Electric Machines & Power

Energy conversion between magnetic, electric, and mechanical.

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Electric Machines & Power

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TO

Rosemary Durham, my wife, best friend, and supporter for all my various ventures.

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1

INTRODUCTION

Thought
Engineering is the tradeoff
between quality, time, and money
You can have two, but you cannot have all three.
MOD

State of the book

Electric machines are simply devices that convert energy between magnetic, electric, and mechanical forms. Therefore, it is necessary to perform analysis in all three systems.

This material is in transition from notes and memos, so much of it will be in outline form at this stage. Therefore, it will be several sections of isolated information.

Credit where credit is due

Everything we know is developed from something we have read, heard, or seen. Therefore, these other thoughts necessarily influence what we write. To the best of our knowledge, we have given specific credit where appropriate.

Rather than footnotes or references, we have listed the works that have provided significant information in one way or another, since this is often in concepts rather than quotes. Some of the information is general and public domain, while some is device specific. The generic information is used where possible.

Statements that are attributed to us are things we have used commonly and do not recall seeing from someone else. Others obviously have similar thoughts. If we have made an oversight in any credits, we apologize and we would appreciate your comments.

Dr. Marcus O. Durham

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2

MECHANICAL

Thought

Fundamentals ___________________

The motion of machines is typically rotational. Therefore the mechanical conversion is usually accomplished with angular convention. There are a few tricks to use when doing energy conversion.

1. Convert the information in one system to energy or power so that it has an equivalent in the other system.
2. Keep units straight and the conversion will be straightforward.

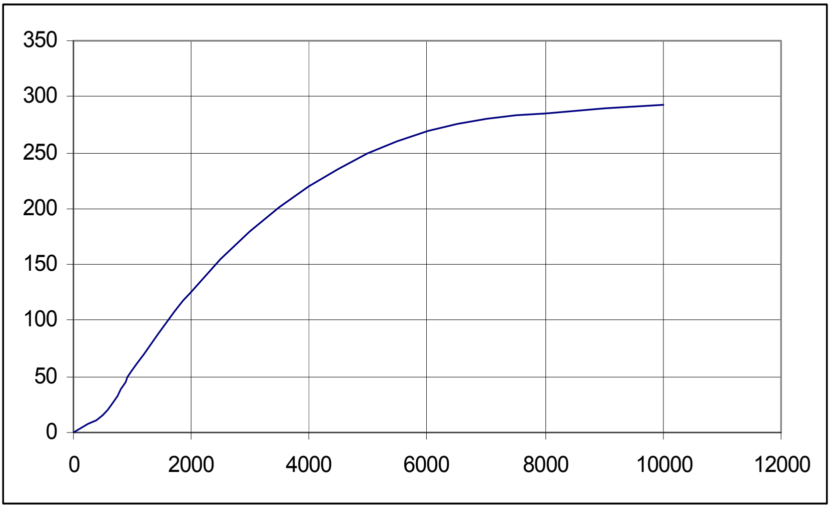
3

MAGNETICS

Thought

Fundamentals

The magnetization curve is a non-linear relationship for the magnetic circuit. It is used to show the conversion between representations of magnetic energy.



The values are strictly representative. Different material alloys will yield other range of values. Nevertheless, the general shape and form can be used for a variety of problems.

The curve then can represent a number of different relationships. Some of the more common are shown in the table.

X	name	unit	Y	name	Units	Function	name	unit
$\mathcal{F}$	mmf	A-turns	Φ	flux	Weber	R	reluctance	
H	intensity	A-turns/m	B	density	Wb/m2	μ	permeability	H/m
I	field I	Amps	V	terminal	Volts	synchronous		
$\mathcal{F}$	field mmf	A-turns	Ea	Internal gen	Volts	dc		

The first portion of the curve has a physical anomaly near zero. The portion portion less than 500 is in the *unsaturated* region. There is an approximate proportional change in the vertical axis as the horizontal changes. About 5000 is called the knee. That is the transition region. The top portion of the curve above about 5000 is the *saturated* region. There is very little change in the vertical parameter as the horizontal is increased.

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4

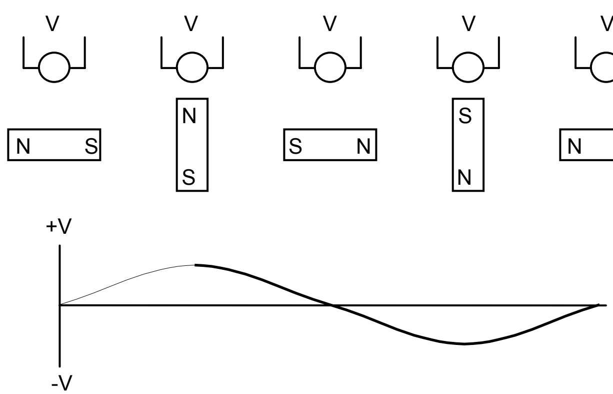
AC POWER

Thought

Alternating current ________________

Alternating current is created in a coil of wire by a magnet rotating very close to the wire. As the magnetic pole distance varies, the magnitude of voltage induced on the coil changes.

