line between the two often becomes blurred:

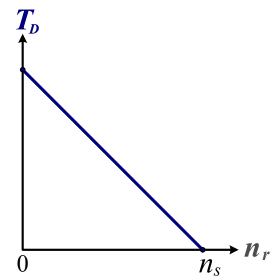
On the other hand, **no-load operation**, during which there is no physical load coupled to the shaft that opposes its rotation, is often **considered to include** any of the **rotational losses** that exist within the motor's mechanical system, because those losses relate to an additional torque being applied to the rotor that also oppose its rotation.

Thus, despite resulting from components that are an integral part of the motor's construction and required for its operation, the **rotational losses** are often neglected during "no-load" operation, even if the electrical and magnetic losses that occur within the motor as still being included during the analysis.

54

Operation of the Induction Motor

Ideal Conditions



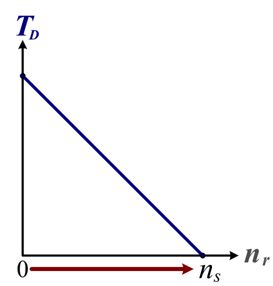
All of the previous discussion has related to __ideal__ operation of the motor since it hasn't included any of the loss components that exist within a practical machine. And we will continue the discussion by first analyzing the operation of an **ideal motor**, after which we will consider aspects of practical operation.

55

Ideal Operation of the Induction Motor

No-Load Conditions

When energized under No-Load conditions:
$n_r \rightarrow n_s$
$T_D \rightarrow 0$
$T_{accel} = T_D - T_{Load} \rightarrow 0$
$n_r \rightarrow n_s$ *(steady-state)*



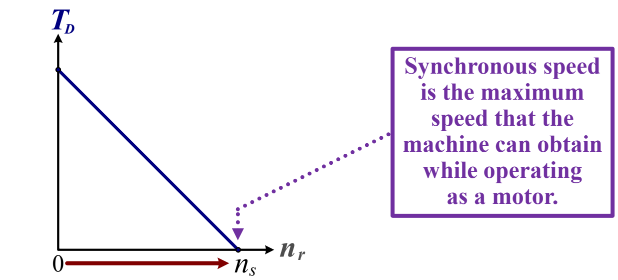
Under "**no-load**" conditions ($T_{Load} = 0$):

The rotor will accelerate up to its **synchronous speed** ($n_r = n_s$), at which point the developed torque (T_D), load torque (T_{Load}), and acceleration torque (T_{accel}) all equal zero, resulting in an equilibrium state where the motor maintains **steady-state** rotation at that speed.

56

Ideal Operation of the Induction Motor

No-Load Conditions

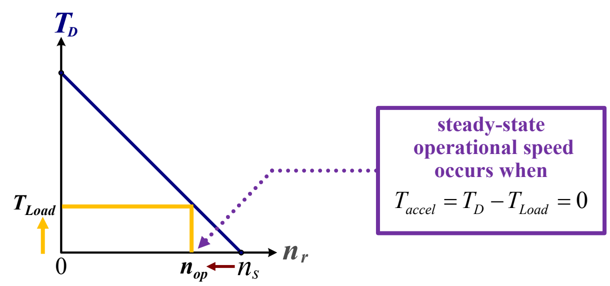


Note that, once the motor reaches **synchronous speed**, it develops no torque because the field lines no longer cut through the rotor conductors (i.e. – they're synchronized). Due to this limiting effect, **an induction motor <u>cannot</u> accelerate beyond synchronous speed** by its own power.

57

Ideal Operation of the Induction Motor

When Loaded after No-Load Operation

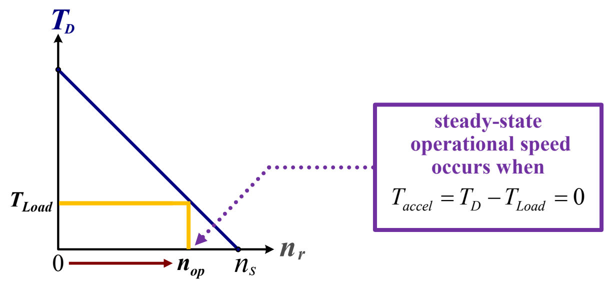


If a **load torque** is applied to the rotor **after** it reaches synchronous speed (no-load conditions), then the rotor will **slow down** to a new **operational speed** ($n_r = n_{op}$) at which the **developed torque**, T_D, is **equal to** the **load torque**, T_{Load}, and $T_{accel} = 0$.

58

Ideal Operation of the Induction Motor

While Under Load at Start-Up



Similarly, if a **load torque** is applied to the rotor at "**startup**", then the rotor will only be able **accelerate** up to the **speed**, $\boldsymbol{n_{op}}$, at which the **developed torque**, $\boldsymbol{T_D}$, **equals** the **load torque**, $\boldsymbol{T_{Load}}$, and $\boldsymbol{T_{accel} = 0}$.

59

Slip

Since the developed torque is proportional to effective speed and not the actual rotor speed, operation of an induction motor is often characterized in terms of "**slip**".

Slip, ***s*****,** is defined as the **relative difference** between the motor's **synchronous speed** and the actual **rotational speed**:

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

and is either expressed as a "unit" value (as defined above), or as a "percent" value when multiplied by 100%.

60

Slip – Calculation Example

Determine the **slip** of a **4-pole**, **60 Hz** induction motor that is rotating at a speed of **1710 rpm**.

Since **slip** is defined by: $s = \frac{n_s - n_r}{n_s}$

First determine **synchronous speed**: $n_s = \frac{120 \cdot f_{elec}}{\#\text{ of poles}} = \frac{120 \cdot 60}{4} = 1800 \text{ rpms}$

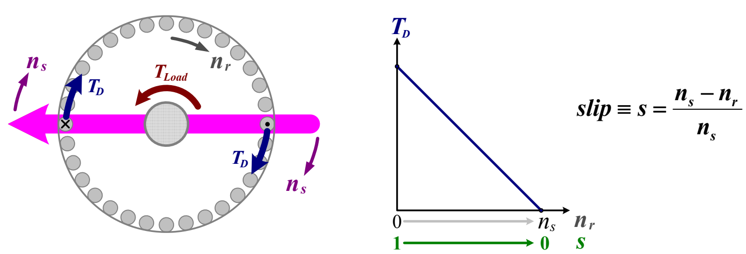
And then **slip**: $s = \frac{n_s - n_r}{n_s} = \frac{1800 - 1710}{1800} = 0.05 \quad \text{(or 5\%)}$

1710rpm is 5% less than the 1800rpm synchronous speed

61

Ideal Operation of the Induction Motor

Slip



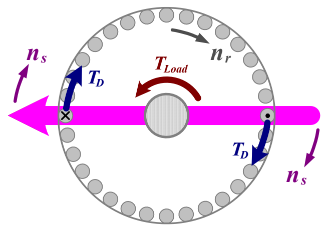
As **rotor speed**, $\boldsymbol{n_r}$, **increases** linearly from $\mathbf{0} \rightarrow \boldsymbol{n_s}$ (synchronous speed), **slip**, s, **decreases** linearly from $\mathbf{1} \rightarrow \mathbf{0}$.

