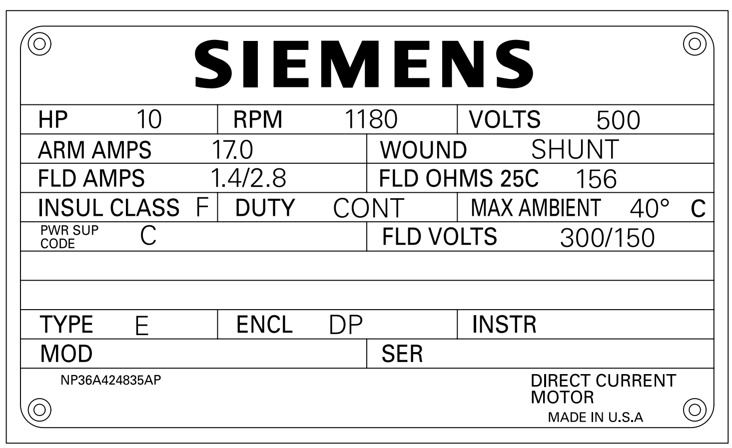
DC Motor Ratings

The nameplate of a DC motor provides important information necessary for correctly applying a DC motor with a DC drive. The following specifications are generally indicated on the nameplate:

- Manufacturer's Type and Frame Designation
- Horsepower at Base Speed
- Maximum Ambient Temperature
- Insulation Class
- Base Speed at Rated Load
- Rated Armature Voltage
- Rated Field Voltage
- Armature Rated Load Current
- Winding Type (Shunt, Series, Compound, Permanent Magnet)
- Enclosure



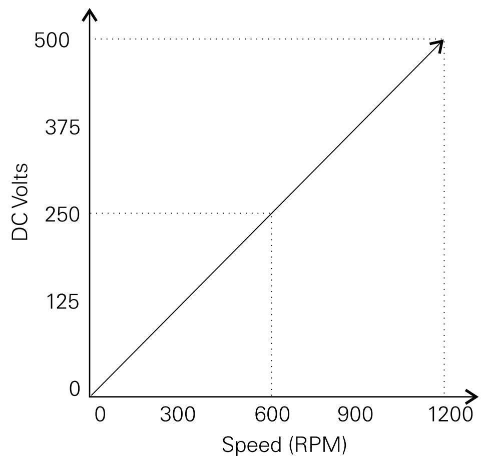
HP

Horsepower is a unit of power, which is an indication of the rate at which work is done. The horsepower rating of a motor refers to the horsepower at base speed. It can be seen from the following formula that a decrease in speed (RPM) results in a proportional decrease in horsepower (HP).

$$HP = \frac{Torque \times RPM}{5250}$$

Armature Speed, Volts, and Amps

Typically armature voltage in the U.S. is either 250 VDC or 500 VDC. The speed of an unloaded motor can generally be predicted for any armature voltage. For example, an unloaded motor might run at 1200 RPM at 500 volts. The same motor would run at approximately 600 RPM at 250 volts.



$$Speed\ (n) = \frac{Va - (IaRa)}{Kt\Phi}$$

or

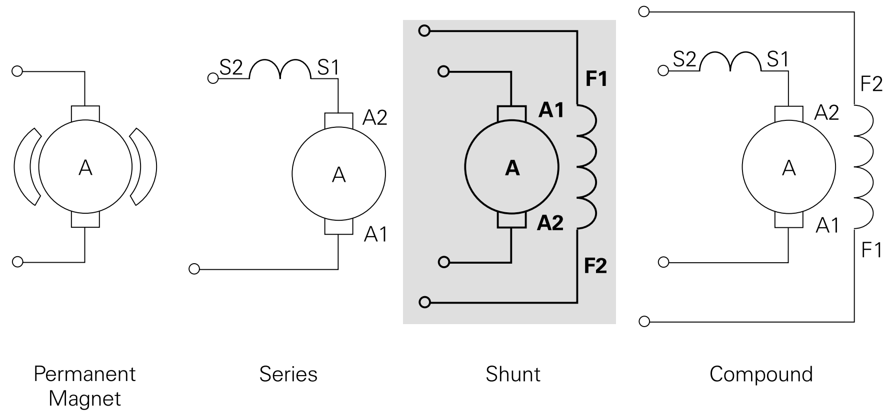
$$Speed\ (n) \approx \frac{CEMF}{\Phi}$$

The base speed listed on a motor's nameplate, however, is an indication of how fast the motor will turn with rated armature voltage and rated load (amps) at rated flux (Φ).