The chart illustrates the magnet at four positions with the fifth position the same as the starting point.



Consider the magnet starts horizontal, in the distance farthest from the coil. The voltage will be zero. As the magnet rotates clockwise, the voltage will increase until the magnet is nearest the coil. That will be the maximum voltage. Then the magnet will rotate away from the coil, with the voltage decreasing. When the magnet is close again, but with opposite polarity, the voltage will again be at maximum, but with a negative polarity. The rotation continues until the magnet is at the starting point.

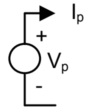
A similar result is obtained by a coil of wire rotating in a magnetic field.

The curve illustrates the 360^o rotation of the magnet and the resulting cycle for the voltage. For machines in the Western Hemisphere, the electrical frequency of rotation is 60 times per second or 60 Hertz (Hz). So each cycle is 1/60 of a second. The time that the voltage crosses the axis can then be expressed equally well as degrees or seconds.

2π radians = 360 degrees = 1 cycle = 1 revolution.
$\theta = 2\pi f t$
$t = \theta / 2\pi f$

Single-phase

A machine contains mechanical rotation, magnetic poles, and electric circuit. A single-phase machine contains only one component set of these three physical components. A single-phase component, whether source or load, can be represented by a two-node network. The voltage across the component is the phase voltage, V_P, and the current through is the phase current, I_P.



The voltage has a time associated with its magnitude, as does the current. This time is represented as an angle which is a portion of a complete rotational cycle.

From the measured voltage, current, and time, three things can be calculated. Impedance is the ratio of the voltage to current. Power is the product of the voltage and current. Time delay is the difference in the time when the voltage and current are at a minimum.

The current is related to the voltage by Ohm's Law. By convention, voltage is used as the reference for measurement comparison. Bold letters represent a vector with magnitude and angular direction. Normal letters are scalar values of magnitude only.

$$\mathbf{Z} = \mathbf{V} / \mathbf{I}$$

$$Z \underline{/ \theta} = \frac{V_P \underline{/ 0^{o}}}{I_P \underline{/ -\theta}}$$

Current lags the voltage by the angle of the impedance. If the impedance has a negative angle value, obviously the current angle will be positive and lead the voltage.

The impedance is the combination of the three physical elements in an electrical circuit. Resistance, R, is a characteristic of the conductor material that opposes the flow of current. An inductance, L, arises if the conductor is wrapped into a coil. A capacitor, C, arises when two conductors are adjacent.

Resistance is independent of time or the resulting phase angle.

$$\mathbf{Z} = R$$

However, an inductor operates as a reactance at an angle of 90°. In a rectangular system this is the +j direction.

$$\mathbf{Z} = +j\ X_L$$

Conversely, a capacitor operates as a reactance at an angle of -90°. In a rectangular system this is the -j direction.

$$\mathbf{Z} = -j\, X_C$$

Obviously, an inductor and a capacitor are complementary devices that can be used to balance a system. The combination of the impedance elements results in a value with an angle.

$$\begin{aligned} Z\, \underline{/\ \theta} &= R + j\, X_L - j\, X_C \\ &= R + j(X_L - X_C) \end{aligned}$$

Apparent power is the product of voltage and current conjugate. The conjugate is simply changing the sign of the current.

$$\begin{aligned} \mathbf{S} &= \mathbf{V}\, \mathbf{I}^* \\ &= (V_P\, \underline{/\ 0^{\circ}}\,)\, (I_P\, \underline{/{-\theta}}\,)^* \\ &= V_P\, I_P\, \underline{/\theta} \end{aligned}$$

The angle has numerous interesting relationships. The current vector is the conjugate of the impedance and power angle. This angle represents the time delay between the current and the voltage crossing the zero-axis.

Because of the angle associated with the apparent power, the power can be separated into two components, the real power, P, and the reactive power, Q. The real power is a mechanical conversion of the resistance. The reactive power represents the magnetic energy stored in the inductor and the electrical energy stored in the capacitor.

$$\begin{aligned} S\, \underline{/\theta} &= P + j\, Q_L - j\, Q_C \\ &= S\, (\cos\theta + j \sin\theta) \end{aligned}$$

The components of apparent power can also be represented in terms of the angle associated with the current and impedance.

$$\begin{aligned} P &= S \cos\theta = V\, I \cos\theta \\ Q &= S \sin\theta = V\, I \sin\theta \end{aligned}$$

