EEP

Unit 2 Notes

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Part II

concept of sanctioned load

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Sanctioned Load

Sanctioned load is the maximum amount of electricity a consumer is permitted to draw from the grid. It's calculated in kilowatts (kW) and is determined by the local electricity distribution company (DISCOM).

Factors that are considered when calculating sanctioned load include: The size of the premises, The anticipated energy consumption, and The devices connected to the meter.

Sanctioned load is different from actual energy consumption and only affects the fixed charges on your electricity bill. If the actual load exceeds the sanctioned load, the fixed charges for that month may be affected. Some DISCOMs may also impose a penalty for increased fixed charges.

Sanctioned load is important for rooftop solar installations because it helps determine the size and capacity of the solar system that's needed. For example, if your building has a sanctioned load of 50 kW, the solar system should be designed to generate a similar or lower capacity of electricity.

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Sanctioned Load Definition: 129 Samples

Sanctioned Load means the mutually agreed load in kilowatts (KW)/Horsepower (HP) between the Licensee and the Low Tension Consumer as entered in the Agreement.

People also ask

What is the meaning of sanctioned load?

Load Factor Calculations

Load factor, in essence, means efficiency. It is the ratio of **actual** kilowatt-hours used in a given period, divided by the total **possible** kilowatt -hours that could have been used in the same period, at the peak kW level established by the customer during the billing period.

A high load factor is "a good thing," and a low load factor is a "bad thing." A low load factor means that you are using electricity inefficiently relative to what you could be if you were controlling your peak demand.

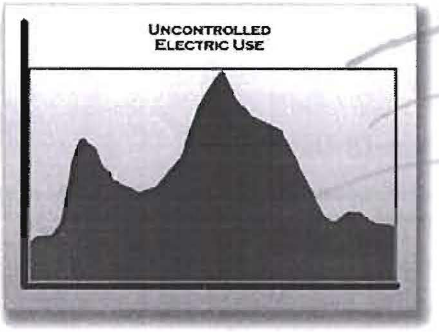
Load factor is calculated using a few simple numbers from the electric bill. The information required is:

- Actual kilowatt-hours used during the billing period, in kwh:
- The Peak kilowatt demand, in kW:
- The number of days in the billing period:

The ratio that the load factor formula expresses is the comparison between the **actual** kilowatt-hours used to the **total possible** kilowatt-hours that *could* be used at the particular kW level.

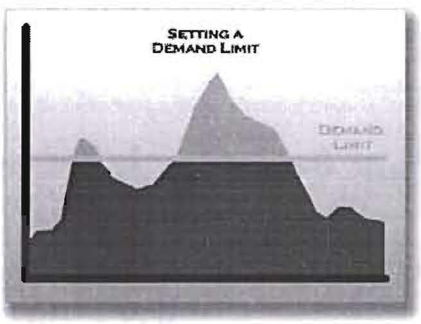
$$\frac{\text{kWh}}{\text{kW} \times \text{Days} \times 24} = \text{LF} = \frac{\text{Avg. Load}}{\text{Max Load}}$$

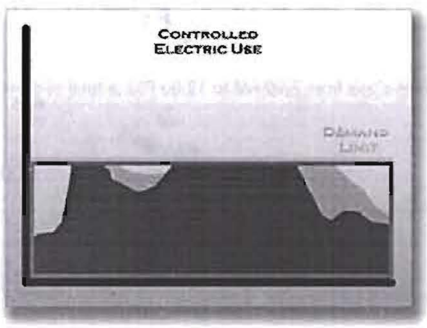
In the diagram to the right, the red box represents the total possible kilowatt-hours that could be used determined by the peak of electric use. The blue area represents the kilowatt-hours actually used over the month (daily profile shown to simplify drawing). The unshaded area represents the wasted capacity—the area where energy could have been used, but wasn't. The point is that you paid for the capacity (demand) of the entire box (the demand charge), but didn't use a large portion of it. Everything in the unshaded area is capacity you paid for but didn't use.



Peak level
Waste
actual kW hours

Conceptually, you can think of demand control as making the total size of the box smaller by decreasing the height. In the figures below, the yellow line is the demand limit or set point. By using an Energy Sentry demand controller, the peak demand is reduced by load management, and the original peak of energy use is redistributed below the limit. It's not about changing how much electricity is used, but when it is used.





Using Load Factor to Determine Demand Limit

Peak Demand & Demand limit are of same dimension

To determine a kW demand limit for a percentage load factor desired, take the actual kWh's used by a home in a given month and divide by 720 (total hours in an average 30-day month):

3000 kWh divided by 720 hours = 4.16 (demand limit if at 100% load factor)

$$\frac{100 \times \text{actual kWh}}{\text{LF} \times \text{Total hours}} = \text{demand Limit (kW)}$$

If a 60% load factor is desired, take the 4.16 (100% load factor) and divide by .60.

0.60

in %

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4.16 divided by .60 = ~7kW ~ 7kW

If the kW peak is known and the kWh is known, load factor can be found by multiplying the kW by total hours, and dividing the actual kWh's into that number. For example:

~~LF = Peak kW × No. of hours~~

20kW multiplied by 720 hours = 14,400 Total kWh (if at 100% load factor)

3000 kWh divided by 14,400 Total kWh = 21% load factor at 20kW

$$LF\ (\text{In }\%) = \frac{\text{actual kWh}}{\text{Peak kW} \times \text{No. of hours}}$$

Recommended Maximum Demand Limits (Typical Residential Application)

$$\text{Demand limit} = \frac{\text{Actual kWh}}{\text{LF} \times \text{No. of hours}} \times 100$$

$$= \frac{\text{Highest Monthly usage}}{\text{LF} \times \text{Hours/month}}$$

Highest Monthly Usage		Hours/Month		Load Factor Desired		Demand Limit
8000	**÷ by**	**720**	**÷ by**	**60%**	**=**	**18.5**
7000	**÷ by**	**720**	**÷ by**	**60%**	**=**	**16**
6000	**÷ by**	**720**	**÷ by**	**60%**	**=**	**14**
5000	**÷ by**	**720**	**÷ by**	**60%**	**=**	**11.5**
5000	**÷ by**	**720**	**÷ by**	**80%**	**=**	**8.5**
4000	**÷ by**	**720**	**÷ by**	**60%**	**=**	**9.5**
4000	**÷ by**	**720**	**÷ by**	**80%**	**=**	**7**
3000	**÷ by**	**720**	**÷ by**	**60%**	**=**	**7**
2000	**÷ by**	**720**	**÷ by**	**60%**	**=**	**4.5**

Note: The demand limit may be higher or lower due to the individual lifestyle or to extreme variations in the weather.

Calculating Load Factor with Time-Of-Use Rates (TOU rate)

Calculate separate for ON peak & offpeak

If you are working with TOU rates, load factor must be calculated in a different way. Time-of-Use rates have separate On-Peak and Off-Peak times which must be calculated separately. The only changes here are:

1. To know how many hours during the billing period were On-Peak and the kilowatt-hours used during this time
2. The Off-Peak hours during the billing period and the kWh's used during this time

If the Peak was different between On and Off-Peak times, use the appropriate Peak kW and use the basic load factor calculation above.

If the TOU rate that you're dealing with does not bill for demand in the Off-Peak periods, then calculating Off-Peak load factor is not necessary.

Imp

Example

Let's suppose that you are in a situation where:

→ 5 hours

- The Time-of-Use Demand rate winter schedule is On-Peak from 7:00 AM to 12:00 PM, a total of 5 hours, Monday through Friday

Noon 12

- There are 31 days in the month
- 9 weekend (Off -Peak Days), leaving 22 On-Peak days
- 744 hours in the period
- 110 On-Peak hours (15%) and 634 Off-Peak hours (85%)

On peak Daily 5 hrs for 22 days
$= 22 \times 5 = 110$ hrs
offpeak: $(24-5) \times 22 + 24 \times 9$
$= 418 + 216 = 634$ hours
Total 744 hours in 31 days

To calculate the On-Peak load factor, simply take the energy used during the On-Peak times and use the load factor calculation. Let's say that a total of 4,000 kilowatt-hours were used during the billing period. We'll assume that 15% or 600 kwh's were used On-Peak with a demand of 8kW. The load factor is:

$$\mathbf{LF = \frac{600}{8 \times 110} = 68\%}$$

So, roughly two-thirds of the total energy (kwh's) that could be used during the billing period are in those 22 five hour periods.

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Understanding Sanctioned Load for Rooftop Solar

Explore what sanctioned load is, why it is important, and how it affects the installation and performance of solar rooftop systems

In recent years, rooftop solar installations have gained immense popularity as a sustainable and cost-effective energy solution. However, to ensure a smooth transition to solar power, it is crucial to understand the concept of "sanctioned load" and its significance in rooftop solar applications. In this blog post, we will explore what sanctioned load is, why it is important, and how it affects the installation and performance of solar rooftop systems. Additionally, we will delve into load extension, uncovering its benefits and how it complements sanctioned load regulations.

What is a Sanctioned Load?

Sanctioned load refers to the maximum amount of electricity a consumer is authorized to draw from the grid. It is determined by the local electricity Distribution Company (henceforth referred to as DISCOM) based on factors such as the size of the premises and anticipated energy consumption. For rooftop solar installations, sanctioned load plays a vital role as it helps determine the capacity and size

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of the solar system required to meet the energy needs of the premises.

Let's look at an example to help you grasp this idea. Suppose your building has a sanctioned load of 50 kilowatts (kW). This means that the solar system installed on the rooftop solar system should be designed to generate a similar or lower capacity of electricity to match the sanctioned load. A system with a higher capacity may not be approved or may require additional approvals from the DISCOM. While sanctioned load sets the framework for solar rooftop installations, there are instances where loads surpass the sanctioned load limits. This is where load extension comes into play.

The Importance of Compliance with Sanctioned load for Rooftop Solar

1. Cost Savings: By installing a solar system designed to match the sanctioned load, consumers can optimize their energy generation and consumption, leading to potential cost savings on electricity bills.
2. Grid Compatibility Issues: Non-compliance with sanctioned load guidelines may lead to technical issues when connecting the solar system to the grid, resulting in inefficiencies and reduced performance.

The Role of Load Extension in Rooftop Solar

Load extension is the process of extending the sanctioned load to accommodate additional electrical loads without compromising the overall stability and safety of the system. The benefits of load extension in rooftop solar installations are manifold.

Firstly, it ensures that heavy-load appliances operate optimally, reducing the risk of damage or underperformance. Secondly, by integrating load extension, consumers can minimize their energy bills by utilizing excess solar energy generated during peak production periods. Lastly, load

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The Costs of Installing Rooftop Solar

Rooftop Solar investments are worth it ⚡ Here's Why

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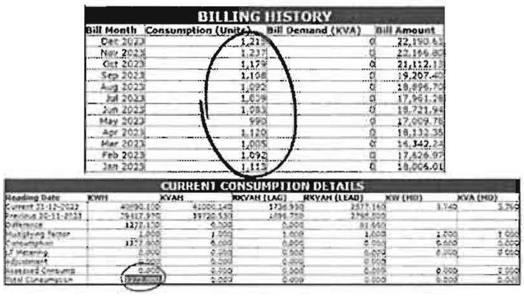
extension promotes a sustainable energy ecosystem, as it diminishes the need for additional non-renewable energy sources.

Calculating the Required Sanctioned Load

Now that we understand the importance of sanctioned load, let's explore how to calculate the required sanctioned load for a solar rooftop installation:

1. Assess Energy Needs: Start by determining your typical energy consumption by examining past electricity bills. Consider peak load requirements during high-energy usage periods.



BILLING HISTORY

Bill Month	Consumption (Units)	Bill Demand (KVA)	Bill Amount
Dec 2023	1,215	0	22,190.61
Nov 2023	1,237	0	22,166.80
Oct 2023	1,179	0	21,112.13
Sep 2023	1,108	0	19,207.40
Aug 2023	1,092	0	18,896.70
Jul 2023	1,039	0	17,961.28
Jun 2023	1,083	0	18,721.94
May 2023	990	0	17,009.76
Apr 2023	1,120	0	18,132.35
Mar 2023	1,005	0	16,342.24
Feb 2023	1,092	0	17,626.97
Jan 2023	1,113	0	18,006.01

CURRENT CONSUMPTION DETAILS

Where to find monthly consumption in your bill

2. Analyze Solar Potential: Evaluate the solar potential of your premises by considering factors such as roof orientation, shading, and available space for solar panels. Consult with solar energy professionals like PeriUrja Energy to estimate the solar generation capacity based on these factors.