The maximum speed of a motor may also be listed on the nameplate. This is an indication of the maximum mechanical speed a motor should be run in field weakening. If a maximum speed is not listed the vendor should be contacted prior to running a motor over the base speed.

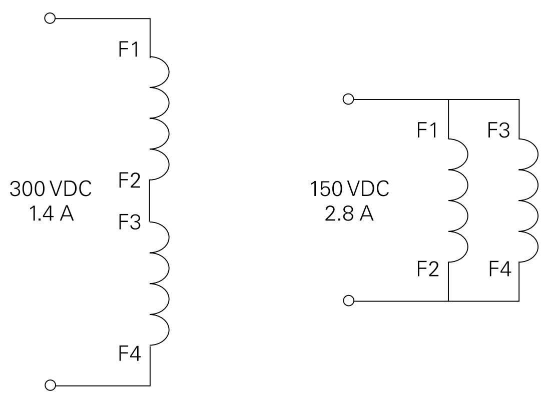
Winding

The type of field winding is also listed on the nameplate. Shunt winding is typically used on DC Drives.



Field Volts and Amps

Shunt fields are typically wound for 150 VDC or 300 VDC. Our sample motor has a winding that can be connected to either 150 VDC or 300 VDC.



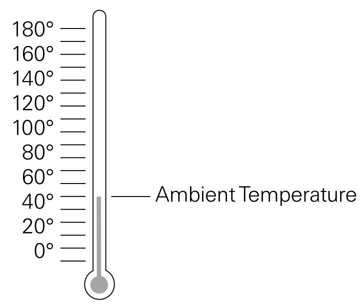
Field Economizing

In many applications it may be necessary to apply voltage to the shunt field during periods when the motor is stationary and the armature circuit is not energized. Full shunt voltage applied to a stationary motor will generate excessive heat which will eventually burn up the shunt windings. Field economizing is a technique used by DC drives, such as the SIMOREG® 6RA70, to reduce the amount of applied field voltage to a lower level when the armature is de-energized (standby). Field voltage is reduced to approximately 10% of rated value. A benefit of field economizing over shuting the field off is the prevention of condensation.

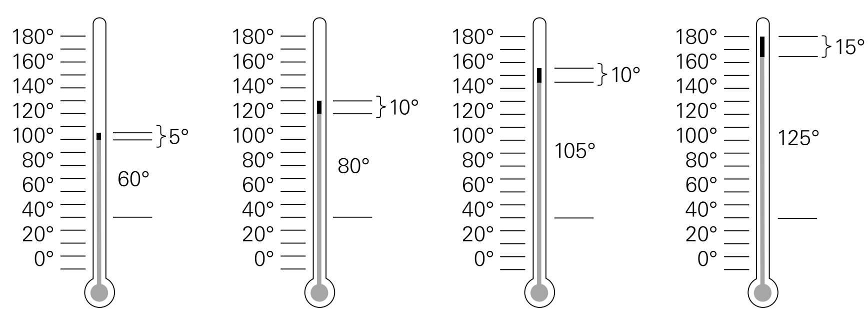
Insulation Class

The National Electrical Manufacturers Association (NEMA) has established insulation classes to meet motor temperature requirements found in different operating environments. The insulation classes are A, B, F, and H.

Before a motor is started the windings are at the temperature of the surrounding air. This is known as ambient temperature. NEMA has standardized on an ambient temperature of 40°C (104°F) for all classes.



Temperature will rise in the motor as soon as it is started. The combination of ambient temperature and allowed temperature rise equals the maximum winding temperature in a motor. A motor with Class F (commonly used) insulation, for example, has a maximum temperature rise of 105°C. The maximum winding temperature is 145°C (40°C ambient + 105°C rise). A margin is allowed to provide for a point at the center of the motor's windings where the temperature is higher. This is referred to as the motor's hot spot.