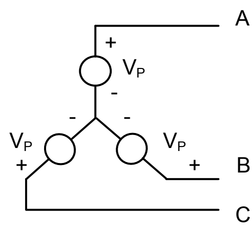
In the power world the real component factor is called the power factor. It is the ratio of the real mechanical component to the total. Another common factor is the ratio of the reactive component to the real mechanical component.

$$pf = \cos\theta = P / S = R / Z$$
$$\tan\theta = Q / P = X / R$$

Three-phase

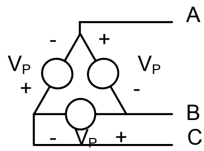
Three-phase indicates 3 sources, 3 lines, and 3 loads. In essence, three-phase is three single-phase systems connected together. Based on the original illustration, the magnets are placed on the rotating member called rotor, separated by 120°. Similarly, the coils are placed on the stationary member called stator, separated by 120°.

The three-phase system can be represented as a three-node network. The arrangement of three coils with six wires can be yields two possible connections to obtain three-phase. If a common connection is made between all three components, then the three phases are connected to the remaining wire on each component. This is called a wye configuration. The connections to the lines are labeled as A-B-C.



WYE

If a connection is made between only two components, then there are only three possible connections. These connect to the three phase lines. The arrangement is called a delta configuration.



The voltage across the phase component, V_P, and the current through is the phase current, I_P are the same as the single-phase values. However the terminal voltages are different and depend on the configuration.

Wye

In the wye configuration, each phase is connected to a common terminal called the neutral. Then the voltage on each phase is equal to the phase magnitude separated by an angle of 120°. By convention, the A phase is assumed to be at an angle of zero degrees.

$$\mathbf{V}_{AN} = V_P \underline{/\ 0^\circ}$$
$$\mathbf{V}_{BN} = V_P \underline{/{-120}^\circ}$$
$$\mathbf{V}_{CN} = V_P \underline{/{-240}^\circ}$$

In voltage designations, the first subscript is assumed to be the higher or positive voltage compared to the second subscript..

The terminal voltage is the voltage between the lines, V_{LL}. The respective line to line voltages are V_{AB}, V_{BC}, and V_{CA}. The magnitude and angle can be calculated from the phase voltages.

$$\begin{aligned}\mathbf{V}_{AB} &= V_{AN} - V_{BN} \\ &= V_P \underline{/\ 0^\circ} - V_P \underline{/{-120}^\circ} \\ &= V_P (1 + j0) - V_P (-0.5 - j0.866) \\ &= V_P (1.5 + j0.866) \\ &= \sqrt{3}\, V_P \underline{/\ 30^\circ}\end{aligned}$$

The other two line to line voltages can be determined similarly. Alternately, they can be found by recognizing the shift of 120° between phases.

$$\mathbf{V}_{BC} = \sqrt{3}\ V_P\ \underline{/\ 30^\circ} - \underline{/-120^\circ} = \sqrt{3}\ V_P\ \underline{/\ -90^\circ}$$
$$\mathbf{V}_{CA} = \sqrt{3}\ V_P\ \underline{/\ 30^\circ} - \underline{/-240^\circ} = \sqrt{3}\ V_P\ \underline{/\ -210^\circ}$$

The current in each line is simply the current in the phase.

$$\mathbf{I}_A = I_P\ \underline{/-\theta}$$
$$\mathbf{I}_B = I_P\ \underline{/-\theta - 120^\circ}$$
$$\mathbf{I}_C = I_P\ \underline{/-\theta - 240^\circ}$$

The current in the neutral is the sum of the current in the three phases.

$$\mathbf{I}_N = \mathbf{I}_A + \mathbf{I}_B + \mathbf{I}_C$$

In a balanced system, the magnitude of the currents is the same. When the angles are resolved, it is found that they cancel each other.

$$I_N = 0$$

A summary of the line and phase relationships is based on the AN phase.

$$\mathbf{V}_{LL} = \sqrt{3}\ V_P\ \underline{/\ 30^\circ}$$
$$\mathbf{I}_L = I_P\ \underline{/-\theta}$$

Often only magnitudes are expressed since the mechanical shift of 30° does not change, regardless of the circuit or calculations. Likewise, the impedance angle is often excluded since it is not readily measured with most current meters. These common simplifications give magnitudes but do not express phase shifts which impact power.

$$\boxed{V_{LL} = \sqrt{3}\ V_P}$$

$$\boxed{I_L = I_P}$$

Delta

In the delta configuration, each phase component is connected to an adjacent phase. Then, the terminal voltage is equal to the phase voltage. Again because of the geometry of the generator, the voltage on each phase is equal to the phase magnitude separated by an angle of 120^{o}.