3. Size the System: Based on your energy needs and solar potential, calculate the required solar system capacity. Ensure it matches or is lower than the sanctioned load specified by the DISCOM or get ready with your documents for load extension application.

need 50 kW
Solar capacity 40
Apply for 10kW load extension

Where to find Sanctioned Load in your bill

Eg present 4123 units

4. Seek Professional Assistance from us: Engage with certified solar installers or energy consultants like PeriUrja Energy to help you design and install a system that complies with sanctioned load regulations and optimizes your energy production.

Conclusion

Sanctioned load serves as a guiding principle in solar rooftop installations, ensuring safe and efficient integration of solar energy into our daily lives. By understanding the significance of sanctioned load and its role in rooftop solar, consumers can make informed decisions regarding their energy needs, comply with regulatory guidelines, and achieve long-term cost savings. Additionally, load extension complements sanctioned load, enabling consumers to embrace heavy-load appliances while maintaining energy efficiency and sustainability.

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sanctioned load calculation

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Sanctioned load is the maximum amount of electricity a consumer is permitted to draw from the grid. The local electricity distribution company (DISCOM) calculates the sanctioned load for a consumer based on a number of factors, including the size of the premises and the expected energy consumption.

Here are some things to consider when calculating sanctioned load:

Simultaneous use

Consider the load of all appliances, machines, fans, and lights that might be used at the same time. For example, an air conditioner might be included in the sanctioned load for the summer, but a geyser might not because they are not usually used together.

Coincidence factor

Multiply the total power of all devices by the coincidence factor, which is typically 0.6 for a single-family home.

Safety margin

Add a safety margin for unexpected power requirements.

Two separate connections

If a facility needs to use appliances that require three-phase power, such as electric cookers, it may need two separate connections.

You can check the online portal of the DISCOM to learn more about how they calculate sanctioned load.

Q. - Tata Power-DDL

Sanctioned load means the load in Kilo Watt, which is agreed to be supplied to the customer. The Sanctioned Load may be calculated...

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Search instead for maximum demand & contract demand

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Contract Demand & Max Demand

Contract demand and maximum demand are both terms related to electricity usage, but they have different meanings:

Contract demand

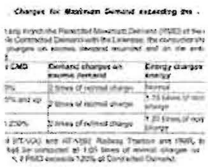
The amount of electricity a customer agrees to take from an electricity provider over a specified period of time. This is usually measured in kilowatt (kW) or kilo-volt ampere (kVA).

→ over a billing cycle

Maximum demand

The highest demand for electricity on a power station over a specific period of time. This is also measured in kW or kVA.

If a customer's maximum demand is higher than their contracted demand, they will be charged a penalty on their electricity bill. This penalty applies even if the customer only exceeds the limit once in a month.



To avoid maximum demand penalties, customers can use real-time monitoring to control their maximum demand.

Maximum Demand - Oneunit
20 Mar 2023 — Thus by Oneunit real time monitoring MD can be brought under control and avoid paying huge penalties which saves time,
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Contract Demand Penalty The contract demand is "the demand in Kilowatt (KW) or Kilo-voltAmpere (KVA) mutually agreed between the e...
Oneunit

[Solved] The maximum demand on a plant is 50 kW and load factor is 0.
15 Jul 2024 — Maximum Demand: It is defined as the greatest demand of load on the power station during a given period. Load Factor: I...
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Differentiate between "Contract Demand" and "Maximum ...

Contract demand is the amount of electric power that a customer demands from utility in a specified interval (Unit used is kVA or kW).

Maximum demand and contract demand formula

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The formulas for calculating maximum demand and contract demand are:

- **Maximum demand**: Maximum demand is the highest power demand on a power station during a specific time period. The formula for calculating maximum demand is:

i.e. highest level of electrical power consumption over a specific period of time

$$MaximumDemand = ConnectedLoad * LoadFactor / PowerFactor$$

- **Contract demand**: Contract demand is the maximum demand in KVA, calculated by taking at least 60% of the connected load in KW and using a power factor of 0.90.

Contract demand $= 0.6 \left(\text{Connected Load}\right) \times \left(\frac{\text{Load factor}}{0.9}\right)$

Here are some other related terms:

- **Load factor:** The ratio of average load to maximum load. $\frac{\text{Avg load}}{\text{Max load}}$
- **Demand integration period (DIP):** The time slot used to determine maximum demand.
- **Block window method:** A method for determining maximum demand over a fixed 30-minute time slot.
- **Sliding window method:** A method for determining maximum demand based on a 30-minute DIP that slides consecutively with 10-minute sub-intervals.

Note
LF = Utility factor × Diversity factor
Utility factor = % of eqmt. used
Diversity Factor (%) = $\frac{\text{Installed load}}{\text{Running load}}$
(i.e. facilities may not operate with full load)

Penalty if MD > Contract demand = 1.5 times normal bill

kVA Maximum Demand Calculation
defined maximum demand as "Twice the largest number of kilo Watt Hours (kWH) or kilo. Volt Ampere Hours (kVAH) supplied and taken ...
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maximum demand. This article furnishes calculation for Maximum Contract Demand. ... denotes in kVA for billing purpose. ... billin...
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Calculation of Electrical Maximum Demand | PDF

General Formula to calculate the Maximum Demand is described below: **Maximum Demand= Connected Load * Load Factor / Power Factor.**

3.5 (8)

kVA Maximum Demand Calculation – Frequently Asked Questions

1. **What is mean by Maximum Demand?**

"Maximum Demand" in kilo-volt-amperes- In relation to any period shall, mean twice the largest number of kilo-volt-ampere-hours supplied and taken during any consecutive thirty minute blocks in that period.

2. **What are components affecting kVA demand?**

The two components decide kVA of the consumer i.e. kW & RkVA. RkVA further split in to RkVA LAG & RkVA LEAD. In earlier methodology RKVA lead component was not considered in calculation of KVA which is now considered. The determination of MD kVA is directly based on integration of kVAH over DIP (Demand integration period) of consecutive 30 min.

3. **What is Regulation Standard for MD Calculation?**

"IS 14697" is INDIAN STANDARD for AC static CT/PT operated Energy meters that specified about the Demand integration period i.e. 15 or 30 min.

CBIP's "guide on Static energy meters- Specification and testing" has mentioned two methods i.e. block & sliding window method for determination of the MD.

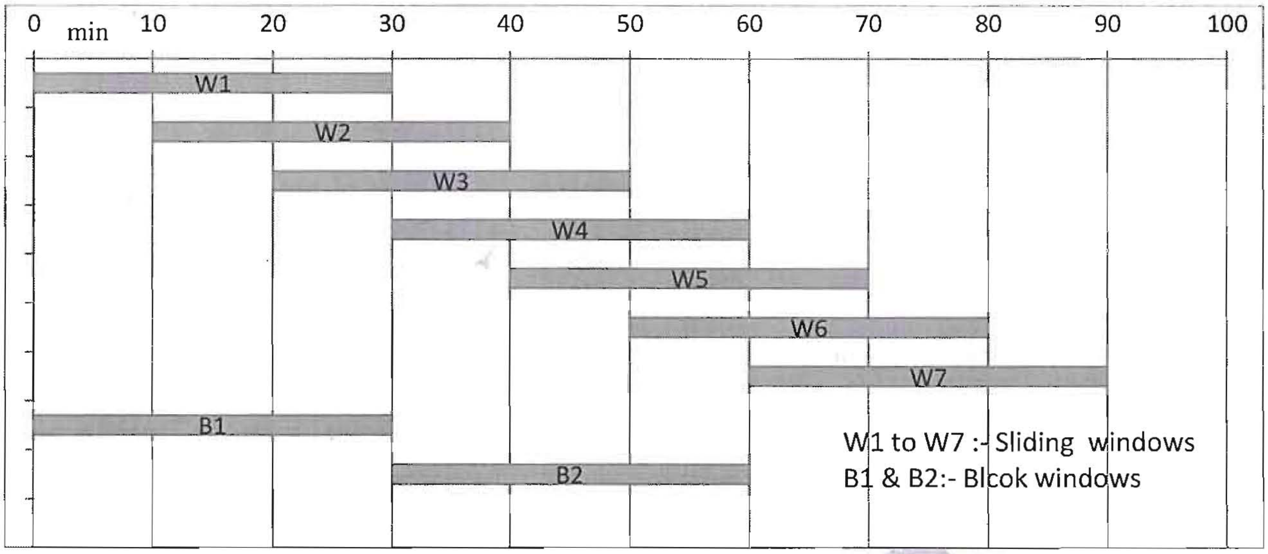
MERC (Electricity Supply Code and other Conditions of Supply) Regulation 2005 has defined maximum demand as "Twice the largest number of kilo Watt Hours (kWH) or kilo Volt Ampere Hours (kVAH) supplied and taken during any consecutive 30 min block in that period"

4. **What is block window method?**

In block window method the MD is determined over a fixed time slot of 30 min i.e. from 10:00 to 10:30 hrs., 10:30 to 11:00 hrs......so on (shown as B1 & B2 time interval in the graph plotted below). The new Demand Integration Period (DIP) starts only after the end of previous DIP.

5. **What is sliding window method of MD Calculations?**

Sliding Window Method: In sliding window method determination of the MD is based on 30 min DIP (Demand Integration Period). Here the 30 min period is not fixed as in case of the block window. The 30 min demand integral period is sliding consecutively with 10 min sub-interval as explained below:



In sliding window method there will be four complete DIP and four overlapping partial 'DIP'. Hence for consumer with 1000 KVA load for 30min duration.

We can observe that B1=W1 & B2=W4

Example:

Consider a 30 min consecutive consumption with constant 1000 kVA load from period 10:15 to 10:45 Hrs

	Time	Load (KVA)	ON Duration min	KVAH recorded (kva x min/60)	KVA MD (kvah X 2)	W1	W2	W3	W4	W5
	10.00 to 10.10	0	0	0	0					
B_1	10.10 to 10.20	1000	5	83.33	166.66	500				
	10.20 to 10.30	1000	10	166.66	333.34		833.33			
B_2	10.30 to 10.40	1000	10	166.66	333.34			833.33		
	10.40 to 10.50	1000	5	83.33	166.66				500	166.66
	10.50 to 11.00	0	0	0	0					

From above table & graphical representation it is observed that:

a. In block window method B1 & B2 would have recorded MD as per W1 & W4 respectively, i.e. 500 kVA

b. In sliding window Maximum of W1 to W6 is 833.33 KVA hence same will be recorded as Billing MD. Hence in sliding window method the load on the grid is determined more accurately. Bill will be calculated on basis of 833.33 KVA Consumption

6. Why method is changed from conventional block window method to Sliding window?

In block window method the demand recorded by the system was split into two blocks of time interval and hence the demand recorded by the system is much less than the actual peak loads on the system i.e. transformers, transmission lines & generation capacity. Hence sliding window demand method was introduced to record demand more accurately

As example, in an industry, if the drawl over a recording cycle of 30 minutes is:

- 2500 kVA for 4 minutes
- 3600 kVA for 12 minutes
- 4100 kVA for 6 minutes
- 3800 kVA for 8 minutes

The MD recorder will be computing MD as:

$$\frac{(2500 \times 4) + (3600 \times 12) + (4100 \times 6) + (3800 \times 8)}{30} = 3606.7 \text{ kVA}$$

1.9 Contracted Maximum Demand (CMD)

- Contracted maximum demand (CMD) is the demand mutually agreed between the supply company and the consumer by way of a signed contract.
- This demand forms the basis for working out of various capacities for the supply company and the consumer. Thus the supply company makes arrangements to supply the required demand and expects the consumer to restrict his demand within that limit.
- If a consumer exceeds that demand, the supply company charges him a penalty. If the consumer draws less than 80% of CMD the supply company charges him for 80% of CMD called Billing Demand. Thus the billing demand is the higher of the two:
  - 80% of CMD
  - Actual maximum demand established by the meter
- This figure of 80% may again vary from state to state but the principle remains same.