Class A
60° C Rise
5° C Hot Spot

Class B
80° C Rise
10° C Hot Spot

Class F
105° C Rise
10° C Hot Spot

Class H
125° C Rise
15° C Hot Spot

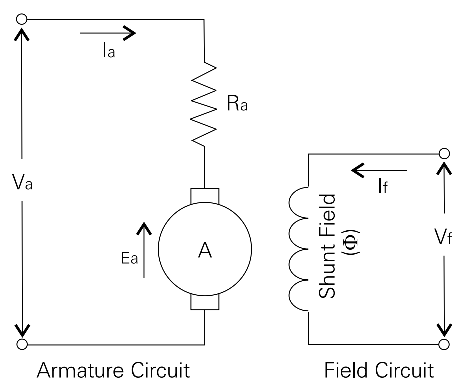
The operating temperature of a motor is important to efficient operation and long life. Operating a motor above the limits of the insulation class reduces the motor's life expectancy. A 10°C increase in the operating temperature can decrease the life expectancy of a motor by as much as 50%. In addition, excess heat increases brush wear.

Speed/Torque Relationships of Shunt Connected Motors

An understanding of certain relationships within a DC motor will help us understand the purposes of various functions in a DC drive later in the course. The formulas given in the following discussion apply to all three types of DC motors (series, shunt, and compound). However, because shunt connected motors are more commonly used with DC drives focus will be on shunt connected DC motors.

DC Motor Equations

In a DC drive voltage applied (V_a) to the armature circuit is received from a variable DC source. Voltage applied to the field circuit (V_f) is from a separate source. The armature of all DC motors contains some amount of resistance (R_a). When voltage is applied (V_a), current (I_a) flows through the armature. You will recall from earlier discussion that current flowing through the armature conductors generates a magnetic field. This field interacts with the shunt field (Φ) and rotation results.



Armature Voltage

The following armature voltage equation will be used to demonstrate various operating principles of a DC motor. Variations of this equation can be used to demonstrate how armature voltage, CEMF, torque, and motor speed interact with each other.

$V_a = (K_t\Phi n) + (I_a R_a)$

Where:

V_a = Applied Armature Voltage
K_t = Motor Design Constants
Φ = Shunt Field Flux
n = Armature Speed
I_a = Armature Current
R_a = Armature Resistance

CEMF

We have already learned that rotation of the armature through the shunt field induces a voltage in the armature (E_a) that is in opposition to the armature voltage (V_a). This is counter electromotive force (CEMF).

CEMF is dependent on armature speed (n) and shunt field (Φ) strength. An increase in armature speed (n) or an increase of shunt field (Φ) strength will cause a corresponding increase in CEMF (E_a).

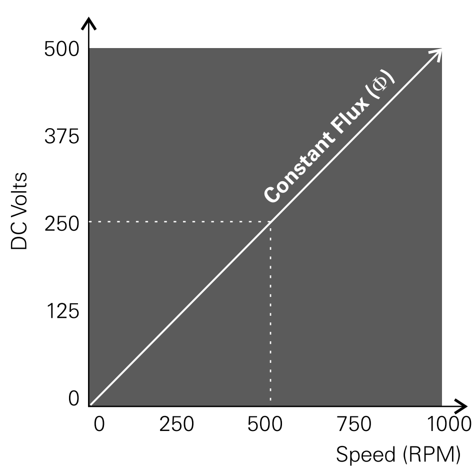
$E_a = K_t\Phi n$

or

$E_a = V_a - (I_a R_a)$

Motor Speed

The relationship between V_A and speed is linear as long as flux (Φ) remains constant. For example, speed will be 50% of base speed with 50% of V_A applied.



$$\text{Speed (n)} = \frac{V_a - (I_a R_a)}{K_t\Phi}$$

or

$$\text{Speed (n)} \approx \frac{\text{CEMF}}{\Phi}$$

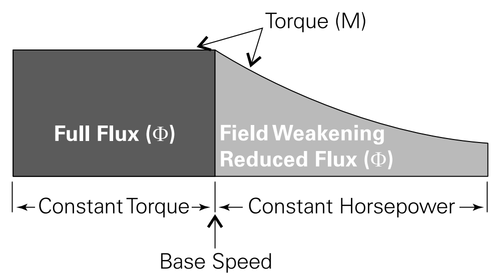
Motor Torque

The interaction of the shunt and armature field flux produces torque (M). An increase in armature current (I_a) increases armature flux, thereby increasing torque. An increase in field current (I_f) increases shunt field flux (Φ), thereby increasing torque.