Since the terminal of a delta system can be connected to a wye system, it is important that the phase and subscript convention be consistent.

$$\mathbf{V}_{AB} = V_P \underline{/\ 0^o}$$
$$\mathbf{V}_{BC} = V_P \underline{/\!-120^o}$$
$$\mathbf{V}_{CA} = V_P \underline{/\!-240^o}$$

The sum of the line current and phase currents at each terminal is zero. Therefore, the line current is the difference in the current in the phases that are connected to the terminal.

$$\mathbf{I}_A = \mathbf{I}_{AB} - \mathbf{I}_{CA}$$
$$= I_P \underline{/\!-\theta} - I_P \underline{/\!-\theta - 240^o}$$
$$= \sqrt{3}\, I_P \underline{/\!-\theta -30^o}$$

The other two currents can be determined similarly. Alternately, they can be found by recognizing the shift of 120^{o} between phases.

$$\mathbf{I}_B = \sqrt{3}\, I_P \underline{/\!-\theta -30^o} - \underline{/\!-120^o} = \sqrt{3}\, I_P \underline{/\!-\theta -150^o}$$
$$\mathbf{I}_C = \sqrt{3}\, I_P \underline{/\!-\theta -30^o} - \underline{/\!-240^o} = \sqrt{3}\, I_P \underline{/\!-\theta -270^o}$$

A summary of the line and phase relationships is based on the A line.

$$\mathbf{V}_{LL} = V_P \underline{/\ 0^o}$$
$$\mathbf{I}_L = \sqrt{3}\, I_P \underline{/\!-\theta -30^o}$$

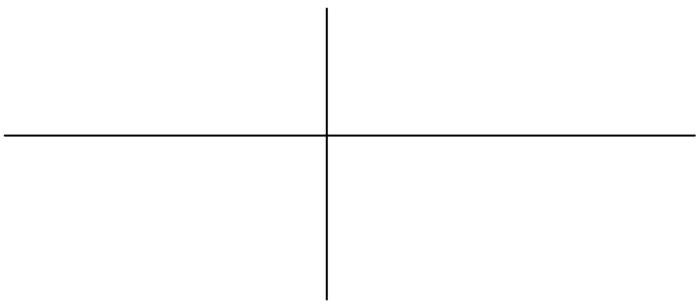
In most references the angles are included similar to the wye configuration discussion.

$$\boxed{V_{LL} = V_P}$$

$$\boxed{I_L = \sqrt{3}\, I_P}$$

Phase sequence graph ____________

A visual representation is convenient for identifying the sequence between phases. The graph also illustrates the angular correspondence between phases and lines. The curves can be either voltage or current, since they are related by the angle, $\underline{\theta}$. Voltage is the reference. Therefore, it is more frequently drawn.



A three-phase machine will rotate based on the sequence or order of the terminal connections. If any two of the terminal lines are exchanged, the direction of rotation will be reversed. Normal rotation is called an ‘ABC’ sequence. If the rotation is changed the negative sequence is called ‘CBA’

The sequence is determined by looking on the zero-axis. Then rotate the phase relationships in a counterclockwise (CCW) pattern. Note the sequence of the phasors that cross the zero-axis. For example looking at a terminal connection, the phasors may be in the order AB – BC – CA. Determine the sequence by taking only the first letter in each pairing, A – B – C. That is a positive sequence.

Power

Three-phase impedance has no real meaning. Impedance is the ratio between the voltage and current in each phase. Therefore, it is not converted to terminal or line values.

On the other hand, three phase power has several representations. In the most basic definition, it is the sum of the power in all three phases. In a balanced system the power in each phase is equal in magnitude and separate by the mechanical configuration of 120^{O}. In a complete three-phase system, the mechanical angles will cancel, but the phase shift between voltage and current persists.

$$\begin{aligned} \mathbf{S}_{3\varphi} &= \mathbf{S}_{P1} + \mathbf{S}_{P2} + \mathbf{S}_{P3} \\ &= V_{P1}\, I_{P1}^{*} + V_{P2}\, I_{P2}^{*} + V_{P3}\, I_{P3}^{*} \\ &= 3\, V_P\, I_P \underline{/\ \theta} \end{aligned}$$

Phase values are the internal parameters of a machine. As such, they are not easily measured. The terminal or line values are a more common representation. The relationship between the terminal values and the phase values depends on the wye or delta configuration. However, because of the symmetry, the three-phase power will be the same for both wye and delta.