1.10 Connected Load

- Connected load is the sum of the nameplate ratings of all the equipments utilising electricity inside the consumer installation. Normally, when the figure is worked out, standby equipments is not considered since only one of them is running at a time. Also the figure is based on end utilising equipment and intermediate equipment like distribution transformers, motor control centres, etc. are not considered.

- Average load is energy consumption recorded divided by the operating hours of the plant.
  - Load Factor = (Average Load)/ (Maximum Demand) always less than 1.
  - Diversity Factor = (Connected Load)/ (Maximum Demand) always more than 1.
  - Utilisation Factor=(Average Load)/(Connected Load) always less than 1.
  - Utilisation Factor = (Load Factor) / (Diversity Factor)
  - Utilisation factor can easily be derived by multiplying both the numerator and the denominator by maximum demand.

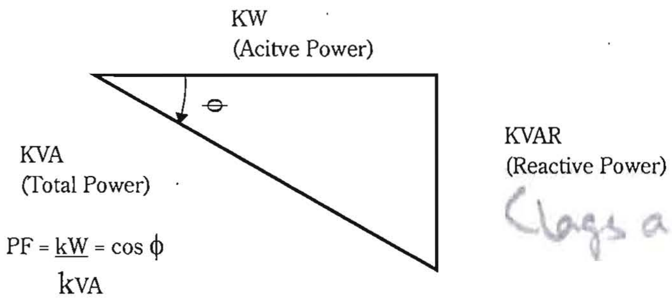
- It is important to note here that all the quantities must be worked out on the same unit basis of KW or KVA. Example, if maximum demand is measured in KVA, then using a power factor, it should be converted to KW. Similarly in a connected load, if the rating of any particular equipment is given in KVA, then using its rated power factor it should be converted to KW.

- From the above it will be amply clear that by reducing maximum demand one can save lot of money and hence the control of maximum demand forms an essential part of the energy conservation programme. Similarly achieving a load factor as close to unity as possible ensures that demand is uniform and energy is uniformly and well utilised. This also ensures that distribution losses are reduced.

- There are various methods of controlling maximum demand. They can be:
  - Shift non essential loads to off peak hours: For example, if one is working in a bottling plant working in two shifts, then loads like the water treatment plant, the effluent treatment plant can be made during the third shift alone.
  - Better co-ordination amongst departments: For example, in a cement plant where mines work only from sunrise to sunset, the colony water pumps, water treatment plants, etc. can be run only during sunset to sunrise.
  - Improvement of the power factor gives a great relief to MD. This is because for the given kW, the unity power factor records the same kVA. But a 0.5 power factor records double the kVA. Since billing is done on the basis of kVA, a better power factor helps in controlling maximum demand.
- The above methods indicated are dependent on manual systems and hence are not reliable. The most modern method is to provide an automatic maximum demand controller. This is a microprocessor - based instrument which monitors the Maximum Demand by iterative projections and cuts off automatically nonessential loads as per priorities decided earlier.

1.11 Power Factor

- In case of pure resistive loads, the voltage(V),current (I), resistance (R)relations are linearly related, i.e. V = I × R and Power (kW) = V × I
- Active power is measured in kW (Kilo Watts). Reactive power is measured in kVAr (Kilo Volt-Amperes Reactive)
- The vector sum of the active power and reactive power make up the total (or apparent) power used. This is the power generated by the SEBs for the user to perform a given amount of work. Total Power is measured in KVA (Kilo Volts-Amperes)
- Power Factor is a ratio of kW to KVA which is always less than or equal to unity. This is represented by a famous triangular relation as shown below:



(lags active power)

Fig.1.4 Power factor triangle

- The active power (shaft power required or true power required) in kW and the reactive power required (kVAr) are 900 apart vectorically in a pure inductive circuit i.e., reactive power kVAr lagging the active kW. The vector sum of the two is called the apparent power or kVA, as illustrated above and the kVA reflects the actual electrical load on distribution system.

1.12 Selection of Power Factor Correction Capacitors

- From the triangle of KW, KVA and kVAr, it is seen that capacitor rating in kVAr should be equal to the kVArR causing the power factor to deviate from Unity. This will ensure that the power factor is properly compensated. But in practice where automatic power factor correction is used extensively now-a-days, these are selected in steps of eight or ten and brought in the circuit as and when required through cutting in and cutting out devices.

- The advantages of PF improvement by capacitor addition are as follows:
  - Reactive component of the network is reduced and so also the total current in the system from the source end.
  - I2R power losses are reduced in the system because of reduction in current.
  - Voltage level at the load end is increased.
  - kVA loading on the source generators as also on the transformers and lines upto the capacitors reduces giving capacity relief. A high power factor can help in utilising the full capacity of your electrical system.

[illegible]

Table 1.2 Multipliers to determine capacitor kVAr requirements for power factor correction

1.13 Leading and Lagging Power Factor

Leading Power Factor	Lagging Power Factor
When the Current in an AC Circuit is leading the voltage in waveform, the power factor is called the leading power factor.	When the Current in an AC Circuit is lagging the voltage in waveform, the power factor is called the lagging power factor.
The leading power factor is caused when the net load is capacitive in nature.	The lagging power factor is caused when the net load is inductive in nature.

- The inductive and capacitive loads cancel each other while responding to an electric supply. Since a majority of the loads by nature are inductive, the best way to improve the power factor is to add capacitors.
- The obvious advantages of improving the power factor are:
  - Reduction in distribution losses.
  - Improvement in voltage.

1.14 Position of Power Factor Correction Capacitors

- The ideal location for capacitors is to provide them as close to the point of utilisation as possible.

CHAPTER 5
AC MACHINE FUNDAMENTALS

AC machines are motors that convert ac electric energy to mechanical energy and generators that convert mechanical energy to ac electric energy. The two major classes of ac machines are synchronous and induction machines. The field current of synchronous machines (motors and generators) is supplied by a separate dc power source while the field current of induction machines is supplied by magnetic induction (transformer action) into the field windings.

AC machines differ from dc machines by having their *armature windings* almost always located on the stator while their *field windings* are located on the rotor. A set of three-phase ac voltages is induced into the stator armature windings of an ac machine by the rotating magnetic field from the rotor field windings (generator action). Conversely, a set of three-phase currents flowing in the stator armature windings produces a rotating magnetic field within the stator. This magnetic field interacts with the rotor magnetic field to produce the torque in the machine (motor action).

THE ROTATING MAGNETIC FIELD

The main principle of ac machine operation is this: A three-phase set of currents, flowing in an armature windings, each of equal magnitude and differing in phase by 120°, produces a rotating magnetic field of constant magnitude.

The stator shown in Fig. 5.1 has three coils, each 120° apart.
The currents flowing in the stator are given by

$$i_{aa'}(t) = I_M \sin \omega t \qquad A$$

$$i_{bb'}(t) = I_M \sin (\omega t - 120°) \qquad A$$

$$i_{cc'}(t) = I_M \sin (\omega t - 240°) \qquad A$$

The resulting magnetic flux densities are

$$\mathbf{B}_{aa'}(t) = B_M \sin \omega t \angle 0° \qquad \text{Wb/m}^2$$

$$\mathbf{B}_{bb'}(t) = B_M \sin (\omega t - 120°) \angle 120° \qquad \text{Wb/m}^2$$

$$\mathbf{B}_{cc'}(t) = B_M \sin (\omega t - 240°) \angle 240° \qquad \text{Wb/m}^2$$

The directions of these fluxes are given by the right-hand rule. When the fingers of the right hand curl in the direction of the current in a coil, the thumb points in the direction of the resulting magnetic flux density.

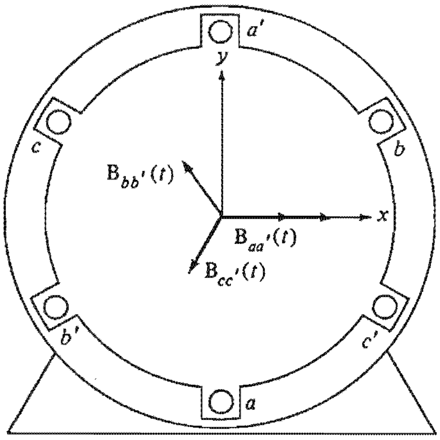


FIGURE 5.1 A simple three-phase stator. Currents in this stator are assumed positive if they flow into the unprimed and out of the primed ends of the coils.

An examination of the currents and their corresponding magnetic flux densities at specific times is used to determine the resulting net magnetic flux density. For example, at time $\omega t = 0°$, the magnetic field from coil aa' will be

$\omega t = 0°$

$$\mathbf{B}_{aa'} = 0$$

The magnetic field from coil bb' will be

$$\mathbf{B}_{bb'} = B_M \sin(-120°)\angle 120°$$

and the magnetic field from coil cc' will be

$$\mathbf{B}_{cc'} = B_M \sin(-240°)\angle 240°$$

The total magnetic field from all three coils added together will be

$$\begin{aligned}\mathbf{B}_{net} &= \mathbf{B}_{aa'} + \mathbf{B}_{bb'} + \mathbf{B}_{cc'} \\ &= 0 + \left(-\frac{\sqrt{3}}{2}B_M\right)\angle 120° - \frac{\sqrt{3}}{2}B_M\angle 240° \\ &= 1.5B_M\angle -90°\end{aligned}$$

As another example, look at the magnetic field at time $\omega t = 90°$. At that time, the currents are

$\omega t = 90°$

$$i_{aa'} = I_M \sin 90° \quad \text{A}$$
$$i_{bb'} = I_M \sin(-30°) \quad \text{A}$$
$$i_{cc'} = I_M \sin(-150°) \quad \text{A}$$

and the magnetic fields are

AC MACHINE FUNDAMENTALS 5.3

$$\mathbf{B}_{aa'} = B_M \angle 0°$$

$$\mathbf{B}_{bb'} = -0.5B_M \angle 120°$$

$$\mathbf{B}_{cc'} = -0.5B_M \angle 240°$$

The resulting net magnetic field is

$$\mathbf{B}_{\text{net}} = B_M \angle 0° + (-0.5)\, B_M \angle 120° + (-0.5)\, B_M \angle 240°$$
$$= 1.5B_M \angle 0°$$

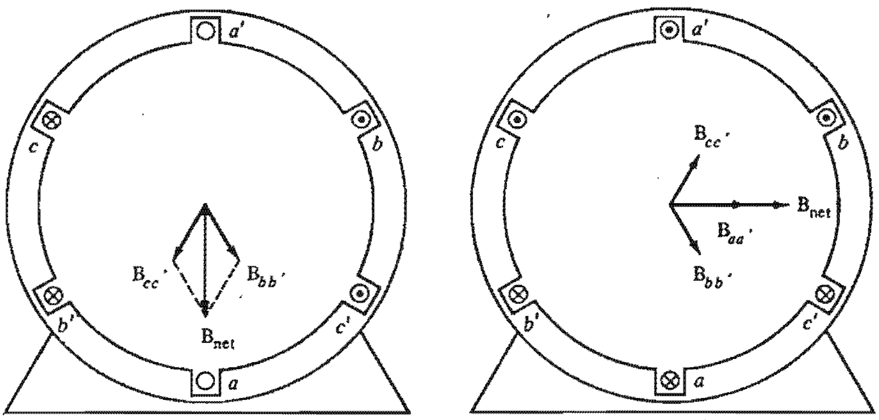
The resulting magnetic flux is shown in Fig. 5.2. Notice that the direction of the magnetic flux has changed, but its magnitude remained constant. The magnetic flux is rotating counterclockwise while its magnitude remained constant.

Proof of the Rotating Magnetic Flux Concept

At any time t, the magnetic flux has the same magnitude $1.5B_M$. ~~It continues~~ to rotate at ~~angular~~ velocity ω. ~~A proof of this concept is presented in Ref.~~ 1.

The Relationship between Electrical Frequency and the Speed of Magnetic Field Rotation

Figure 5.3 illustrates that the rotating magnetic field in the stator can be represented as a north and a south pole. The flux leaves the stator at the north pole and enters the stator at the south pole. The magnetic poles complete one complete revolution around the stator surface for each electrical cycle of the applied current. Therefore, the mechanical angular speed of rotation in revolutions per second is equal to the electrical frequency in hertz:



ωt = 0° (a)

ωt = 90° (b)

FIGURE 5.2 (*a*) The vector magnetic field in a stator at time $\omega t = 0°$. (*b*) The vector magnetic field in a stator at time $\omega t = 90°$.