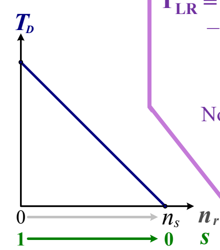
Note that **slip** and **developed torque** are proportional because they both decrease linearly $\rightarrow \mathbf{0}$ as rotor speed increases from $0 \rightarrow n_s$.

62

Ideal Operation of the Induction Motor

Torque-Slip Relationship





T_{LR} ≡ Locked-Rotor Torque – the torque developed by the machine when the rotor isn't moving (**n_r = 0**).

Note: Locked-Rotor Torque may also be referred to as Blocked-Rotor Torque and/or Starting Torque.

And, since it is linearly proportional to slip, **developed torque**, T_D, can be expressed in terms of both the **locked-rotor torque**, T_{LR}, and **slip** as:

$$T_D = T_{LR} \cdot s$$

63

Practical Operation

of a

3Φ Squirrel Cage Induction Motor

64

Practical Operation of an Induction Motor

Now that we've discussed the basic operational characteristics of an "ideal" induction motor, both under no-load conditions and when a load is coupled to the shaft of the motor, we need to begin taking a look at:

The operational characteristics of an Induction Motor if it is no longer considered ideal…

I.e. – if it's a **Practical Induction Motor**.

But, due to the fact that we could spend several weeks simply discussing and analyzing the different loss components that occur within the motor, the remaining portion of this presentation will instead focus on:

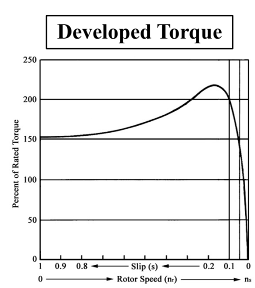
- ❶ the operational characteristics of a practical induction motor,
- ❷ methods that can be used to determine those characteristics and/or predict the motor's operation, and
- ❸ the impact to those characteristics, along with other concerns, from a motor-control perspective.

65

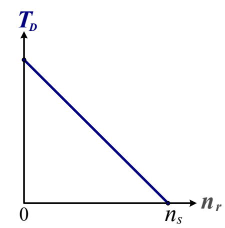
Practical Motor Operation

If an induction motor's **internal losses** are taken into account, one of the primary changes that occurs in the motor's operation (compared to ideal) is a reshaping of its **torque-speed response** curve due to a major decrease in the torque developed at slower speeds.

As can be seen, torque-speed response curves for the practice machines differ greatly compared to that for an ideal induction motor.



Practical Motor



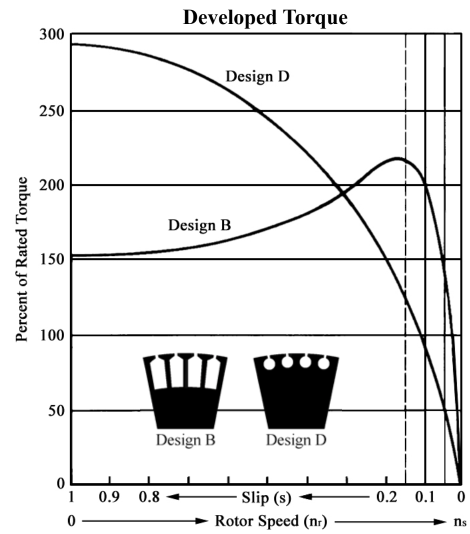
Ideal Motor

66

Practical Motor Operation

The torque-speed response curve shown in the previous slide was representative of the curve for a standard NEMA Design B* motor.

It turns out that shape of the curve can be tailored to suit a specific application by modifying the size, shape, and/or placement of the conductors that are embedded within the rotor.



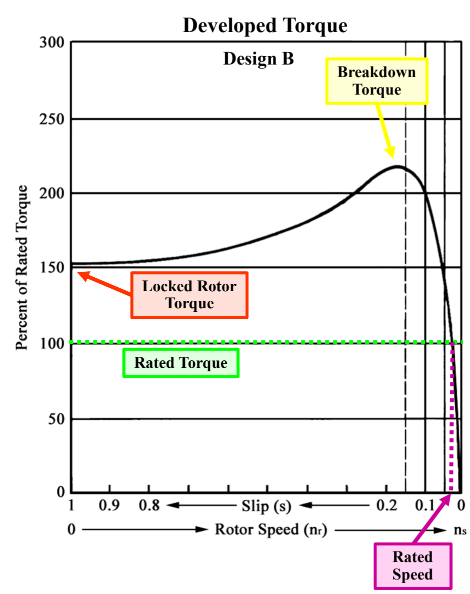
*** – NEMA ≡ National Electrical Manufacturers Association**
NEMA standards will be discussed in a different presentation.

67

Practical Motor Operation

The non-linear torque-speed curve introduces many changes in the overall operation of the motor, especially when a load is coupled to its shaft.

But, in order to help clarify the importance of both the changes due to the torque-speed curve, and several of the motor's other operational characteristics that we've yet to discuss, there are a few terms that must be defined.



68

Induction Motor Ratings / Parameters

Ratings

Horsepower ≡ The maximum continuous shaft power that the motor can provide in order to drive the load coupled to its shaft. (May be referred to as "Rated Load".)

Rated Voltage ≡ The specified operational line voltage. (Operating an IM with less-than-rated line voltage may result in larger-than-rated line currents.)

Rated Current ≡ The current that the motor will draw when supplied at rated voltage and driving rated load. (Line currents is excess of this value will result in motor overheating.)

Rated Torque ≡ The maximum continuous torque that the motor can develop in order to drive the load coupled to its shaft. (Rotational Force) (May be referred to as "Rated Load".)

Rated Speed ≡ The speed at which the motor will rotate when supplied with rated voltage and driving rated load. (Rated speed is typically within 5% of synchronous speed.)

Additional Parameters

Synchronous Speed ≡ The speed at which the motor will rotate under 'no-load' conditions.

Locked-Rotor Current ≡ The amount of current that the motor will draw at standstill when supplied with rated voltage. (LR current is typically 4-10x larger than rated current.)

Locked-Rotor Torque ≡ The amount of torque that the motor will develop at standstill when supplied with rated voltage. (Often associated with Starting Torque.)

Breakdown Torque ≡ The maximum instantaneous torque that the motor can develop during "normal operation" without stalling.

Determining the Characteristics/Parameters

There are many possible methods for obtaining the operating characteristics or parameters of a specific motor, including:

- Obtain the information from the motor's **nameplate***.
- Obtain the information from the **manufacturer**.
- Obtain the information from a **NEMA Standards Publication***.
- Take **measurements** to determine the motor's parameters.
- Create a **theoretical model** for the machine and analyze the model in order to determine the motor's operational characteristics and/or parameters.

* – We will discuss both of these topics later in the semester during a different presentation.