Consider a wye configuration. A similar analysis of a delta design would yield the same results. The angles associated with the mechanical phase shifts are not included. As has been discussed, these will cancel each other.

$$V_{LL} = \sqrt{3}\, V_P$$
$$V_P = 1/\sqrt{3}\, V_{LL}$$

$$\mathbf{I}_L = \mathbf{I}_P \underline{/\text{-}\theta}$$
$$\mathbf{I}_P = \mathbf{I}_L \underline{/\ \theta}$$

$$\begin{aligned} \mathbf{S}_{3\varphi} &= 3\, \mathbf{S}_{1\varphi} \\ &= 3\, [1/\sqrt{3}\, V_{LL}\ \ I_L \underline{/\ \theta}\,] \\ &= \sqrt{3}\, V_{LL}\ I_L \underline{/\ \theta} \end{aligned}$$

The three-phase power can be segregated into real and reactive components exactly as the single-phase variables.

$$S_{3\varphi} \underline{/\theta} = P + j\,Q_L - j\,Q_C$$
$$= S\,(\cos\theta + j\sin\theta)$$

The components of apparent power can also be represented in terms of the angle associated with the current and impedance.

$$P_{3\varphi} = S_{3\varphi}\cos\theta$$
$$= 3\,V_P\,I_P\cos\theta$$
$$= \sqrt{3}\,V_{LL}\;I_L\cos\theta$$

$$Q_{3\varphi} = S_{3\varphi}\sin\theta$$
$$= 3\,V_P\,I_P\sin\theta$$
$$= \sqrt{3}\,V_{LL}\;I_L\sin\theta$$

To recap, the three phase power is expressed in terms of phase voltage and current or line voltage and current.

$$\mathbf{S}_{3\varphi} = 3\,V_P\,I_P\,\underline{/\,\theta}$$
$$= \sqrt{3}\,V_{LL}\;I_L\,\underline{/\,\theta}$$

Recap

The relationships between phase and line values are identified for three-phase systems. The terms are separated into magnitude and directions.

$V_{LL} = \sqrt{3}\,V_L$:wye
$I_L = I_P$:wye
V_L leads V_P by an angle of $\underline{/\,30^o}$

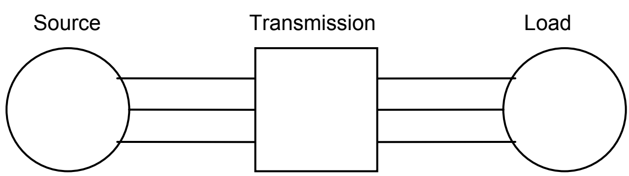
$V_{LL} = V_P$:delta
$I_L = \sqrt{3}\,I_P$:delta
I_L lags I_P by an angle of $\underline{/\!-30^o}$

$S_{3\varphi} = 3\,V_P\,I_P$
$S_{3\varphi} = \sqrt{3}\,V_{LL}\;I_A$
Impedance angle is $\underline{/\,\theta}$

	wye	**delta**
V_{LL}	√3 V_P	V_P
I_L	I_P /-θ	√3 I_P /-θ
/phase	/ 30º	/-30º
	V line leads phase	I line lags phase
/ Z	/ θ	/ θ

One-line diagram ________________

A power system consists of sources or generators, transmission lines, and loads which are commonly motors.

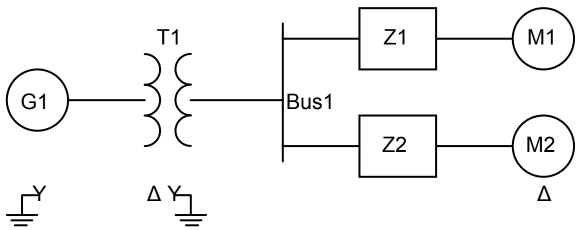


In a single-phase system, the source and load are each represented as a two-noe network. However, for a three-phase system, each is a three-node network. The network can be either delta or wye. The three-nodes can also be analyzed as a two-port network. In network analysis a delta is also called a pi-network, while a wye is also called a T-network.

Each transmission line is a combination of resistors and inductors in series and capacitors in shunt. Therefore, each line is also a three-port net. These are connected in such a way that the input is a three-port with the output as a three-port and a transfer function between them that is impedance.

Traditional circuit analysis of three-phase networks would require many lines and connections. This actually makes the investigation appear quite complicated.

As a result, most power analysis uses a one-line diagram. The sources or generators (G), loads or motors (M), and transformers (T) are identified with a note about wye or delta connection. Transmission lines (Z) are described by an impedance. A connection is called a bus (B). Voltage, current, and power transfer is calculated at each bus.



The description and specification of each component is displayed on the one-line. If there is inadequate room, a table may be used. Impedance is often in terms of Ohms per distance.

	kVA	**pf or /Z**	**P**	**Q**	**V_{LL}**	**/V**	**I_L**	**/I**	**Z**	**long**
G1										
T1										
B1										
Z1										
M1										
Z2										
M2										

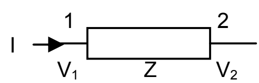
The known values are placed in the table. Other values in the table are calculated as required based on the known parameters. The voltage, current, and power transfer is simply calculated at each node.

One phase ________________________

A generator is often modeled as a voltage source in series with an inductive reactance. A transformer is resistor and inductive reactance. A transmission line is an impedance. A motor may be an impedance.