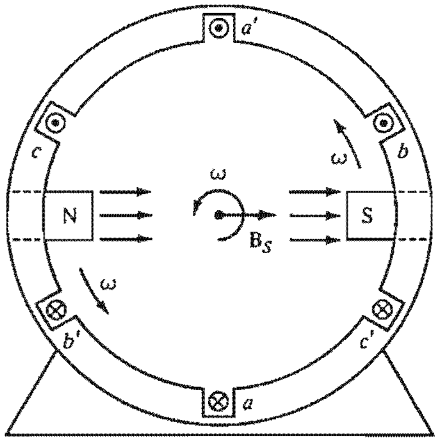


FIGURE 5.3 The rotating magnetic field in a stator represented as moving north and south stator poles.

$$f_e = f_m \qquad \text{two poles}$$

$$\omega_e = \omega_m \qquad \text{two poles}$$

where f_m and ω_m are the mechanical speed of rotation in revolutions per second and radians per second, respectively. Both f_e and ω_e are the electrical frequency (speed) in hertz and radians per second, respectively.

The windings on the two-pole stator shown in Fig. 5.1 occur in the order (taken counterclockwise)

$$a - c' - b - a' - c - b$$

If this pattern is repeated twice within the stator, the pattern of windings becomes

$$a - c' - b - a' - c - b' - a - c' - b - a' - c - b'$$

Figure 5.4 illustrates the *two* north poles and *two* south poles that are produced in the stator when a three-phase set of currents is applied to the stator. 3φ 4pole stator

In this stator, the pole moves around half the stator surface in one electrical cycle. Since the mechanical motion is 180° for a complete electrical cycle (360°), the electrical angle θ_e is related to the mechanical angle θ_m by

$$\theta_e = 2\theta_m \qquad \text{four poles}$$

Therefore, for a four-pole stator, the electrical frequency is double the mechanical frequency of rotation:

$$f_e = 2f_m \qquad \text{four poles}$$

$$\omega_e = 2\omega_m \qquad \text{four poles}$$

In general, if P is the number of magnetic poles on the stator, then there are $P/2$ repetitions of the windings. The electrical and mechanical quantities of the machine are related by

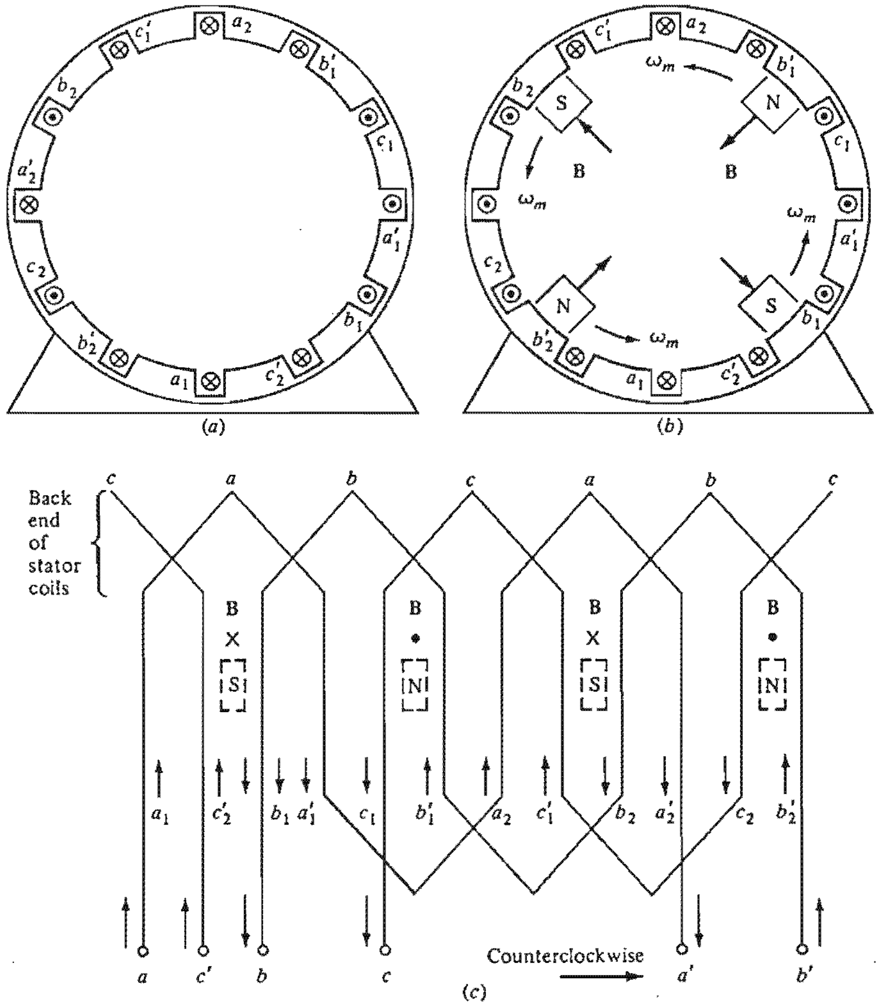


FIGURE 5.4 (*a*) A simple four-pole stator winding. (*b*) The resulting stator magnetic poles. Notice that there are moving poles of alternating polarity every 90° around the stator surface. (*c*) A winding diagram of the stator as seen from its inner surface, showing how the stator currents produce north and south magnetic poles.

✓ $$\boxed{\theta_e = \frac{P}{2}\theta_m}$$ for P no. of poles

✓ $$\boxed{f_e = \frac{P}{2}f_m}$$

$$\boxed{\omega_e = \frac{P}{2}\,\omega_m}$$

Since the mechanical frequency $f_m = n_m/60$, the electrical frequency in hertz is related to the mechanical speed of the magnetic fields in revolutions per minute by

$$\boxed{f_e = \frac{n_m P}{120}}$$

$f_e = \frac{P}{2} f_m$
$= \frac{n_m P}{120}$

$n_m =$

Reversing the Direction of the Magnetic Field Rotation

The direction of the magnetic field's rotation is reversed when the current in any two of three coils is swapped. Therefore, it is possible to reverse the direction of rotation of an ac motor by just switching any two of the three phases (~~Ref. 1~~).

THE INDUCED VOLTAGE IN AC MACHINES

Current → Mag field → Induced Voltage

Just as a rotating magnetic field can be produced by three-phase set of currents in a stator, a three-phase set of voltages in the coils of a stator can be produced by a rotating magnetic field.

The Induced Voltage in a Coil on a Two-Pole Stator

Figure 5.5 illustrates a *stationary* coil with a *rotating* magnetic field moving in its center. The induced voltage in a wire is given by

$$e_{\text{ind}} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

where $\mathbf{v}$ = velocity of wire *relative to magnetic field*
$\mathbf{B}$ = magnetic flux density of field
$\mathbf{l}$ = length of wire

This equation was derived for a *wire moving within a stationary magnetic field*. In ac machines, the magnetic field is moving, and the wire is stationary.

Figure 5.6 illustrates the velocities and vector magnetic field from the point of view of a moving wire and a stationary magnetic field. The voltages induced in the sides of the coil are

1. *Segment ab.* The angle between $\mathbf{v}$ and $\mathbf{B}$ in segment bc is $180° - \theta$, while the quantity $\mathbf{v} \times \mathbf{B}$ is in the direction of $\mathbf{l}$, so

$$e_{ba} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$
$$= vBl \sin(180° - \theta) \qquad \text{directed } \textit{into} \text{ page}$$

The direction of e_{ba} is given by the right-hand rule. By trigonometric identity, $\sin(180° - \theta) = \sin\theta$. So

AC MACHINE FUNDAMENTALS

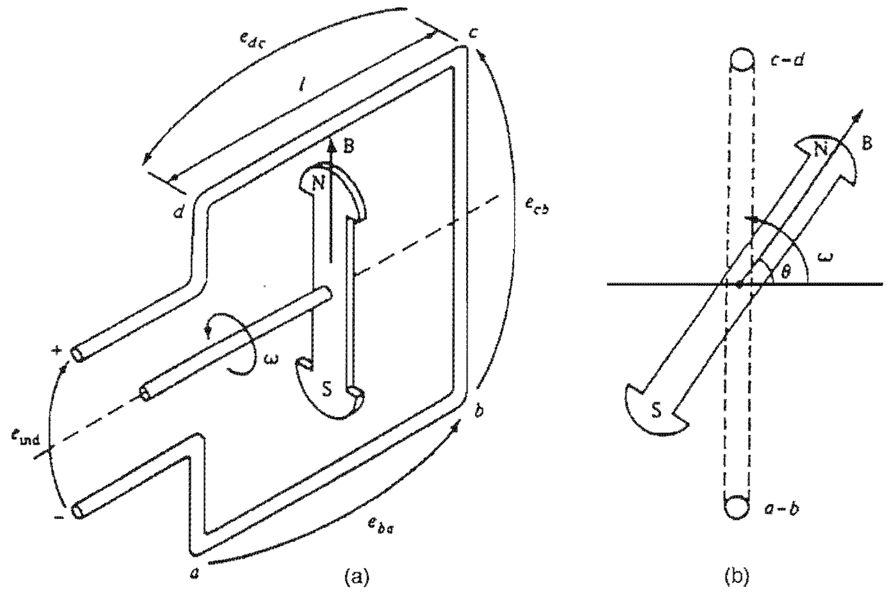


FIGURE 5.5 A rotating magnetic field inside a fixed coil: (*a*) Perspective view; (*b*) end view.

$$e_{ba} = vBl \sin \theta$$

2. *Segment bc.* The voltage on segment *bc* is zero, since the vector quantity $\mathbf{v} \times \mathbf{B}$ is perpendicular to **l**.

$$e_{cb} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$
$$= 0$$

3. *Segment cd.* The angle between v and B in segment *cd* is θ, while the quantity $\mathbf{v} \times \mathbf{B}$ is in the direction of **l**. So

$$e_{dc} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$
$$= vBl \sin \theta \qquad \text{directed } \textit{out of} \text{ page}$$

4. *Segment da.* The voltage on segment *da* is zero, for the same reason as in segment *bc:*

$$e_{ad} = 0$$

The total voltage induced within a single-turn coil is given by

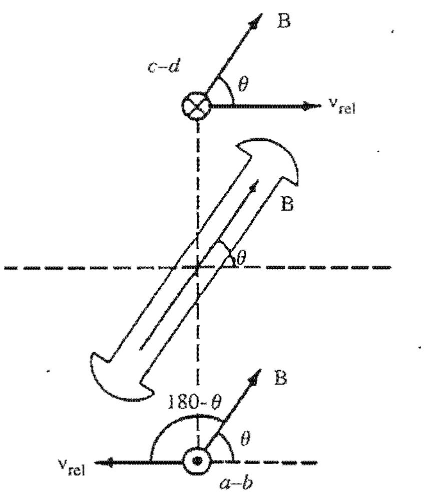


FIGURE 5.6 The magnetic fields and velocities of the coil sides as seen from a frame of reference in which the magnetic field is stationary.

$$e_{ind} = 2vBl \sin \theta$$

Since angle $\theta = \omega_e t$,, the induced voltage can be rewritten as

$$e_{ind} = 2vBl \sin \omega_e t$$

Since the cross-sectional area A of the turn is $2rl$ and the velocity of the end conductors is given by $v = r\omega_m$, the equation can be rewritten as

$$e_{ind} = 2(r\omega_m)Bl \sin \omega_e t$$

$$= (2rl)B\omega_m \sin \omega_e t$$

$$= AB\omega_m \sin \omega_e t$$

$v = r\omega_m$
$2rl = A$

The maximum flux passing through the coil is $\phi = AB$. For a two-pole stator $\omega_m = \omega_e = \omega$, the induced voltage is

$$\boxed{e_{ind} = \phi\omega \sin \omega t}$$

This equation describes the voltage induced in a single-turn coil; if the coil (phase) has N_c turns of wire in it, the total induced voltage will be

$$\boxed{e_{ind} = N_c \phi\omega \sin \omega t}$$

The Induced Voltage in a Three-Phase Set of Coils

Figure 5.7 illustrates three coils each of N_c turns placed around the rotor magnetic field. The voltage induced in each has the same magnitude but differs in phase by 120°. The resulting voltages in the three phases are

$$e_{aa'}(t) = N_c \phi\omega \sin \omega t \qquad \text{V}$$

$$e_{bb'}(t) = N_c \phi\omega \sin (\omega t - 120°) \qquad \text{V}$$

$$e_{cc'}(t) = N_c \phi\omega \sin (\omega t - 240°) \qquad \text{V}$$

Therefore, a set of three-phase currents generates a rotating uniform magnetic field within the stator of the machine, and a uniform magnetic field induces a set of three-phase voltages in such a stator.