$$M \approx I_a\Phi$$

Constant Torque

Base speed corresponds to full armature voltage (V_a) and full flux (Φ). A DC motor can operate at rated torque (M) at any speed up to base speed, by selecting the appropriate value of armature voltage. This is often referred to as the constant torque region. Actual torque (M) produced, however, is determined by the demand of the load (I_a).



$$\text{Speed (n)} = \frac{Va - (IaRa)}{Kt\Phi}$$

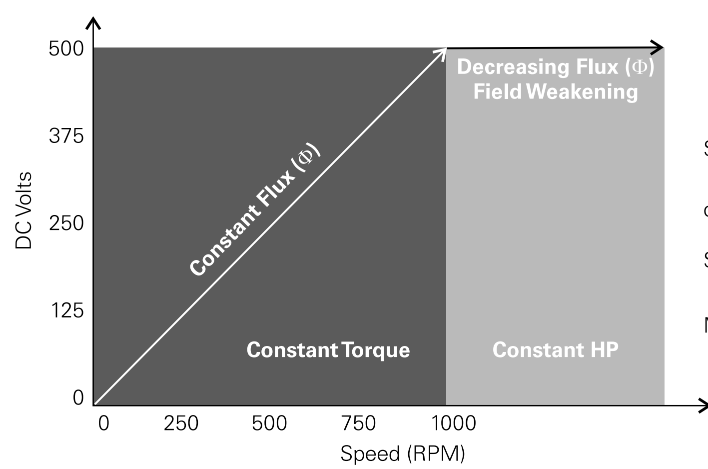
or

$$\text{Speed (n)} \approx \frac{CEMF}{\Phi}$$

$$M \approx I_a\Phi$$

Constant Horsepower

Some applications require the motor to be operated above base speed. Armature voltage (V_a), however, cannot be higher than rated nameplate voltage. Another method of increasing speed is to weaken the field (Φ). Weakening the field reduces the amount of torque (M) a motor can produce. Applications that operate with field weakening must require less torque at higher speeds.



$$\text{Speed (n)} = \frac{Va - (IaRa)}{Kt\Phi}$$

or

$$\text{Speed (n)} \approx \frac{CEMF}{\Phi}$$

$$M \approx I_a\Phi$$

Horsepower is said to be constant because speed (N) increases and torque (M) decreases in proportion.

$$\text{Horsepower (HP)} = \frac{\text{Torque (M) x Speed (N)}}{5250}$$

$$\text{HP (Remains Constant)} = \frac{\text{M (Decreases) x N (Increases)}}{5250}$$

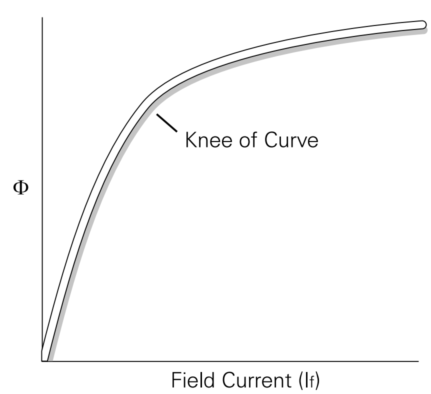
Field Saturation

It can be seen from the speed (n) and torque (M) formulas that field flux (Φ) density has a direct effect on motor speed and available torque. An increase in field flux (Φ), for example, will cause a decrease in speed (n) and an increase in available motor torque (M).

$$\text{Speed (n)} \approx \frac{\text{CEMF}}{\Phi} \qquad M \approx I_a\Phi$$

The relationship between field current (I_f) and flux (Φ) is not as directly proportional as it may appear. As flux density increases the field's ability to hold additional flux decreases. It becomes increasingly difficult to increase flux density. This is known as saturation.