In looking at the one-line diagram, it is apparent that the voltage and current on one side of an impedance can be related to the voltage and current on the other side. The relationships can be determined by the power transfer across the impedance.

Consider a two node model for an impedance with the input at terminal 1 and the output at terminal 2.



The voltage across the impedance network is the difference in the voltage on the input and output.

$$\mathbf{V}_{12} = \mathbf{V}_1 - \mathbf{V}_2$$

The current through the impedance is related by Ohm's Law.

$$\mathbf{V}_{12} = \mathbf{I}\,\mathbf{Z}$$

The apparent power is the product of the voltage and current.

$$\begin{aligned} \mathbf{S} &= \mathbf{V}\,\mathbf{I}^* \\ &= \mathbf{V}_{12}\ \mathrm{I}\ \underline{/\theta} \end{aligned}$$

Ohm's Law and power can be combined to have different terms for power.

$$\begin{aligned} \mathbf{S} &= \mathbf{V}_{12}\,\mathbf{I}^* \\ &= \mathrm{I}^*\mathrm{I}\ \mathrm{Z} = \mathrm{I}^2\ \mathrm{Z} \\ &= \mathrm{V}_{12}^{\ 2} / \mathrm{Z} \end{aligned}$$

The impedance has been defined as the sum of the resistance, the inductive reactance and the capacitive reactance.

$$\mathbf{Z} = \mathrm{R} + \mathrm{j}\ \mathrm{X}_L - \mathrm{j}\ \mathrm{X}_C$$

In many problems, one of the impedance elements will dominate. Then the others can be reasonably ignored.

Power transfer

Two special cases of impedance are considered. The first is a resistance only. The second is reactance only.

The power across a resistor is real power only. It represents conversion to real mechanical energy, generally in the form of heat. There is no angle or phase shift associated with a resistance.

The relationships for real and reactive power are determined when θ = 0.

$$\begin{aligned} P &= S \cos \theta \\ &= V_{12}\, I \\ &= I^2 R \\ &= V_{12}^{\,2} / R \end{aligned}$$

$$Q = S \sin \theta = 0$$

The second example has a reactance only. Power can be transferred across the reactance but there is no power converted. Reactive power can also be transferred. The voltage angle is denoted as δ. These relationships will be stated simply rather than derived.

$$P_{12} = \frac{1}{X} [\, V_1\, V_2 \sin(\delta_1 - \delta_2)$$

$$Q_{12} = \frac{1}{X} [\, V_1^{\,2} – (V_1\, V_2 \cos(\delta_1 - \delta_2))]$$

Although the illustration has been single-phase, it can readily be extended to three phase using the relationships developed earliey. An application of the power transfer is the transfer from Bus 1 to Motor 2 in the one-line diagram. This is also used with generators which have only a reactance.

Summary

These calculations determine the external performance of electrical equipment.

1. Use per unit if multiple voltages are used in the problem.

2. Convert Hp to real power (KW).

   P = ? Hp | 0.746 KW | 1

   | Hp | eff

   Alternately, the Hp can be converted to apparent power (KVA).

   S = ? Hp | .746 KW | 1 | 1

   | Hp | eff | pf

3. Use the following equations to obtain the desired quantity.

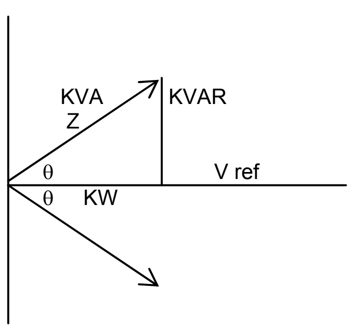
$S = V I^* = P + jQ = \sqrt{(P2 + Q2)}$	: apparent power- KVA
$P = V I pf = S pf = v i$	:real power- KW
$Q = V I \sin (\cos\text{-}1pf) = V I \sin \theta$	:reactive power- KVAR
$pf = \cos \theta = P / S = v i / V I$	:power factor

4. Complex numbers are easiest to manipulate in the following manner.

   Add & Subtract: P's and Q's

   Multiply & Divide: Convert P & Q to S,
   then multiply magnitudes & add angles

5. The relationship between the power terms is shown graphically.



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6. The angle has several interesting relationships. It is also the time delay between the voltage and the current crossing the axis (going through zero value). The time conversion is based on a cycle.

2π radians = 360 degrees = 1 cycle = 1 revolution.