The RMS Voltage in a Three-Phase Stator

The peak voltage in any phase is

$$E_{max} = N_c \phi\omega$$

(Sin lim = 1)

Since $\omega = 2\pi f$, the rms voltage in any phase is

$$E_A = \frac{2\pi}{\sqrt{2}} N_c \phi f$$

AC MACHINE FUNDAMENTALS

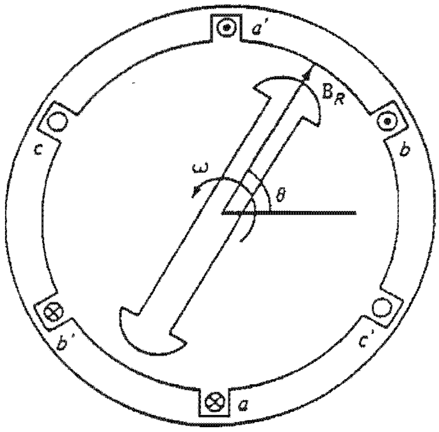


FIGURE 5.7 The production of three-phase voltages from three coils spaced 120° apart.

$$\boxed{E = \sqrt{2}\pi N_c \phi f}$$ ✓

The rms voltage at the terminals of the machine depends on whether the stator is Y- or Δ-connected. If the machine is Y-connected, the terminal voltage is 3 times E_A. In Δ-connected machines, the terminal voltage is the same as E_A.

Y : E= 3 EA
Δ : E=EA

THE INDUCED TORQUE IN AN AC MACHINE

During normal operation of ac machines (motors and generators), there are two magnetic fields: a magnetic field from the rotor and another from the stator. A torque is induced in the machine due to the interaction of the two magnetic fields.

A synchronous machine is illustrated in Fig. 5.8. A magnetic flux density $\mathbf{B}_R$ is produced by the rotor, and a magnetic flux density $\mathbf{B}_S$ is produced by the stator. The induced torque in a machine (motors and generators) is given by

$$\tau_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$$

$$\tau_{ind} = kB_R B_S \sin\gamma$$

where τ_{ind} = induced torque in machine
$\mathbf{B}_R$ = rotor flux density
$\mathbf{B}_S$ = stator flux density
γ = angle between $\mathbf{B}_R$ and $\mathbf{B}_S$

The net magnetic field in the machine is the vector sum of the fields from the stator and rotor

$$\mathbf{B}_{net} = \mathbf{B}_R + \mathbf{B}_S$$

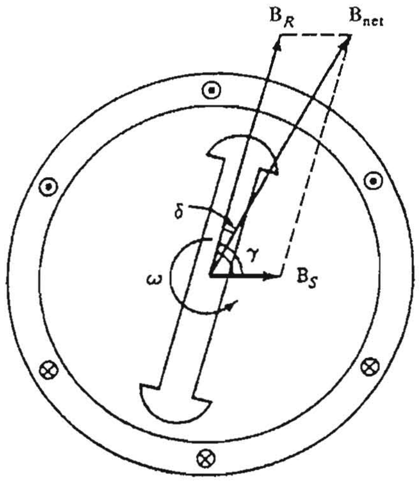


FIGURE 5.8 A simplified synchronous machine showing its rotor and stator magnetic fields.

The induced torque can be expressed as

$$\boxed{\tau_{\text{ind}} = k\mathbf{B}_R \times \mathbf{B}_{\text{net}}}$$

The magnitude of the torque is

$$\boxed{\tau_{\text{ind}} = kB_R\, B_{\text{net}} \sin \delta}$$

The magnetic fields of the synchronous machine shown in Fig. 5.8, are rotating in a counterclockwise direction. What is the direction of the induced torque on the rotor of the machine?

By applying the right-hand rule to the equation of the induced torque, we see that the induced torque is clockwise. It is opposing the direction of rotation of the rotor. Therefore, this machine is working as a generator.

WINDING INSULATION IN AC MACHINES

In ac machine design, one of the most critical parts is the insulation of the windings. When the insulation breaks down, the machine shorts out. The repair of machines with shorted insulation is expensive and sometimes impossible.

The temperature of the windings should be limited to prevent the insulation from breaking down due to overheating. This can be done by providing circulation of cool air over the windings. The continuous power supplied by the machine is usually limited by the maximum temperature of the windings. The increase in temperature usually degrades the insulation, causing it to fail by another cause such as shock, vibration, or electrical stress. A rule of thumb indicates that the life of an ac machine is halved for a temperature rise of 10 percent above the rated temperature of the windings.

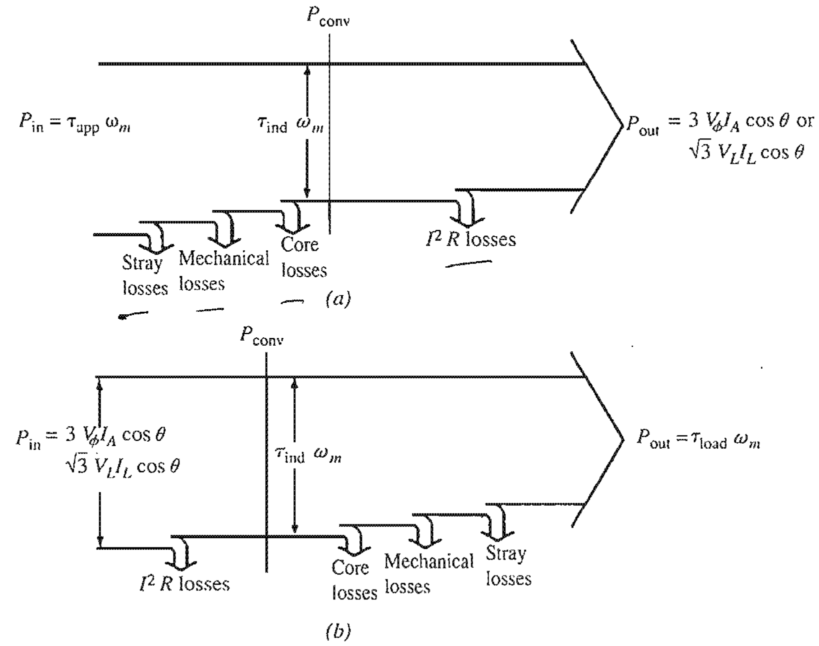
The temperature limits of machine insulation have been standardized by the National Electrical Manufacturers Association (NEMA). A series of insulation system classes have been defined. Each insulation system class specifies the maximum temperature rise allowed for the insulation. The most common NEMA insulation classes for ac motors are B, F, and H. Each class has a higher permissible winding temperature than the one before it. For example, the temperature rise above ambient of the armature windings in continuously operating induction machines is limited to 80°C for class B, 105°C for class F, and 125°C for class H insulation.

Similar standards have been defined by the International Electrotechnical Commission (IEC) and by other national standards organizations.

AC MACHINE POWER FLOW AND LOSSES

A power flow diagram is a convenient tool to analyze ac machines. Figure 5.9 illustrates the power flow diagram of an ac generator and an ac motor.
The losses in ac machines are

1. Rotor and stator copper (I^2R) losses
2. Core losses



P= Torque × Wm

FIGURE 5.9 (*a*) The power flow diagram of a three-phase ac generator. (*b*) The power flow diagram of a three-phase ac motor.

3. Mechanical losses
4. Stray losses

The stator copper losses in ac machines are the heat losses from the conductors of the stator. They are given by

$$\boxed{P_{\mathrm{SCL}} = 3I_A^2R_A}$$

$3 \times I^2 R$

where I_A is the current flowing in each armature phase and R_A is the resistance of the conductor in each armature phase. The rotor copper losses are given by

$$\boxed{P_{\mathrm{RCL}} = I_F^2R_F}$$

The mechanical losses are caused by bearing friction and windage effects while the core losses are caused by hysteresis and eddy currents. These losses are called the *no-load* rotational losses of the machine.

All the input power at no load is used to overcome these losses. Therefore, these losses can be obtained by measuring the power to the stator at no load.

Stray load losses are all miscellaneous losses that do not fall into one of these categories. They are taken by convention as 1 percent of the output power of the machine. The overall efficiency of an ac machine is defined as the useful power output to the total input power:

$$\boxed{\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \times 100\%}$$

REFERENCE

1. S. J. Chapman, *Electric Machinery Fundamentals*, 2d ed., McGraw-Hill, New York, 1991.

CHAPTER 6
INDUCTION MOTORS

In induction machines, the rotor voltage (which produces the rotor current and the rotor magnetic field) is not physically connected by wires to the rotor windings—it is *induced* in the rotor. The main advantage of induction motors is that there is no need for *dc field current* to run the machine. An induction machine can be used as a motor or a generator. However, it has many disadvantages as a generator.

INDUCTION MOTOR CONSTRUCTION

Figure 6.1 illustrates a typical two-pole stator for an induction motor. The two main types of rotors are *squirrel-cage* and *wound* rotors. Figures 6.2 and 6.3 illustrate squirrel-cage induction motor rotors.

The rotor consists of a series of conducting bars installed into slots carved in the face in the rotor. These bars are shorted at both ends by shorting rings. This design is known as a squirrel-cage rotor. The second type is known as a wound rotor. A *wound rotor* (Figs. 6.4 and 6.5) has three phase windings that are mirror images to the stator windings.

The three rotor phases are usually Y-connected. Slip rings on the rotor shaft tie the ends of the three rotor wires. Brushes riding on the slip rings short the rotor windings.

The rotor currents are accessible. They can be examined, and extra resistance can be added to the rotor circuit. This is a significant advantage of this design because the torque-speed characteristic of the motor can be modified.

BASIC INDUCTION MOTOR CONCEPTS

Figure 6.6 illustrates a squirrel-cage induction motor. A set of three-phase currents is flowing in the stator. A magnetic field $\mathbf{B}_S$ is produced. It rotates in a counterclockwise direction. The rotational speed of the magnetic field is given by

$$\boxed{n_{\text{sync}} = \frac{120 f_e}{P}}$$

where f_e is the electrical frequency in hertz and P is the number of poles in the machine. The rotating magnetic field $\mathbf{B}_S$ crosses the rotor bars and induces a voltage in them.

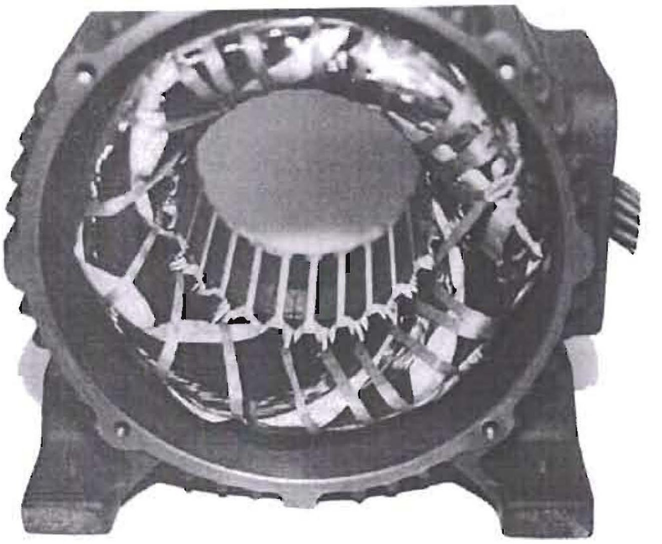


FIGURE 6.1 The stator of a typical induction motor, showing the stator windings. (*Courtesy of MagneTek, Inc.*)

The induced voltage in a given rotor bar is given by

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

where $\mathbf{v}$ = velocity of rotor bars *relative to magnetic field*
$\mathbf{B}$ = magnetic stator flux density
$\mathbf{l}$ = length of rotor bar

The voltage in a rotor bar is induced by the *relative* motion of the rotor compared to the magnetic field. The velocity of the upper rotor bars relative to the magnetic field is to the right. Therefore, the induced voltage in the upper bars is out of the page, and the induced voltage in the lower bars is into the page.