A saturation curve, such as the example shown below, can be plotted for a DC motor. Flux (Φ) will rise somewhat proportionally with an increase of field current (I_f) until the knee of the curve. Further increases of field current (I_f) will result in a less proportional flux (Φ) increase. Once the field is saturated no additional flux (Φ) will be developed.



Review 3

1. One way to increase motor speed is to ___________ armature voltage.

   a. increase
   b. decrease

2. CEMF is zero when the armature is ___________ .

   a. turning at low speed
   b. turning at max speed
   c. not turning
   d. accelerating

3. A ___________ - connected motor is typically used with DC drives.

4. A DC motor, operating from zero to base speed, can be said to be operating in the constant ___________ range.

   a. horsepower
   b. torque

5. No additional ___________ can be developed once the field becomes saturated.

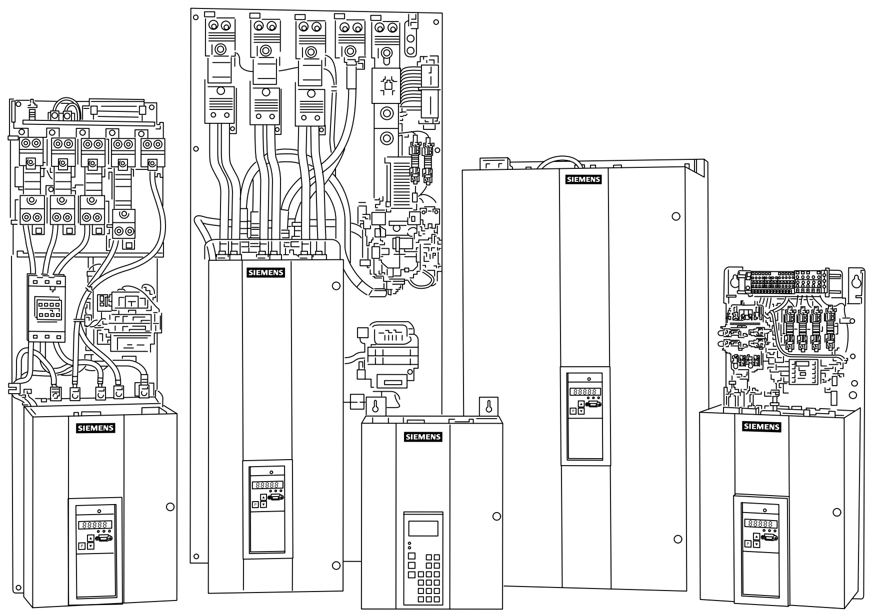
Basic DC Drives

The remainder of this course will focus on applying the SIMOREG DC MASTER® 6RA70, to DC motors and associated applications. The SIMOREG DC MASTER 6RA70 drives are designed to provide precise DC motor speed control over a wide range of machine parameters and load conditions. Selection and ordering information, as well as engineering information can be found in the SIMOREG 6RA70 DC MASTER catalog, available from you local Siemens sales representative.

SIMOREG drives are designed for connection to a three-phase AC supply. They, in turn, supply the armature and field of variable-speed DC motors. SIMOREG drives can be selected for connection to 230, 400, 460, 575, 690, and 830 VAC, making them suitable for global use.

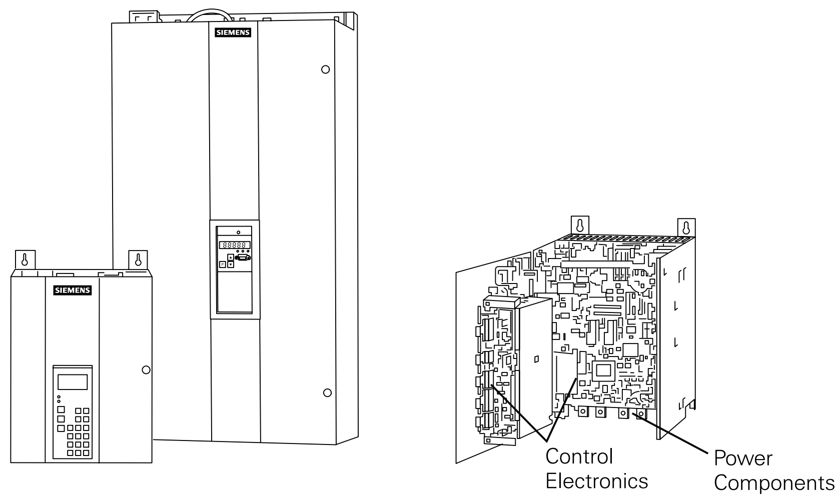
Siemens SIMOREG DC MASTER 6RA70 drives are available up to 1000 HP at 500 VDC in standard model drives. In addition, drives can be paralleled, extending the range up to 6000 HP.