$\theta = \underline{/V} - \underline{/I} = \underline{/Z} = \underline{/S} = \cos\text{-}1\ pf = 2\ \pi\ f\ t$

$t = \theta / 2\ \pi\ f$

7. Impedance is the ratio of voltage and current (Ohm's Law).

$Z = V / I = R + jX = \sqrt{(R2 + X2)}$

8. Phasor rotation is used to explain the relationship between the lines of a three-phase power system.

⇐⇑⇒

5

EQUIVALENT CIRCUITS

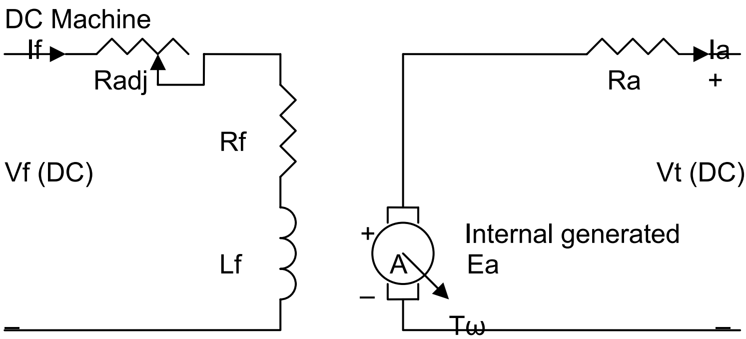
Thought

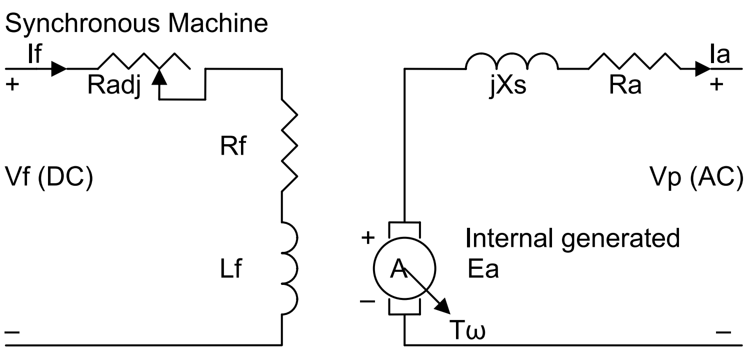
Fundamentals ____________________

What is the difference between the machines?

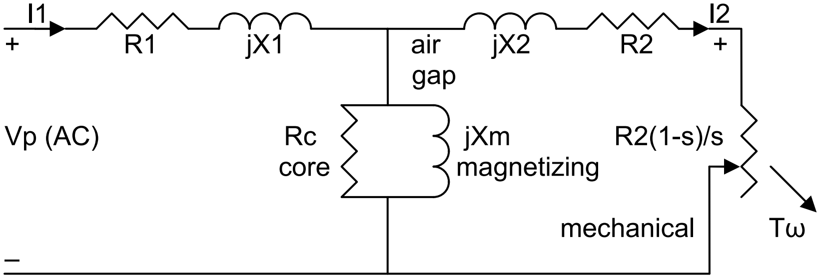
There are four fundamental classes – DC, synchronous, induction, and transformer.

The input energy and output enegy determine the use. A motor has electrical in and mechanical out. A generator has mechanical in and electric out. The same machine can be used in either form. It simply depends on the driver input and the driven output.

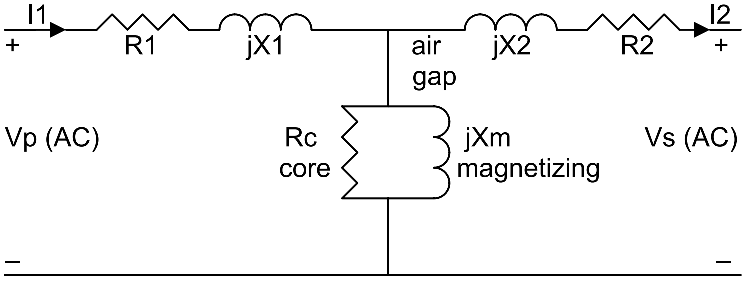

DC Machine
If
Radj
Rf
Vf (DC)
Lf
Ra
Ia
+
Vt (DC)
+
A
−
Internal generated
Ea
Tω
−
−


Synchronous Machine
If
+
Radj
Rf
Vf (DC)
Lf
−
jXs
Ra
Ia
+
Vp (AC)
+
A
−
Internal generated
Ea
Tω
−

Induction Machine



Transformer



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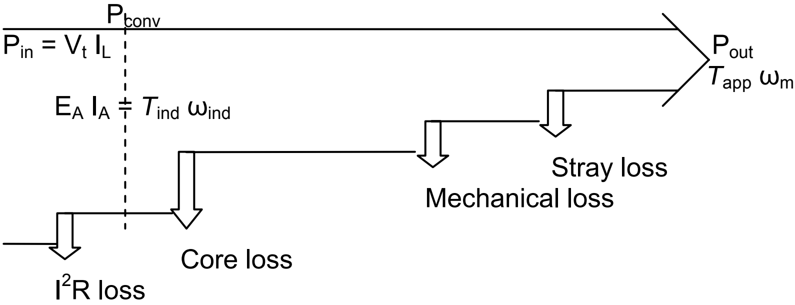
POWER LOSS