The current is flowing out of the upper bars and into the lower bars. However, the peak rotor current lags behind the peak rotor voltage due to the inductive nature of the rotor assembly. A rotor magnetic field $\mathbf{B}_R$ is produced by the current flowing in the rotor. Since the induced torque is given by

$$\tau_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$$

the resulting torque is counterclockwise. The rotor accelerates in this direction.

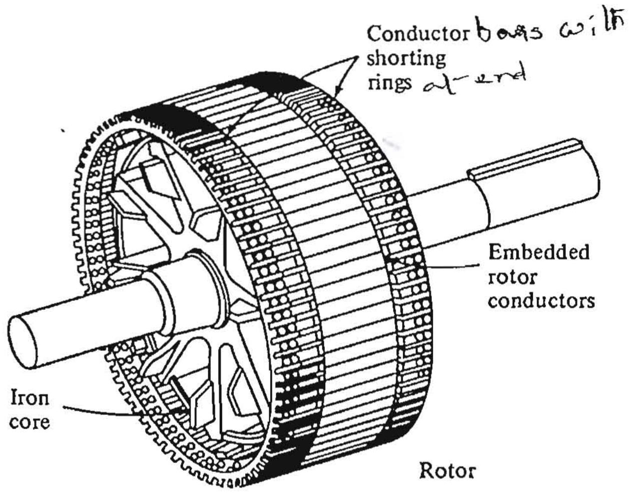
The Concept of Rotor Slip

The speed of the rotor *relative* to the magnetic fields determines the voltage induced in the rotor. The relative speed is used because the behavior of the motor depends on the voltage and current in the rotor.

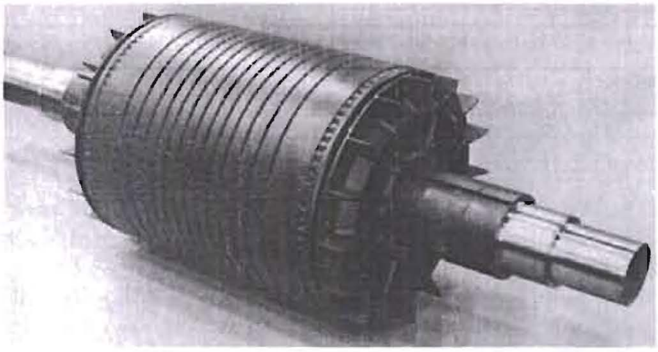
The two terms used to define the relative motion between the rotor and the magnetic fields are the *slip speed* and the *slip*. The *slip speed* is the difference between synchronous speed and rotor speed:

INDUCTION MOTORS

3phase current in stator.



(a)



(b)

FIGURE 6.2 (*a*) Sketch of squirrel-cage rotor. (*b*) A typical squirrel-cage rotor. (*Courtesy of General Electric Company.*)

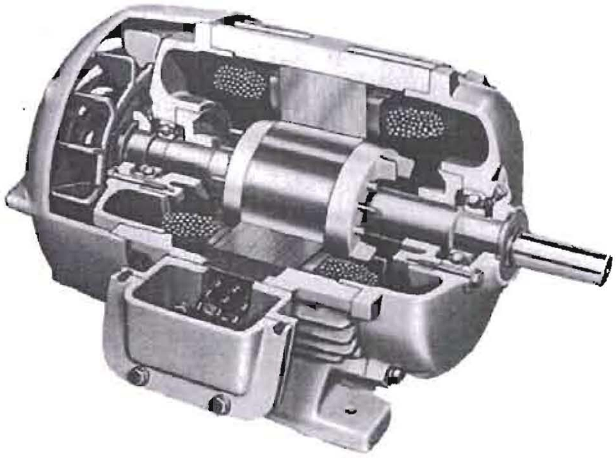
$$\boxed{n_{\text{slip}} = n_{\text{sync}} - n_m}$$

where n_{slip} = slip speed of machine
n_{sync} = speed of magnetic fields
n_m = mechanical shaft speed of rotor

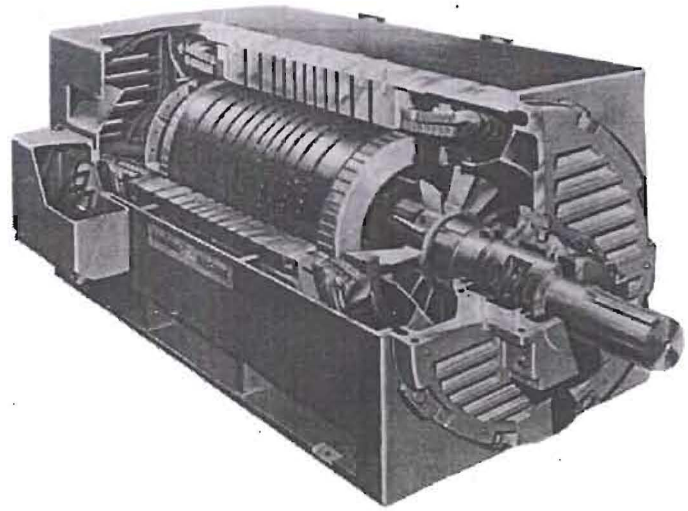
The second term used to describe the relative motion is the slip. The *slip* is defined as

$$s = \frac{n_{\text{slip}}}{n_{\text{sync}}} \times 100\%$$

$$\boxed{s = \frac{n_{\text{sync}} - n_m}{n_{\text{sync}}} \times 100\%}$$



(a)



(b)

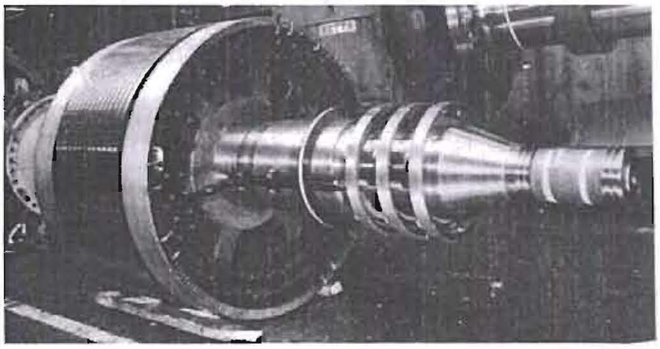
FIGURE 6.3 (*a*) Cutaway diagram of a typical small squirrel-cage induction motor. (*Courtesy of MagneTek, Inc.*) (*b*) Cutaway diagram of a typical large squirrel-cage induction motor. (*Courtesy of General Electric Company.*)

When the rotor turns at synchronous speed, $s = 0$. When the rotor is stationary, $s = 1$. All motor speeds fall between these two limits.

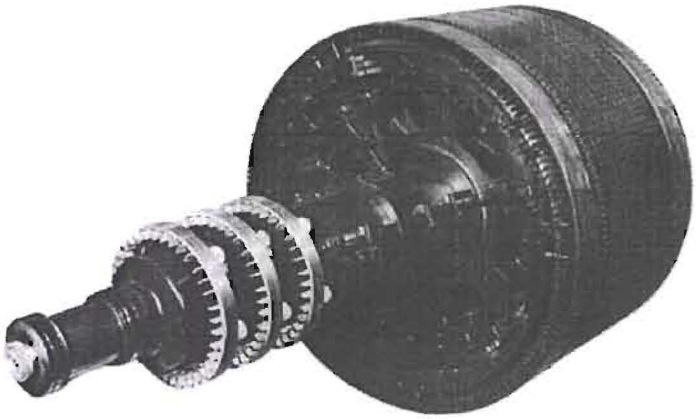
The mechanical speed of the rotor shaft can be expressed in terms of the synchronous speed and slip as

$$\boxed{n_m = (1 - s)n_{\text{sync}}}$$

INDUCTION MOTORS 6.5



(a)



(b)

FIGURE 6.4 Typical wound rotors for induction motors. Notice the slip rings and the bars connecting the rotor windings to the slip rings. (*Courtesy of General Electric Company.*)

Rotor → Y connected
- 3phase winding which are mirror image of stator winding
- Accessible rotor current
⇒ Torque-Speed characteristic can be modified

$$\boxed{\omega_m = (1 - s)\omega_{sync}}$$

The Electrical Frequency of the Rotor

Induction motors have been called *rotating transformers* because they work by inducing voltages and currents in the rotor. The primary (stator) induces a voltage in the secondary (rotor), but the secondary frequency is not necessarily the same as the primary frequency. If the rotor is locked, it will have the same frequency as the stator. If the rotor turns at synchronous speed, the frequency of the rotor will be equal to zero. For any speed in between,

Define: $f_r = \frac{n_{sync} - n_m}{n_{sync}} f_e$ = El. freq. of rotor = 0 if $n_m = n_{sync}$ $= \frac{P}{120}(n_{sync} - n_m)$

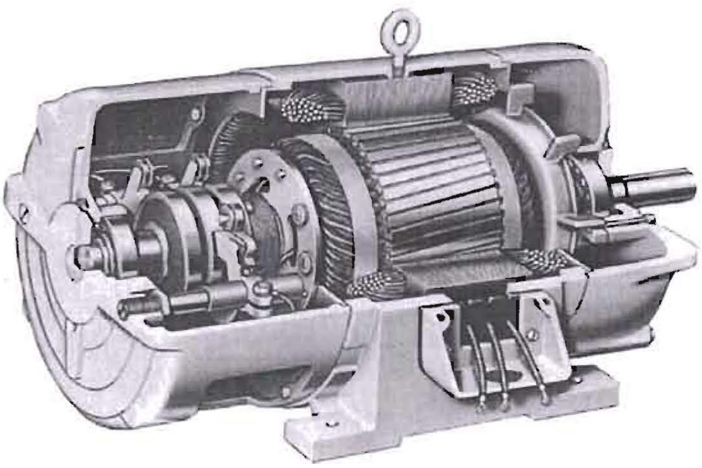


FIGURE 6.5 Cutaway diagram of a wound-rotor induction motor. Notice the brushes and slip rings. (*Courtesy of MagneTek, Inc.*)

Therefore,

$$\boxed{f_r = \frac{P}{120}(n_{\text{sync}} - n_m)}$$

Using nsync. $= \frac{120 f_e}{P}$

THE EQUIVALENT CIRCUIT OF AN INDUCTION MOTOR

It is possible to derive the equivalent circuit of an induction motor from the knowledge of transformers. Figure 6.7 illustrates the equivalent circuit, representing the operation of an induction motor. The effective turns ratio a_{eff} couples the primary internal stator voltage $\mathbf{E}_1$ to the secondary $\mathbf{E}_R$. A current flow in the shorted rotor (or secondary) is produced by $\mathbf{E}_R$.

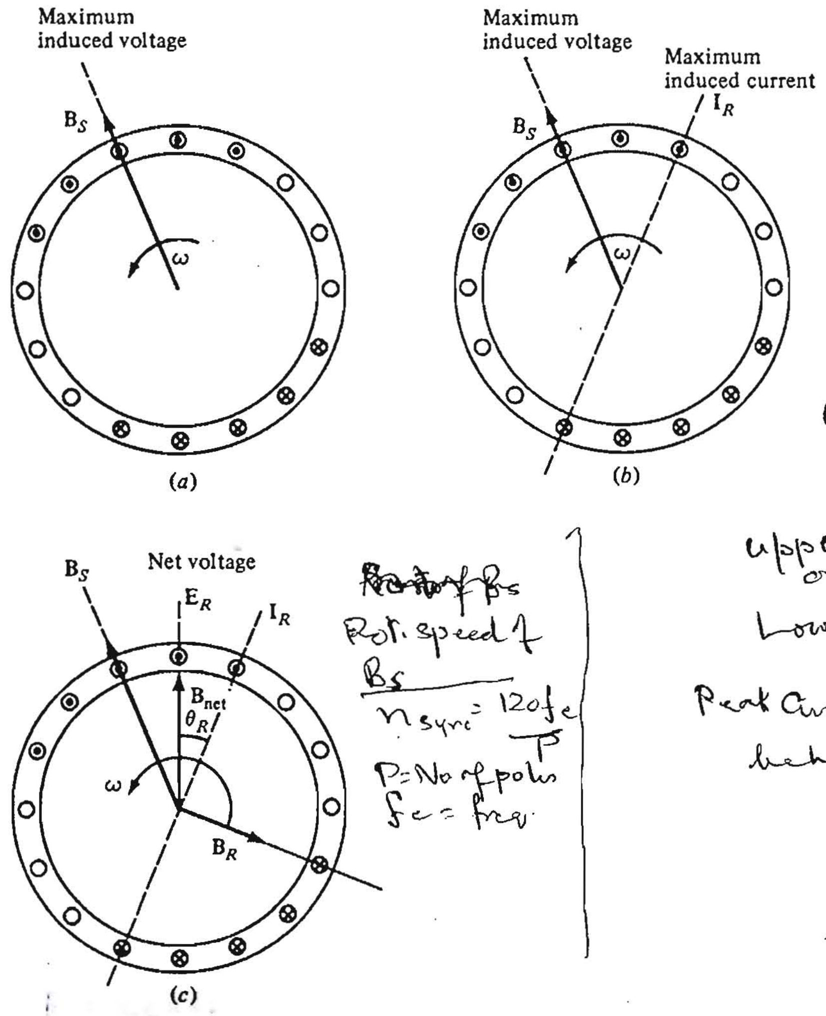
The Rotor Circuit Model

In induction motors, the higher the relative motion between the rotor and the stator magnetic fields, the higher the resulting rotor voltage. The relative motion is largest when the rotor is stationary. This is called the *locked-* or *blocked-rotor* condition. The induced voltage in the rotor is at maximum during this condition. When the rotor moves at the same speed as the stator magnetic field (no relative motion), the induced voltage in the rotor is zero.