Determining the Characteristics/Parameters

The first three options:

- Obtain the information from the motor's **nameplate**.
- Obtain the information from the **manufacturer**.
- Obtain the information from a **NEMA Standards Publication**.

tend to be the easiest and quickest, although each may provide only a limited amount of information, and the values obtained are typically average values for motors with those ratings.

Yet, taking **measurements** in order to determine a specific motor's parameters may be impractical due to the equipment needed to perform such measurements, especially when testing large motors or when needing mechanical parameters (torque, speed, …).

71

Machine Modeling

On the other hand, if highly detailed information is required and direct measurements are not feasible, a **theoretical model** for the machine that can be used to determine the motor's operational characteristics under various conditions.

The **complexity of the models** can vary greatly, ranging from a simple circuit model of the motor's electrical components to a highly-complex finite-element model that encompasses every aspect of the machine's construction, including the exact dimensions of each component, the mass of the components, and even the magnetic material properties of the steel used for the construction of the motor.

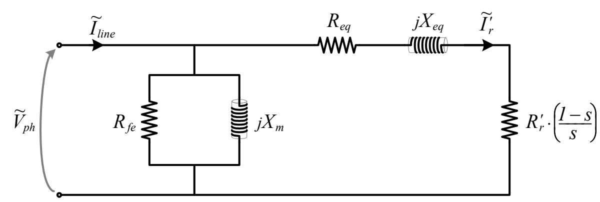
72

Machine Modeling

Although **machine modeling** is **beyond the scope** of this course, it is worth taking a look at the results that can be obtained from even a simple model of an induction motor, especially as they relate to its operating characteristics, and the implications that arise when considering its operation from a control perspective.

Thus, the following 1Φ equivalent circuit will be used to model the operation of a motor:

*** – limited information regarding the theory behind this model is available upon requested.**



73

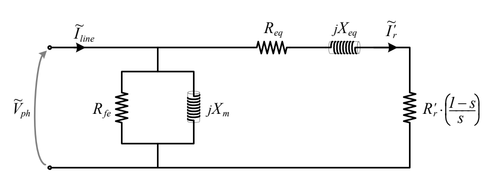
Induction Motor Modeling Example

Given a **150 hp**, **1160 rpm**, **460 V**, **160 A**, **3Φ**, **SC** Induction Motor,

where: $T_{rated\,(\text{lb}\cdot\text{ft})} = \dfrac{P_{rated\,(\text{hp})} \cdot 5252}{n_{rated\,(\text{rpm})}} = \dfrac{150 \cdot 5252}{1160} = 679\ (\text{lb}\cdot\text{ft})$,

utilize the following 1Φ equivalent circuit in order to determine the **line current**, $\boldsymbol{I_{line}}$, that the motor will draw and the **torque**, $\boldsymbol{T_D}$, that the motor will develop, at rotor speeds ranging from:

(locked-rotor) $\boldsymbol{0 \leq n_r \leq n_s}$ (synchronous speed)



Note that this model does not account for the motor's mechanical losses.

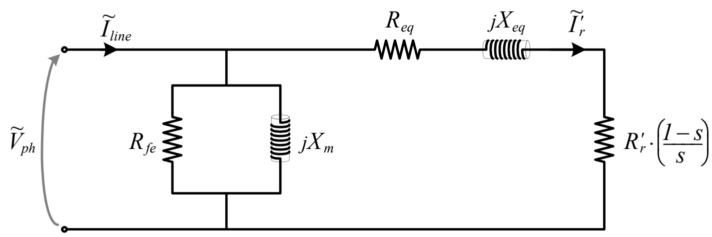
74

Induction Motor Model Parameters

No-Load* and **Locked-Rotor*** tests were performed on the motor, the results of which provided the following equivalent circuit parameters:

$$R_{eq} = 0.1236\Omega \qquad R_r' = 0.0556\Omega \qquad X_{eq} = 0.179\Omega$$

$$R_{fe} = 67.0\Omega \qquad X_m = 11.22\Omega$$



*** – information regarding these tests will not be presented here.**

75

Induction Motor Model & Equations

The model was then utilized to determine the **line current**, $\boldsymbol{I_{line}}$, and the **torque**, $\boldsymbol{T_D}$, at speeds ranging from $\boldsymbol{0 \le n_r \le n_s}$.

$$\tilde{I}_r' = \frac{\tilde{V}_{ph}}{R_{eq} + jX_{eq} + R_r' \cdot \left(\frac{1-s}{s}\right)}$$

$$\tilde{I}_{line} = \tilde{I}_r' + \frac{\tilde{V}_{ph}}{R_{fe} \parallel jX_m}$$

$$1\text{ hp} \cong 746\text{ watts}$$

$$n_s = \frac{120 \cdot f_{elec}}{\#\,poles}$$

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

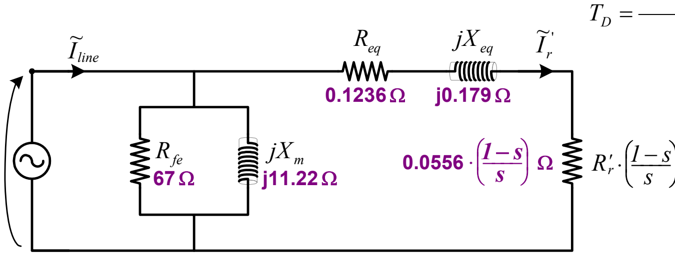
$$P_{mech} = \frac{3}{746} \cdot \left|\tilde{I}_r'\right|^2 \cdot R_r' \cdot \left(\frac{1-s}{s}\right) \text{ (hp)}$$

$$T_{D(lb \cdot ft)} = \frac{5252 \cdot P_{mech(hp)}}{n_{r(rpm)}}$$

$$T_D = \frac{21.12 \cdot \left|\tilde{I}_r'\right|^2 \cdot R_r'}{s \cdot n_s} \text{ (lb} \cdot \text{ft)}$$

$$\tilde{V}_{ph} = \frac{\tilde{V}_{line}}{\sqrt{3}\angle 30^\circ}$$

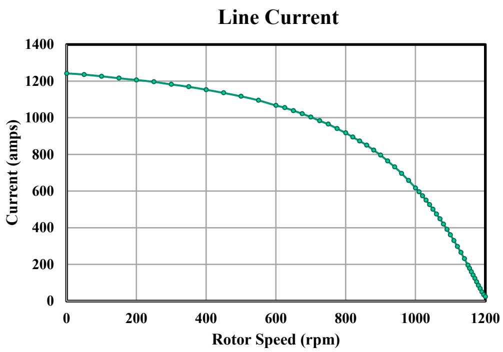
265.6∠0° volts

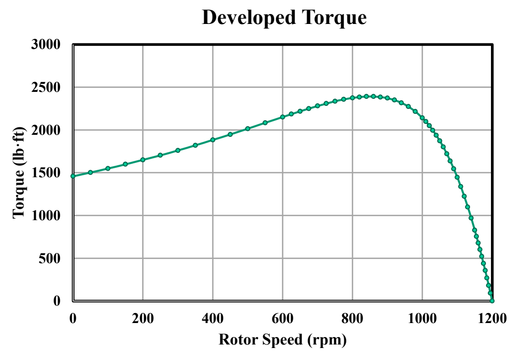


76

Analysis of the Results

The following **line current** (***I**$_{line}$*) and **developed torque** (***T**$_D$*) plots are based on the results obtained from the equivalent circuit of the **150 hp**, **679 lb·ft 1160 rpm**, **460 V**, **160 A**, **3Φ**, **SC** induction motor for rotor speeds, n_r, ranging from $0 \le n_r \le n_s$.