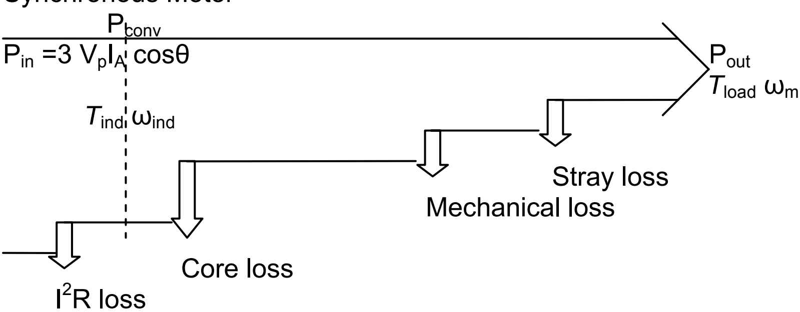
Thought

Fundamentals

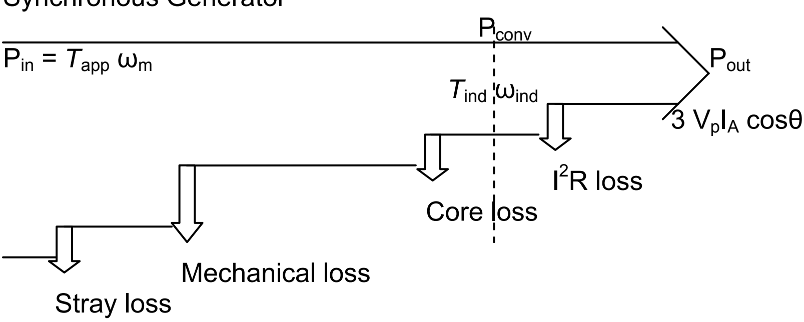
DC Motor

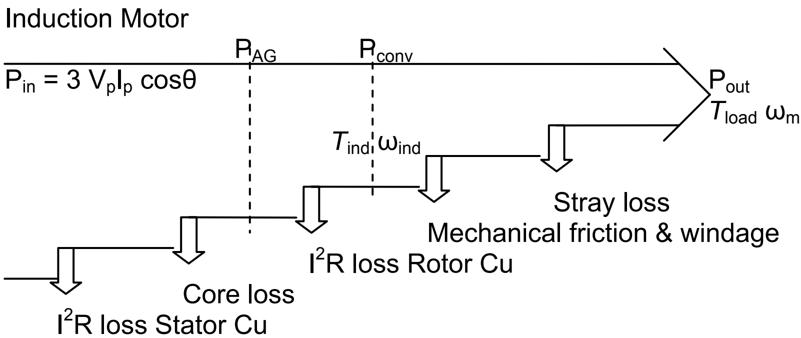


Synchronous Motor



Synchronous Generator




Induction Motor
P_AG
P_conv
P_in = 3 V_p I_p cosθ
P_out
T_load ω_m
T_ind ω_ind
Stray loss
Mechanical friction & windage
I²R loss Rotor Cu
Core loss
I²R loss Stator Cu

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7

DC

Thought

Fundamentals

⇐⇑⇒

8

SYNCHRONOUS

Thought

Fundamentals

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9

INDUCTION

Thought

Fundamentals

$\Leftarrow \Uparrow \Rightarrow$

END

Thought

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⇐ ⇑ ⇒

AUTHOR

Dr. Marcus O. Durham brings very diverse experience to his writing and lectures. He is an engineer, who owns THEWAY Corp., an international consulting practice. He is an entrepreneur on the internet with Advanced Business Technology, Inc. He is a Professor at The University of Tulsa. He is formerly Dean of Graduate Studies and Professor at Southwest Biblical Seminary.

He is a commercial pilot who flies his own plane, is a ham radio amateur extra class operator, and has a commercial radiotelephone license. He is a registered Professional Engineer and a state licensed electrical contractor.

Professional recognition includes Fellow of Institute of Electrical and Electronic Engineers, Diplomate of American College of Forensic Examiners, Certified Homeland Security Level III (highest), and Kaufmann Medal by IEEE.

Dr. Durham is acclaimed in *Who’s Who of American Teachers* (multiple editions), *National Registry of Who's Who*, *Who’s Who of the Petroleum and Chemical Industry*, *Who’s Who in Executives and Professionals*, *Who’s Who Registry of Business Leaders*, Congressional Businessman of the Year, and Presidential Committee Medal of Honor. Honorary recognition includes Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu.

He has published over 100 papers and articles and has authored six books. He has developed a broad spectrum of projects for both U.S. and international companies. He has traveled in over 22 countries and has mentoring relationships with students in 15 additional nations.

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