Siemens SIMOREG drives have a wide range of microprocessor-controlled internal parameters to control DC motor operation. It is beyond the scope of this course to cover all of the parameters in detail, however; many concepts common to most applications and drives will be covered later in the course.



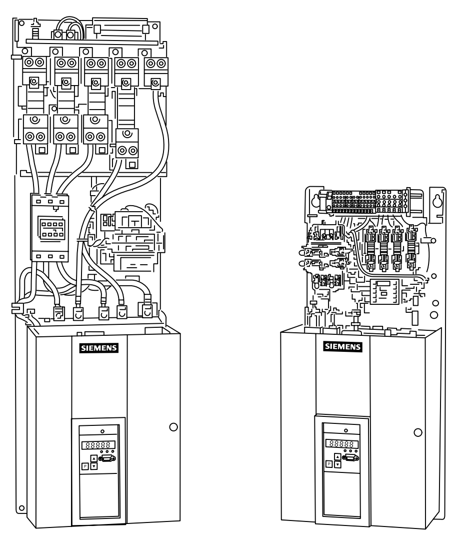
Power Modules

The SIMOREG 6RA70 is available in a power module and base drive panels. The power module contains the control electronics and power components necessary to control drive operation and the associated DC motor.



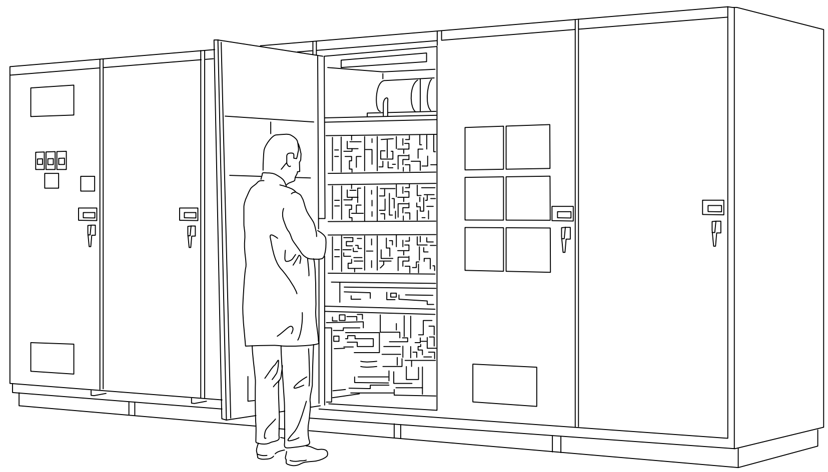
Base Drive Panels

The base drive panel consists of the power module mounted on a base panel with line fuses, control transformer, and contactor. This design allows for easy mounting and connection of power cables.



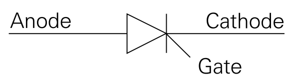
High Horsepower Designs

High horsepower designs are also available with ratings up to 14,000 amps. These drives have input ratings up to 700 VAC and can operate motors with armature ratings up to 750 VDC. For additional information on high horsepower design SIMOREG 6RA70 DC MASTER drives, contact your Siemens sales representative.



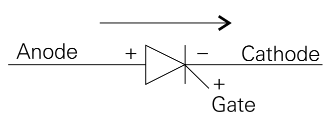
Thyristor

A primary function of a DC drive, such as the SIMOREG 6RA70 DC MASTER, is to convert AC voltage into a variable DC voltage. It is necessary to vary to DC voltage in order to control the speed of a DC motor. A thyristor is one type of device commonly used to convert AC to DC. A thyristor consists of an anode, cathode, and a gate.