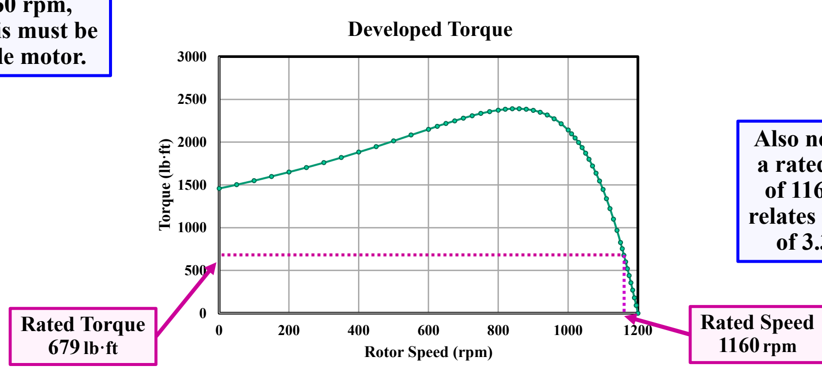
77

Analysis of the Results – Torque

Let's begin by taking a closer look at the **torque-speed response** curve to which the associated motor **ratings** have been added:

679 lb·ft, 1160 rpm

Note that, if the rated speed is 1160 rpm, then this must be a 6-pole motor.



Also note that a rated speed of 1160 rpm relates to a slip of 3.33%.

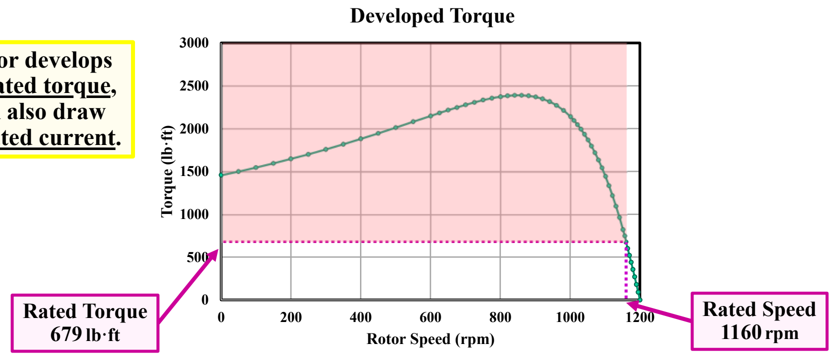
78

"Overload" Conditions – Torque

Note that, whenever the motor is rotating at **less-than-rated speed**, the motor will be developing **greater-than-rated torque**:

679 lb·ft, 1160 rpm

When the motor develops greater-than-rated torque, the motor will also draw greater-than-rated current.



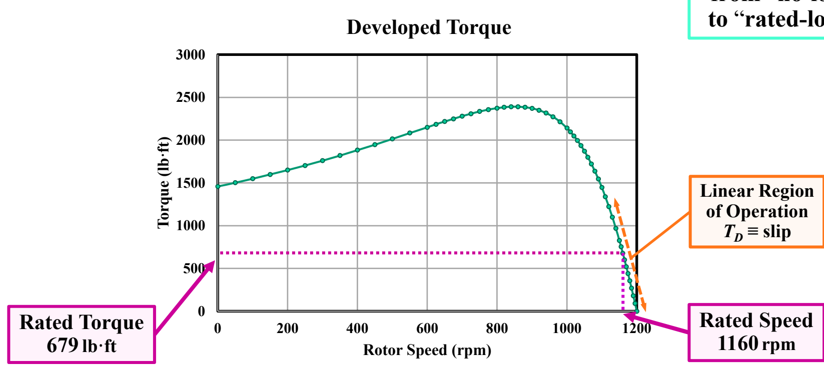
79

Linear Region of Operation

Within the region of **normal operation***, the torque-speed curve is relatively **linear**, and thus torque is proportional to slip:

$$T_D = k \cdot s$$

*** – with respect to loads ranging from "no-load" to "rated-load".**

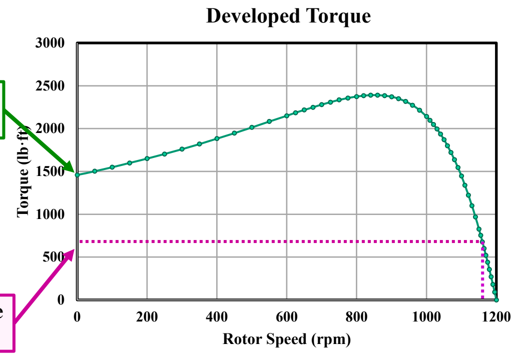


80

Locked-Rotor Torque

Locked-Rotor Torque is the torque that the motor develops if the shaft is held in position ($n_r = 0$) while supplied at rated voltage.

Locked-rotor torque is indicative of the **Starting Torque** developed by the motor.



Locked-Rotor Torque – 1459 lb·ft

$$\frac{T_{LR}}{T_{rated}} = \frac{1459}{679} = 2.15$$

Rated Torque 679 lb·ft

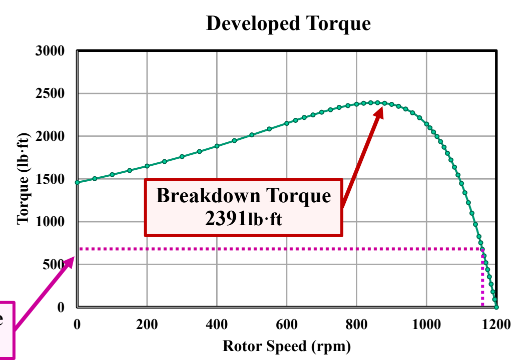
Standard IMs have:
- **starting torques that typically range from 70% → 250% of T_{rated} depending on their size and design class.**

81

Breakdown Torque

Breakdown Torque is the maximum torque that the motor can develop <u>after</u> it has already been operating normally ($n_r \approx n_{rated}$).