If the induced rotor voltage at locked-rotor conditions is $\mathbf{E}_{R_0}$, the induced voltage at any slip is

$$\mathbf{E}_R = s\mathbf{E}_{R_0}$$

The rotor has a resistance and a reactance. Its resistance R_R is constant independent of slip while the rotor reactance depends on the slip.



~~Rotor of Bs~~
Rot. speed of B_S

$n_{sync} = \frac{120 f_e}{P}$

P = No of poles
f_e = freq.

FIGURE 6.6 The development of induced torque in an induction motor. (*a*) The rotating stator field $\mathbf{B}_S$ induces a voltage in the rotor bars. (*b*) The rotor voltage produces a rotor current flow, which lags behind the voltage because of the inductance of the rotor. (*c*) The rotor current produces a rotor magnetic field $\mathbf{B}_R$ lagging 90° behind itself, and $\mathbf{B}_R$ interacts with $\mathbf{B}_{net}$ to produce a counterclockwise torque in the machine.

3phase current in stator
↓
B_S (rotating mag. field in stator)
↓
Induces voltage in rotor
$e_{ind} = (v \times B) \cdot l$
(l = length of rotor, v = velo. of rotor, B = mag stator flux density)
upper rotor bar → Towards right → out of page
Lower - - - - into the page
e_{ind}
↓
Peak Current in rotor bars (lags behind peak voltage)
↓
Current produces mag field B_R
↓
Induced torque = $k B_R \times B_S$
↓
Anticlockwise

The reactance of a rotor depends on the rotor inductance and the frequency of the voltage and current in the rotor. If the rotor inductance is L_R, the rotor reactance is given by

$$X_R = \omega_r L_R = 2\pi f_r L_R$$

Since $f_r = sf_e$, the rotor reactance becomes

$$X_R = 2\pi s f_e L_R$$
$$= s(2\pi f_e L_R)$$
$$= sX_{R_0}$$

<u>Rotor Speed</u>
(1) <u>Slip Speed</u> = $n_{slip} = n_{sync} - n_m$
n_{sync} = Speed of mag. field
n_m = Mechanical shaft speed of rotor
(2) <u>Slip</u> = $S = \frac{n_{slip}}{n_{sync}} \times 100\%$
$= \frac{n_{sync} - n_m}{n_{sync}} \times 100\%$
= Relative motion
S = 0, when $n_m = n_{sync}$
S = 1 when $n_m = 0$
$0 \le S \le 1$
Also, $n_m = (1-S) n_{sync}$
$\omega_m = (1-S)\omega_{sync}$

Equivalent circuit of an Induction Motor

When Rotor is stationary rotor voltage is max. (highest relative motion between stator & rotor mag field) → LOCKED COND.

E_I = Internal stator voltage

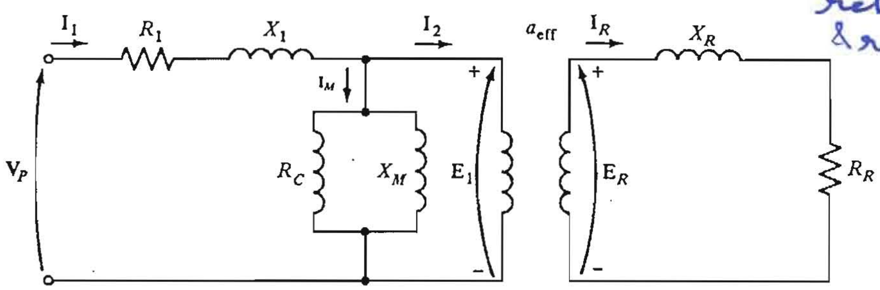


FIGURE 6.7 The transformer model of an induction motor, with rotor and stator connected by an ideal transformer of turns ratio a_{eff}.

E_R = Secondary rotor = induced rotor voltage at any slip

Rotor reactance $= X_R = \omega_r L_R$

(L_R = rotor inductance)

$\omega_r = 2\pi f_r = 2\pi s f_e$

$\Rightarrow X_R = 2\pi s f_e L_R = s X_{R0}$

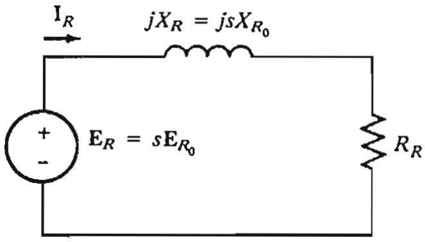


FIGURE 6.8 The rotor circuit model of an induction motor.

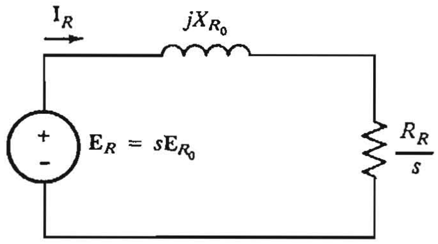


FIGURE 6.9 The rotor circuit model with all the frequency (slip) effects concentrated in resistor R_R.

Fig 6-8 Rotor Equiv. ckt.

$I_R = \dfrac{E_R}{R_R + jX_R} = \dfrac{sE_{R0}}{R_R + jsX_0}$

(using $E_R = sE_{R0}$ under locked rotor condition. (rotor voltage is highest at E_{R0})

The rotor equivalent circuit is shown in Fig. 6.8. The rotor current can be found as

$$\mathbf{I}_R = \frac{\mathbf{E}_R}{R_R + jX_R}$$

$$\boxed{\mathbf{I}_R = \frac{s\mathbf{E}_{R_0}}{R_R + jsX_{R_0}}}$$

The voltage supplied $\mathbf{E}_{R_0}$ can be treated as constant. The final rotor equivalent circuit is shown in Fig. 6.9. The equivalent impedance containing all the effects of varying rotor slip is

$$Z_{R,\,eq} = \frac{R_R}{s} + jX_{R_0}$$

a_{eff} = Effective turns ratio which couples E_I to E_R

Figure 6.10 illustrates the variation of rotor current with speed.

At high slips (rotor speed is much lower than normal operating speed or synchronous speed), X_{R_0} is much larger than R_R/s. The rotor current approaches a *steady-state* value. At low slips (rotor speed is near normal operating speed or synchronous speed), the resistive term R_R/s is much larger X_{R_0}. The rotor resistance is the dominant term, and the rotor current vary *linearly with slip*.

Or, $I_R = \dfrac{E_{R0}}{\frac{R_R}{s} + jX_{R0}} = \dfrac{E_{R0}}{Z_{R,eq}}$ (Fig 6-9)

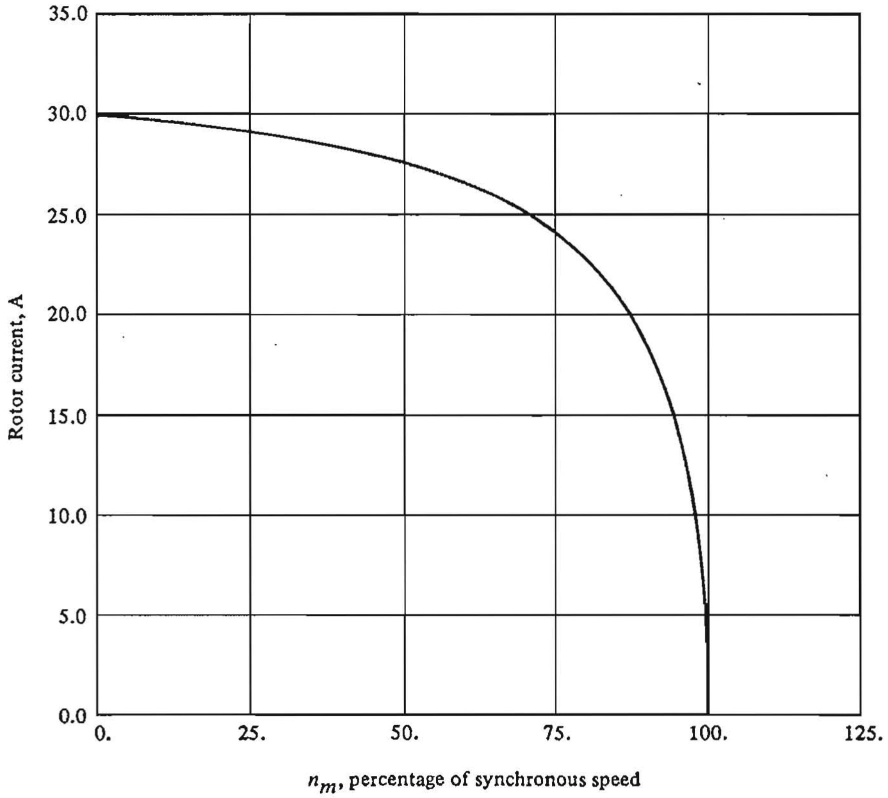


FIGURE 6.10 Rotor current as a function of rotor speed.

LOSSES AND THE POWER FLOW DIAGRAM

Induction motors have been described as rotating transformers. The input is a three-phase system of voltages and currents. The secondary windings of the motor (the rotor) are shorted out. Figure 6.11 illustrates the relationship between the input electric power and the output mechanical power. The stator copper losses are I^2R in the stator windings. The core losses include the hysteresis and eddy currents losses.

INDUCTION MOTOR TORQUE-SPEED CHARACTERISTICS

No load
$n_m = n_{syn.}$

Figure 6.12*a* illustrates a squirrel-cage rotor of an induction motor that is operating at no load (near synchronous speed). The magnetization current $\mathbf{I}_M$ flowing in the motor's equivalent circuit (Fig. 6.7) creates the net magnetic field $\mathbf{B}_{net}$. Current $\mathbf{I}_M$ and hence $\mathbf{B}_{net}$ are proportional to $\mathbf{E}_1$. Since $\mathbf{E}_1$ remains constant with the changes in load, then $\mathbf{I}_M$ and $\mathbf{B}_{net}$ remain constant also. At no load (Fig. 6.12*a*), the rotor slip (the relative motion between the rotor

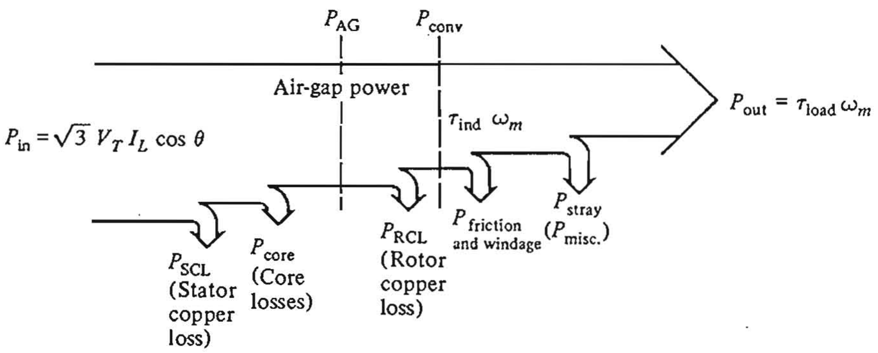
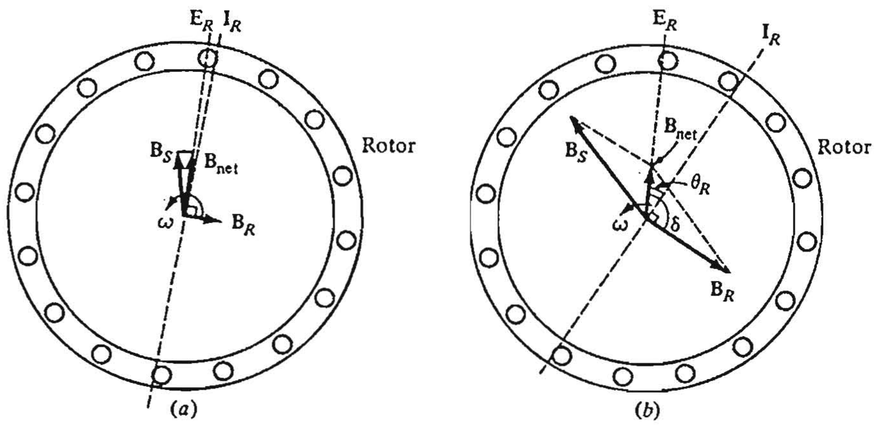


FIGURE 6.11 The power flow diagram of an induction motor.