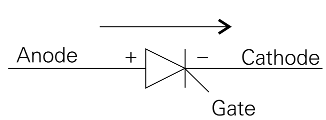
Gate Current

A thyristor acts as a switch. Initially, a thyristor will conduct (switch on) when the anode is positive with respect to the cathode and a positive gate current is present. The amount of gate current required to switch on a thyristor varies. Smaller devices require only a few milliamps; however, larger devices such as required in the motor circuit of a DC drive may require several hundred milliamps.

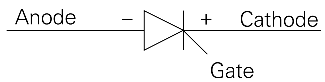


Holding Current

Holding current refers to the amount of current flowing from anode to cathode to keep the thyristor turned on. The gate current may be removed once the thyristor has switched on. The thyristor will continue to conduct as long as the anode remains sufficiently positive with respect to the cathode to allow sufficient holding current to flow. Like gate current, the amount of holding current varies from device to device. Smaller devices may require only a few milliamps and larger devices may require a few hundred milliamps.

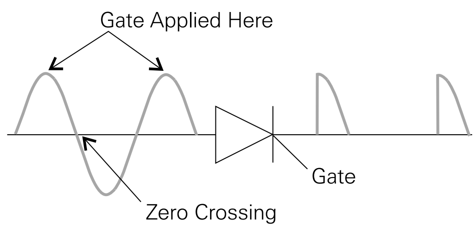


The thyristor will switch off when the anode is no longer positive with respect to the cathode.

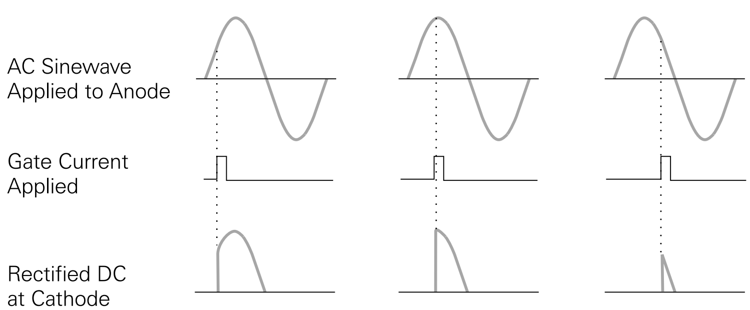


AC to DC Conversion

The thyristor provides a convenient method of converting AC voltage to a variable DC voltage for use in controlling the speed of a DC motor. In this example the gate is momentarily applied when AC input voltage is at the top of the sinewave. The thyristor will conduct until the input's sinewave crosses zero. At this point the anode is no longer positive with respect to the cathode and the thyristor shuts off. The result is a half-wave rectified DC.

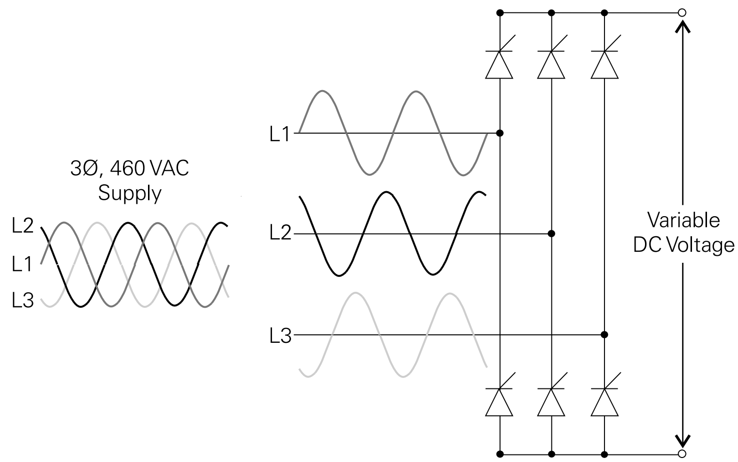


The amount of rectified DC voltage can be controlled by timing the input to the gate. Applying current on the gate at the beginning of the sinewave results in a higher average voltage applied to the motor. Applying current on the gate later in the sinewave results in a lower average voltage applied to the motor.



DC Drive Converter

The output of one thyristor is not smooth enough to control the voltage of industrial motors. Six thyristors are connected together to make a 3Ø bridge rectifier.