If the **load torque** rises above this value while operational, the induction motor will **stall** ($n_r \to 0$).



$$\frac{T_{BD}}{T_{rated}} = \frac{2391}{679} = 3.5$$

Breakdown Torque 2391 lb·ft

Rated Torque 679 lb·ft

Standard IMs have:
- **breakdown torques that typically range from 175% → 250% of T_{rated} depending on their size and design type.**

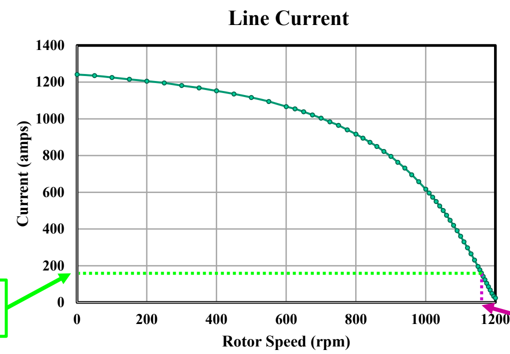
82

Analysis of the Results – Current

Now let's take a closer look at the **current-speed response** curve to which the associated motor **ratings** have been added:

160 A, 1160 rpm

Remember that <u>rated current</u> is associated with the <u>maximum continuous</u> current that the motor can draw without overheating.



Rated Current 160 A

Rated Speed 1160 rpm

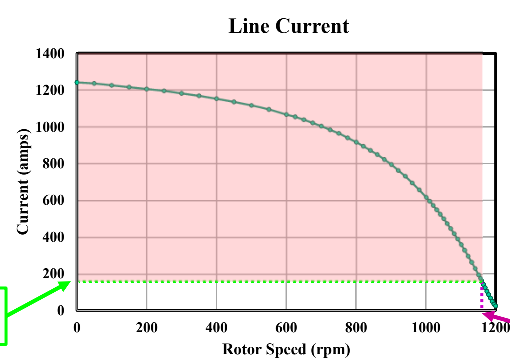
83

Overload Conditions – Current

Note that, whenever the motor is rotating at **less-than-rated speed**, the motor will be drawing **greater-than-rated current**:

160 A, 1160 rpm

Remember that <u>rated current</u> is associated with the <u>maximum continuous</u> current that the motor can draw without overheating.



Rated Current 160 A

Rated Speed 1160 rpm

84

Locked-Rotor Current

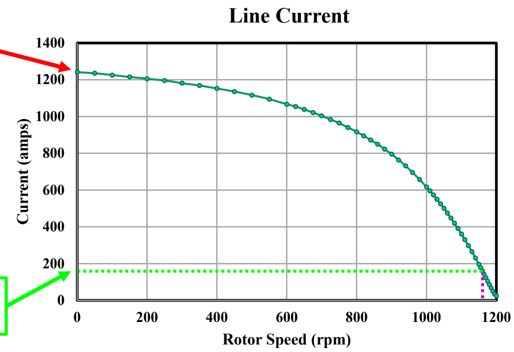
Locked-Rotor Current is the current that the motor will draw when the shaft is held in position (**n_r=0**) while supplied at rated voltage.

Although not exactly the same, locked-rotor current is indicative of the **Starting Current** for the motor.

Locked-Rotor Current – 1242A

$$\frac{I_{LR}}{I_{rated}} = \frac{1242}{160} = 7.76\ !!!$$

Rated Current 160 A



Since the heat produced by a lossy conductor is proportional to I^2, if the L-R current is 7.76x larger than I_{rated}, then the motor produces almost <u>60x more heat</u> at LR compared to that at rated operation!!!

85

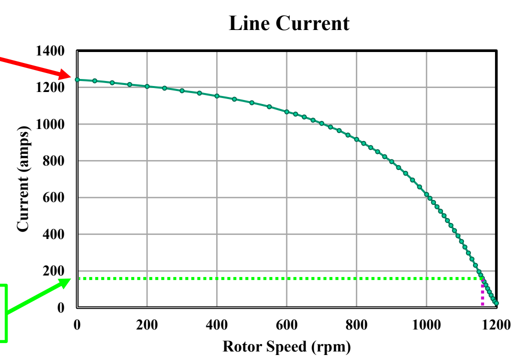
Locked-Rotor Current

Locked-Rotor currents are often **4-10x larger** than a motor's rated current, which can present a special challenge when designing the branch circuit that supplies power to the motor and the system that protects and controls the motor.

Locked-Rotor Current – 1242A

$$\frac{I_{LR}}{I_{rated}} = \frac{1242}{160} = 7.76\ !!!$$

Rated Current 160 A



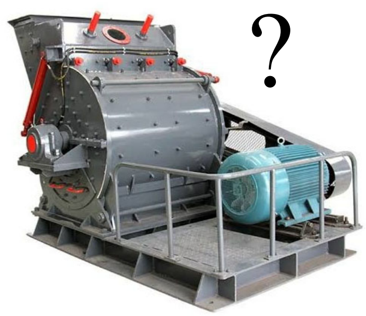
Note that the multiplication factor relating a motor's locked-rotor current to its rated current tends to increase with increasing motor size.

86

Predicting the Motor’s Operation

Although we have a fair amount of information regarding the motor’s operational characteristics, there’s still one important piece of the puzzle that’s missing…

the characteristics of the **load** that’s coupled to the motor’s shaft.



?

87

Motor Loads

A motor’s **load** is any mechanical device that is coupled to the shaft of the motor with the intent of using the motor to provide the torque required, and in-turn the energy required, to rotate the device at a specific speed.

Common motor loads include **fans**, **pumps**, **elevators**, **conveyors**, **hoists**, **compressors**, and **winches**.

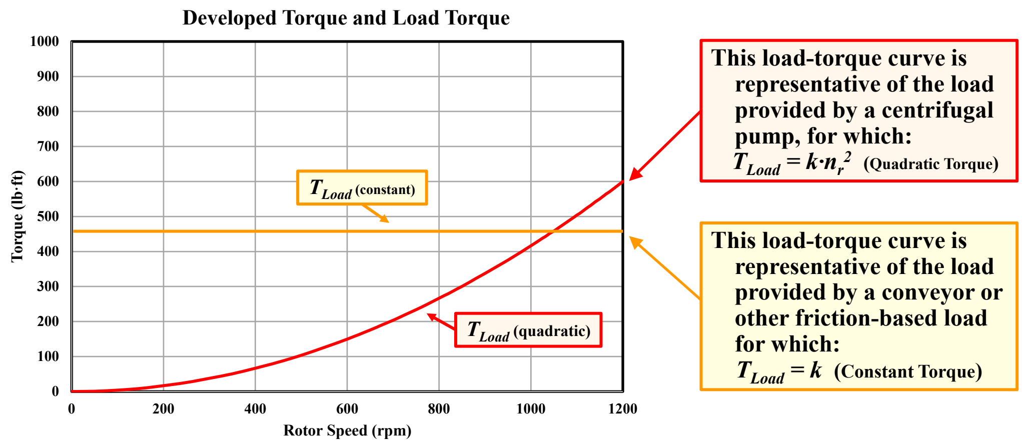
Despite their differences, motor loads often fall into one of three categories based on their **torque-speed** characteristics:

- **Constant Torque**
- **Quadratic Torque**
- **Constant Power**

88

Characteristics of a Motor Load

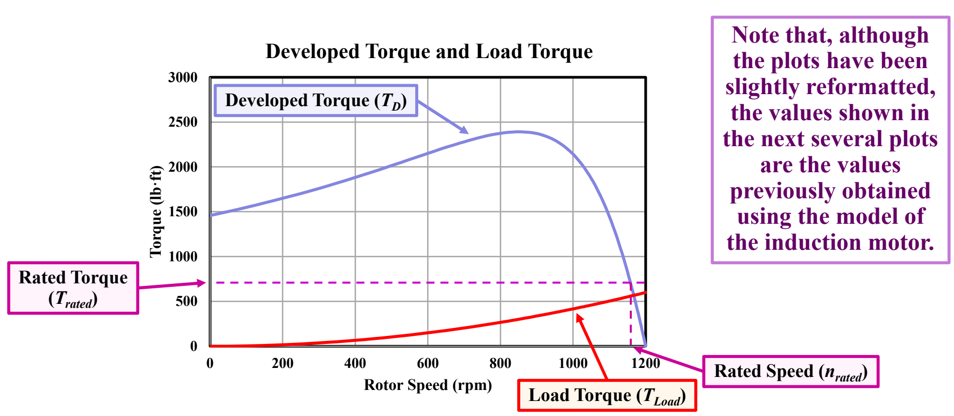
The following plot shows representative **torque-speed response curves** for **constant torque** and **quadratic torque** type loads.



89

Motor Operation with a Load

If a **load** having the torque characteristic, T_{Load}, (shown below) is coupled to the motor's shaft, how will this affect the **mechanical operation** of the motor?

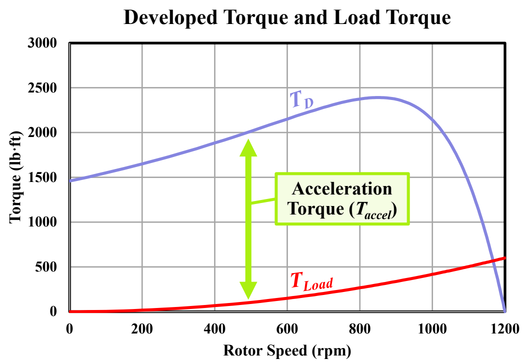


90

Motor Operation with a Load

In terms of rotation, the motor's operation depends on the available **acceleration torque**, where:

$$T_{accel} = T_D - T_{Load}$$



such that the **rotational speed** of the shaft will:

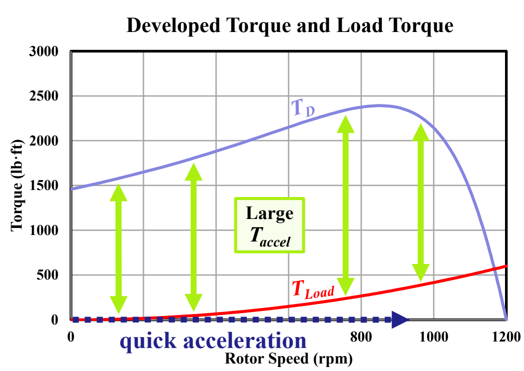
- **increase** when $\boldsymbol{T_{accel} > 0}$,
- **decrease** when $\boldsymbol{T_{accel} < 0}$,
- **remain constant** when $\boldsymbol{T_{accel} = 0}$.

91

Motor Operation from Startup

For the load shown, once started, the motor will **quickly speed-up** since the **acceleration torque** is initially **large** ($\boldsymbol{T_{accel} >> 0}$).

$$T_{accel} = T_D - T_{Load}$$

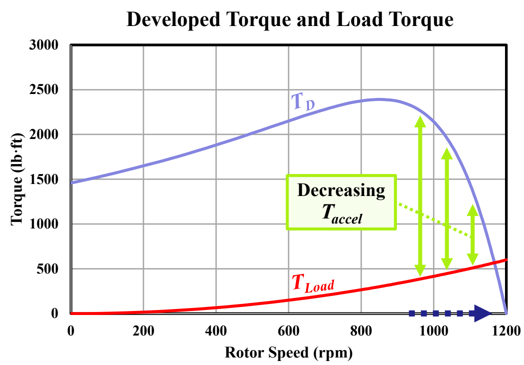


92

Motor Operation from Startup

As the rotor **approaches** synchronous speed, $\boldsymbol{T_D}$ begins to decrease while $\boldsymbol{T_{Load}}$ continues to increase, in-turn causing $\boldsymbol{T_{accel}}$ to **decrease**.

$$T_{accel} = T_D - T_{Load}$$



Although the rate of acceleration has decreased, the rotor speed still continues to increase as long as $T_{accel} > 0$.

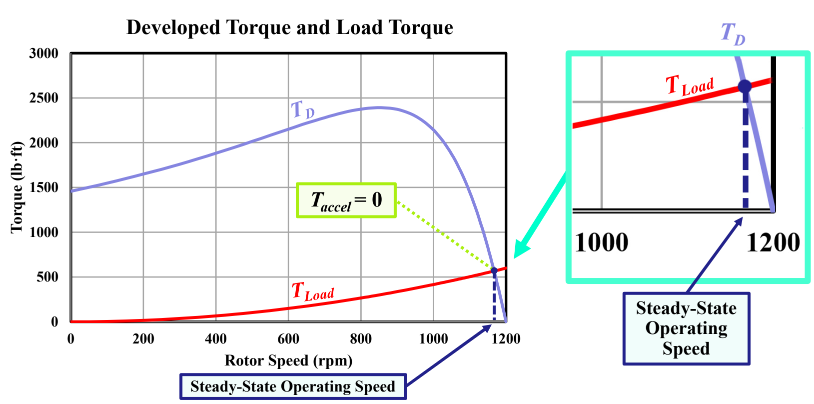
93

Steady-State Operation

Eventually the rotor will reach an operational speed where $\boldsymbol{T_{accel} = 0}$.

When this occurs, the rotor no longer accelerates, and thus the motor will maintain (constant) **steady-state rotation** at that speed.

Steady-state rotation occurs when $T_D = T_{Load}$.

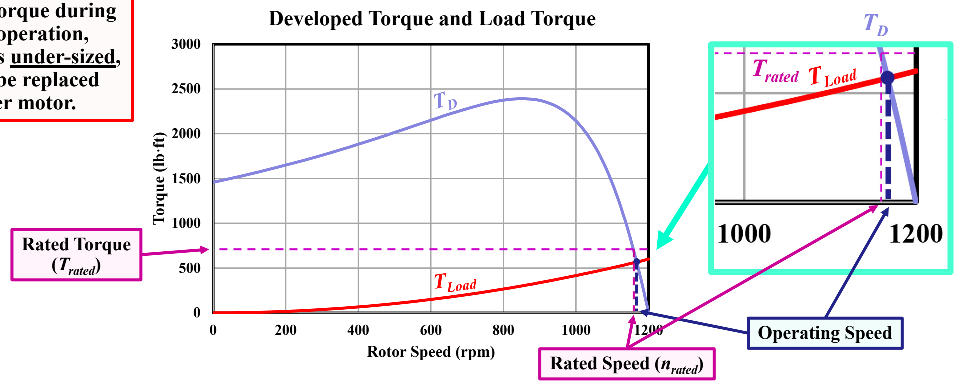


94

Motor Size vs. Load Requirements

Note that, in this example, the (**150 hp**) motor is appropriately-sized for the mechanical load that is coupled to its shaft since, during steady-state operation, $T_{Load} < T_{rated}$.