Small E_R

I_R = max.



Light load $n_m \simeq 0$

$n_m \simeq n_{sync.}$

FIGURE 6.12 (*a*) The magnetic fields in an induction motor under light loads. (*b*) The magnetic fields in an induction motor under heavy loads.

$n_m \cong n_{syn.}$

and the magnetic fields) and the rotor frequency are very small. Since the relative motion is small, the induced voltage in the rotor bars $\mathbf{E}_R$ is very small and the resulting current $\mathbf{I}_R$ is small. Also, since the rotor frequency is small ($f_r = sf_e$), the reactance of the rotor ($\mathbf{X}_R = sX_{R_0}$) is negligible, and the maximum rotor current $\mathbf{I}_R$ is almost in phase with the rotor voltage $\mathbf{E}_R$.

The induced torque in this region is small (just enough to overcome the motor's rotational losses) because the rotor magnetic field is quite small. When the motor is loaded down (Fig. 6.12*b*), the slip increases and the rotor speed falls. Now there is more relative motion between the rotor and the magnetic fields because the rotor speed is slower. Higher rotor voltage $\mathbf{E}_R$ is now produced because of the higher relative motion. This in turn produces a larger rotor current $\mathbf{I}_R$.

Since the induced torque is given by

$$\tau_{ind} = kB_R B_{net} \sin\delta$$

the resulting torque-speed characteristic is shown in Fig. 6.13. The torque-speed curve is divided into three regions. The first is the *low-slip region.* In this region, the motor slip

INDUCTION MOTORS

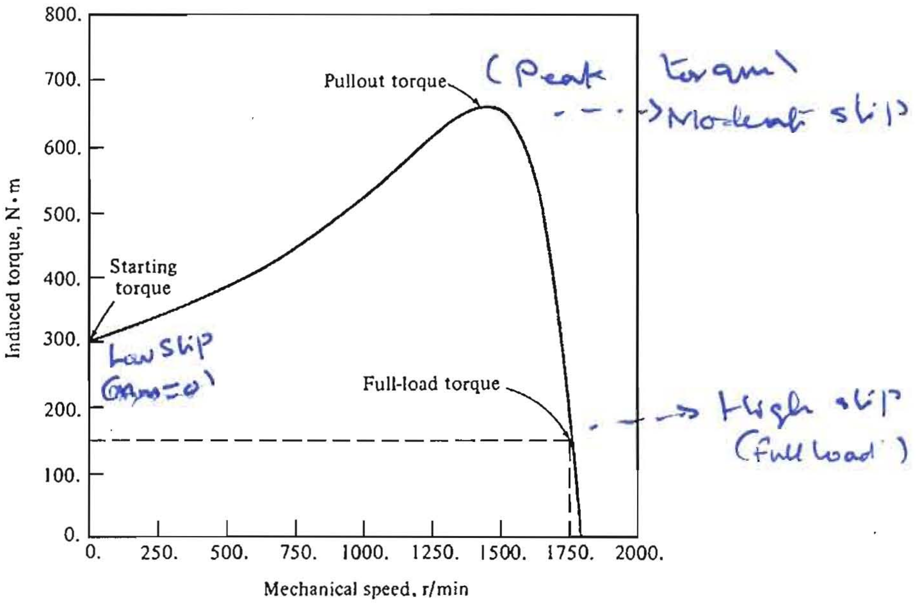


FIGURE 6.13 Induction motor torque-speed characteristic curve.

and mechanical speed change linearly with the load. The second region is the *moderate-slip region*. The peak torque (the pullout torque) of the motor occurs in this region. The third region is the *high-slip region*. In this region, the induced torque decreases with increasing load. Typically, the pullout torque is about 200 to 250 percent of the rated full-load torque of the machine. The starting torque (at zero speed) is about 150 percent of the full-load torque.

Comments on the Induction Motor Torque-Speed Curve

1. There is no induced torque at synchronous speed.
2. The torque-speed curve is linear between no load and full load. In this range, the rotor reactance is much smaller than the rotor resistance, so the rotor current, magnetic field, and induced torque varies linearly with slip.
3. There is a maximum possible torque that the motor cannot exceed. This torque is called the *pullout torque* or *breakdown torque* and is 2 to 3 times the rated full torque of the motor.
4. The starting torque is about 150 percent of the full-load torque. The motor can start carrying any load that it normally handles at full power.
5. The motor torque is proportional to the square of the applied voltage.
6. If the motor turns backward, the induced torque will stop the rotor quickly and will try to rotate it in the opposite direction. Since switching any two of the stator phases will reverse the direction of magnetic field rotation, this fact can be used to stop motors quickly. This technique is known as *plugging*.
7. If the motor is driven beyond synchronous speed, it will operate as an induction generator (Fig. 6.14).
8. The variation of power converted to mechanical form ($P_{conv} = \tau_{ind}\omega_m$) is shown in Fig. 6.15.

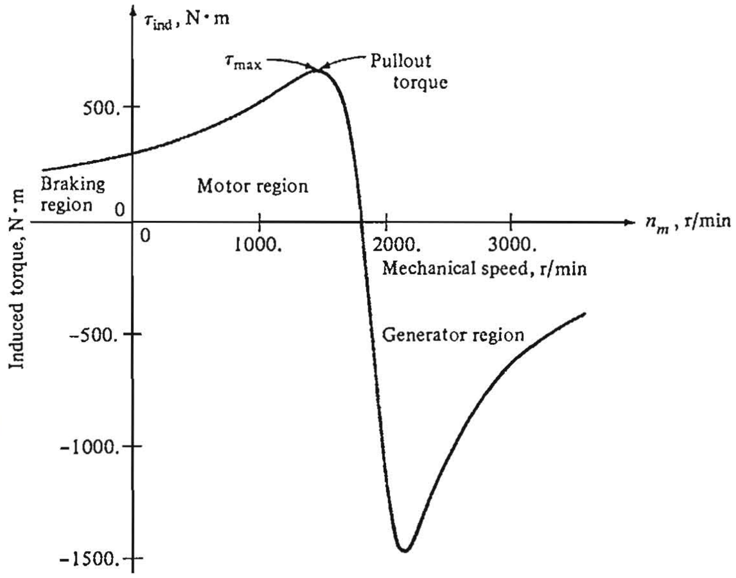


FIGURE 6.14 Induction motor torque-speed characteristic curve, showing the extended operating ranges (braking region and generator region).

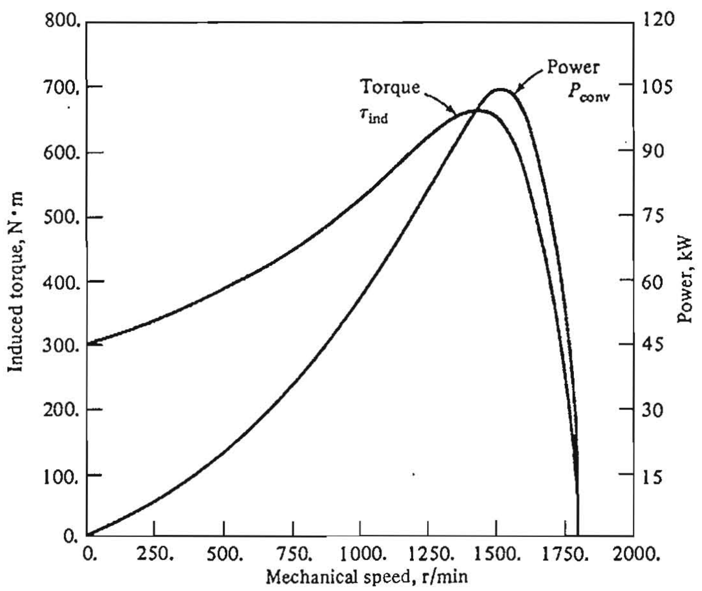


FIGURE 6.15 Induced torque and power converted versus motor speed in revolutions per minute for a four-pole induction motor.

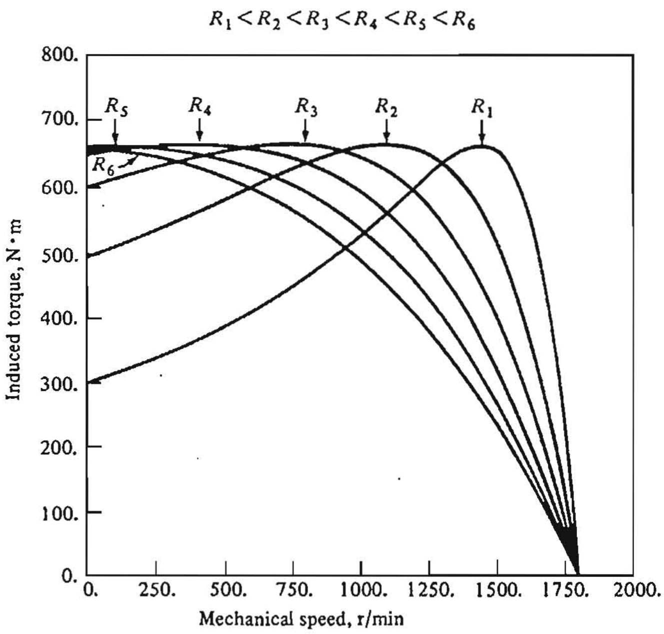
Variation of the Torque-Speed Characteristics

Figure 6.16 illustrates the variation of the torque-speed characteristic of a wound rotor induction motor. Recall that the resistance of the rotor circuit can be changed because the rotor circuit is brought out to the stator through slip rings. As the rotor resistance increases, the pull-out speed of the motor decreases, but the maximum torque remains constant. The advantage of this characteristic of wound rotor induction motors is the ability to start very heavy loads.

The maximum torque can be adjusted to occur at starting conditions by inserting a high resistance. Once the load starts to turn, the extra resistance can be removed from the circuit, and the maximum torque will shift up to near synchronous speed for normal operation. If the rotor is designed with high resistance, then the starting torque is high, but the slip is also high during normal operation. However, the higher the slip during normal operation, the smaller the fraction of power converted to mechanical power, and the lower the efficiency. A motor with a high rotor resistance has a high starting torque and poor efficiency during normal operation.

If the rotor resistance is low, then the starting torque is low and the starting current is high. However, the efficiency is high during normal operation. A compromise between high starting torque and good efficiency is needed.

A wound rotor induction motor can be used to provide high starting torque during start-up by inserting extra resistance. The extra resistance can be removed during normal operation to increase the efficiency. However, wound rotor induction motors are more expensive, require more maintenance, and have a more complex automatic control circuit than squirrel-cage induction motors. Also, wound rotor induction motors cannot be used in hazardous and explosive environments because completely sealed motors are needed. Figure 6.17 illustrates the desired motor characteristic.



Torque-Speed for Variable rotor resistance (wound rotor)

FIGURE 6.16 The effect of varying rotor resistance on the torque-speed characteristic of a wound-rotor induction motor.