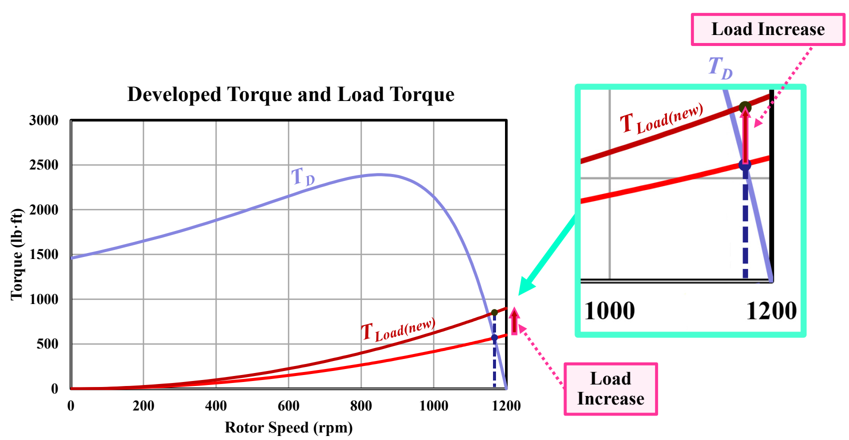
If the load torque is larger than the rated torque during steady-state operation, then the motor is under-sized, and it should be replaced with a larger motor.



95

Motor Operation if the Load Increases

What if the **load torque** suddenly **increases** after the motor has achieved steady-state operation**?**

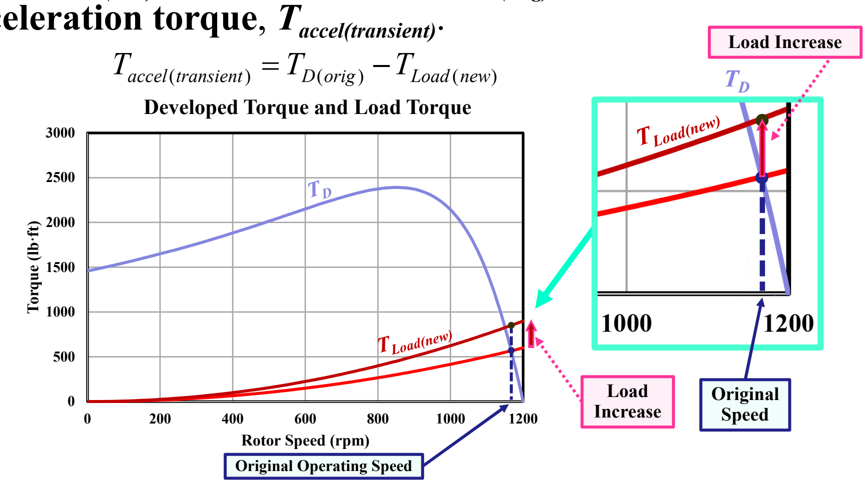


96

Motor Operation if the Load Increases

If the **load torque** suddenly **increases**, then while rotating at the original speed, $\boldsymbol{T_{Load(new)}}$ will be greater than $\boldsymbol{T_{D(orig)}}$, resulting in a **negative acceleration torque**, $\boldsymbol{T_{accel(transient)}}$.

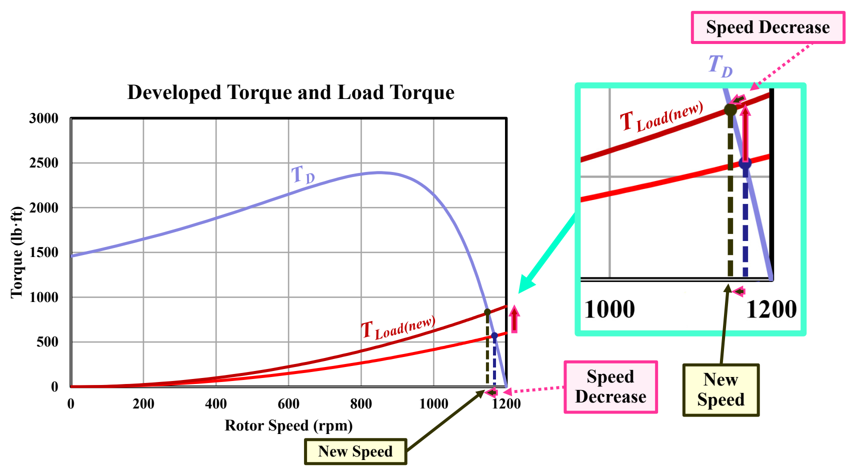
$$T_{accel(transient)} = T_{D(orig)} - T_{Load(new)}$$



97

Motor Operation if the Load Increases

When $\boldsymbol{T_{accel(transient)}}$ **is negative**, the rotor will begin to **slow down** until to a new speed is reached where $\boldsymbol{T_{D(new)}}$ is equal to $\boldsymbol{T_{Load(new)}}$.

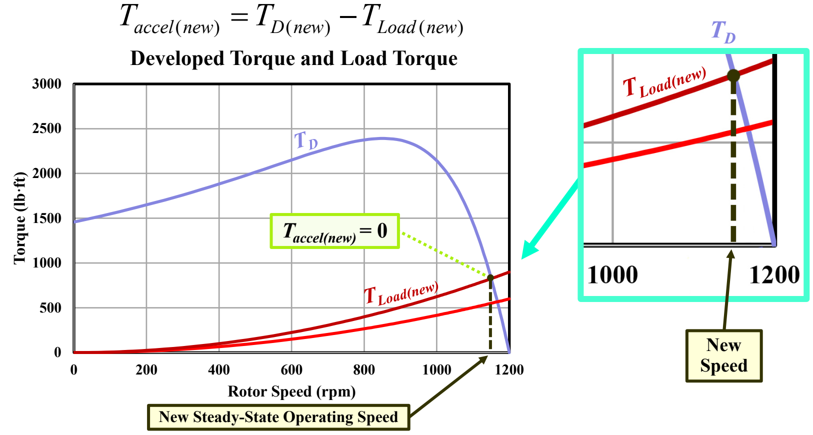


98

Motor Operation if the Load Increases

And if $T_{D(new)}$ is equal to $T_{Load(new)}$, then the new $T_{accel(new)} = 0$, once again resulting in **steady-state operation**, but now at a **slightly-slower rotational speed**.

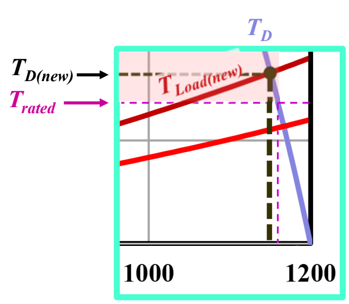
$$T_{accel(new)} = T_{D(new)} - T_{Load(new)}$$



99

Overload Conditions

Note that, in this case, the new steady-state operating point that resulted from the new (increased) load torque, in-turn results in an **overload condition** where $T_{D(new)} > T_{rated}$ (or $n_{r(new)} < n_{rated}$).



Whenever T_D is greater than rated torque, **the motor will draw larger-than-rated currents** that, if allowed to flow for an **extended amount of time**, will cause the **motor to overheat**.

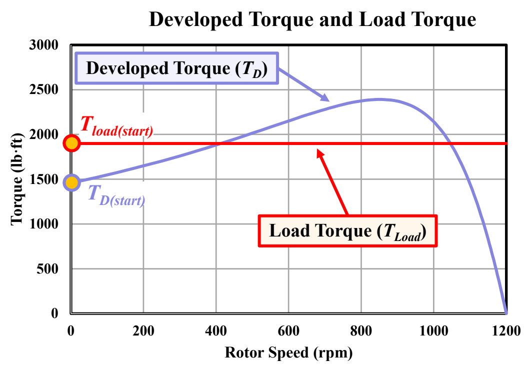
If the load returns to normal in a relatively short amount of time, then the motor will be okay.

Otherwise, overload protection would be required in order to prevent the motor from being damaged.

100

Startup Concerns

What if the applied **load torque**, $\boldsymbol{T_{Load}}$, is greater than the torque developed by the motor at startup?

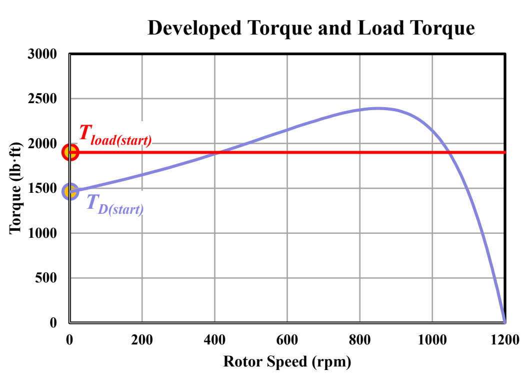


101

Insufficient Starting Torque

If $\boldsymbol{T_{Load} > T_D}$ **at startup**, the motor will **not** be able to accelerate.

Thus, it will **remain at a speed of zero**. (I.e. – **Failed Startup**)



If the motor fails to start, the large starting currents that the motor normally draws will quickly overheat the motor unless overload protection is provided.

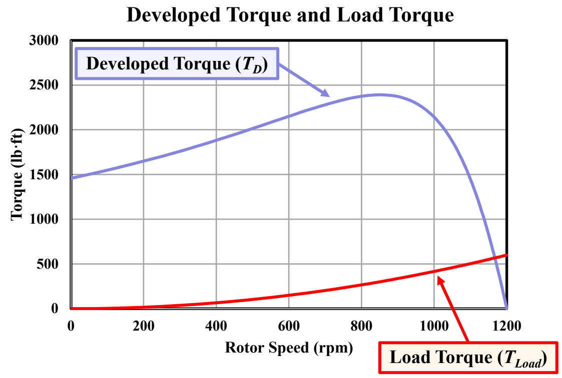
But, the overload protection method must still allow the motor to temporarily draw the same large currents that also occur during a successful startup.

102

Rate of Acceleration

What determines the **length of time** that it takes for the motor to **reach steady-state operation** after a change occurs?

(I.e. – What determines its **rate of acceleration**?)

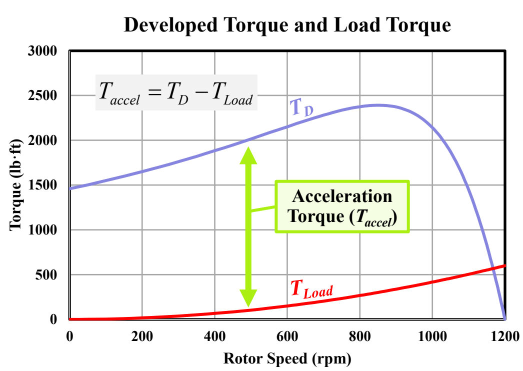


103

Angular Acceleration

Angular acceleration, ***α***, is proportional to **acceleration torque** and inversely proportional to the **moment of inertia** (mass), ***I***, of both the rotor and the coupled load.

$$\alpha = \frac{T_{accel}}{I} \quad \left(\text{radians}/\text{seconds}^2\right)$$



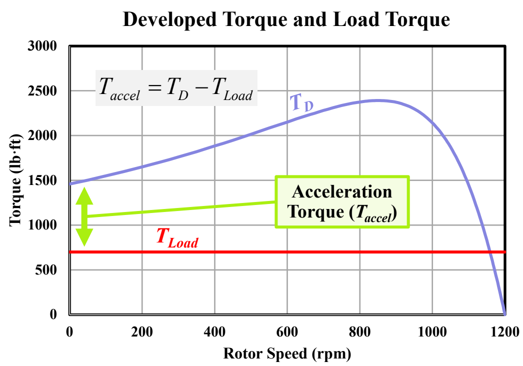
Note that the information regarding rate of acceleration is provided for informational purposes only.

Although it may be an important consideration when selecting, sizing or protecting a motor, or when designing either the branch circuit that supplies the motor or the control system for the motor, actually calculating the rate of acceleration or any associated value is beyond the scope of this course.

104

Concerns During Acceleration

If the rate of acceleration is too small, **larger-than-rated currents** may be **sustained** even during a "successful startup", resulting in possible motor damage* due to excessive heating of the motor.



*** - as well as a variety of other problems that we will consider during an upcoming presentation.**

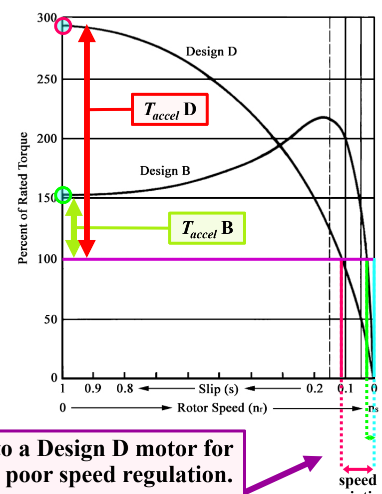
There are many factors that can result in a slow rate of acceleration:
- **The torque developed by the load at startup is too large,**
- **The locked-rotor torque developed by the motor is too small,**
- **The moment of inertia of the rotational system (load & rotor) is too large, or**
- **A drop is the supply voltage due to due to the normally-large starting currents.**

105

Low Acceleration Options

If the startup **characteristics of the load** can not be modified, then the **motor's size** may need to be increased, or the motor may need to be replaced by one that provides a larger starting torque.

For example, a **Design D** motor is able to develop a locked-rotor torque that is typically **~2x larger** than that of a similarly-sized Design B motor.



As often occurs, there is a trade-off when switching to a Design D motor for the increased "starting torque", and that trade-off is poor speed regulation.

In comparison to a Design B, changes in load torque result in a much greater variation of the rotational speed for a Design D motor.

106