Gating Angle

As we have learned, the gating angle of a thyristor in relationship to the AC supply voltage, determines how much rectified DC voltage is available. However, the negative and positive value of the AC sine wave must be considered when working with a fully-controlled 3Ø rectifier.

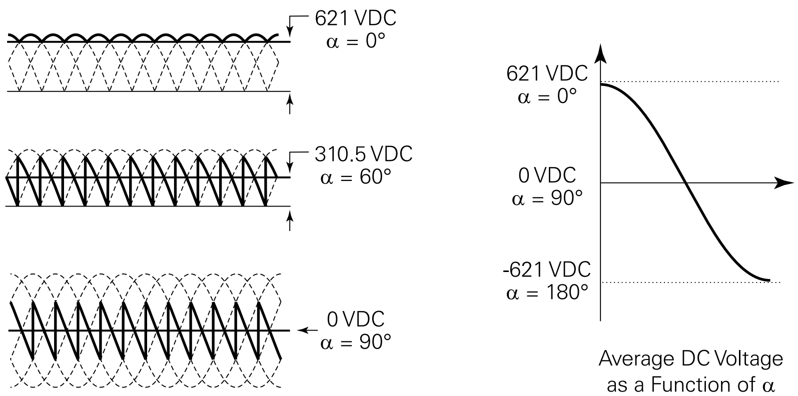
A simple formula can be used to calculate the amount of rectified DC voltage in a 3Ø bridge. Converted DC voltage (V_{DC}) is equal to 1.35 times the RMS value of input voltage (V_{RMS}) times the cosine of the phase angle ($\cos\alpha$).

$$V_{DC} = 1.35 \times V_{RMS} \times \cos\alpha$$

The value of DC voltage that can be obtained from a 460 VAC input is -621 VDC to +621 VDC. The following table shows sample values of rectified DC voltage available from 0° to 180°. It is important to note that voltage applied to the armature should not exceed the rated value of the DC motor.

Volts RMS	α	Cosine	Formula	VDC
460 VAC	0	1.00	VDC = 460 x 1.35 x 1	621
460 VAC	30	0.87	VDC = 460 x 1.35 x 0.87	538
460 VAC	60	0.50	VDC = 460 x 1.35 x 0.50	310.5
460 VAC	90	0.00	VDC = 460 x 1.35 x 0	0
460 VAC	120	-0.50	VDC = 460 x 1.35 x (-0.50)	-310.5
460 VAC	150	-0.87	VDC = 460 x 1.35 x (-0.87)	-538
460 VAC	180	-1.00	VDC = 460 x 1.35 x (- 1)	-621

The following illustration approximates the output waveform of a fully controlled thyristor bridge rectifier for 0°, 60°, and 90°. The DC value is indicated by the heavy horizontal line. It is important to note that when thyristors are gated at 90° the DC voltage is equal to zero. This is because thyristors conduct for the same amount of time in the positive and negative bridge. The net result is 0 VDC. DC voltage will increase in the negative direction as the gating angle (α) is increased from 90° to a maximum of 180°.



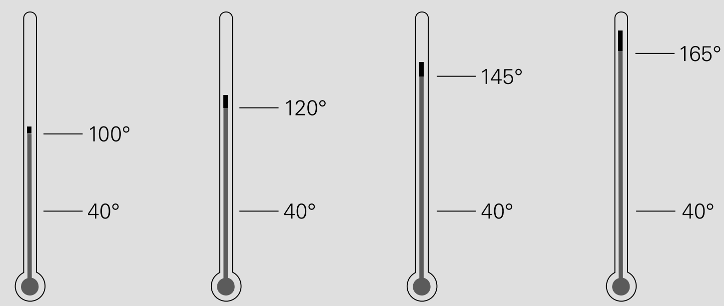
Review 4

1. An increase of torque causes a corresponding ___________ in horsepower

   a. increase
   b. decrease

2. Typically, DC motor armature voltage is either rated for ___________ VDC or ___________ VDC.

3. Identify the following insulation classes.



a. _____ b. _____ c. _____ d. _____

4. The SIMOREG 6RA70 DC MASTER ___________ drive consists of the power module mounted on a panel with line fuses, control transformer, and a contactor.

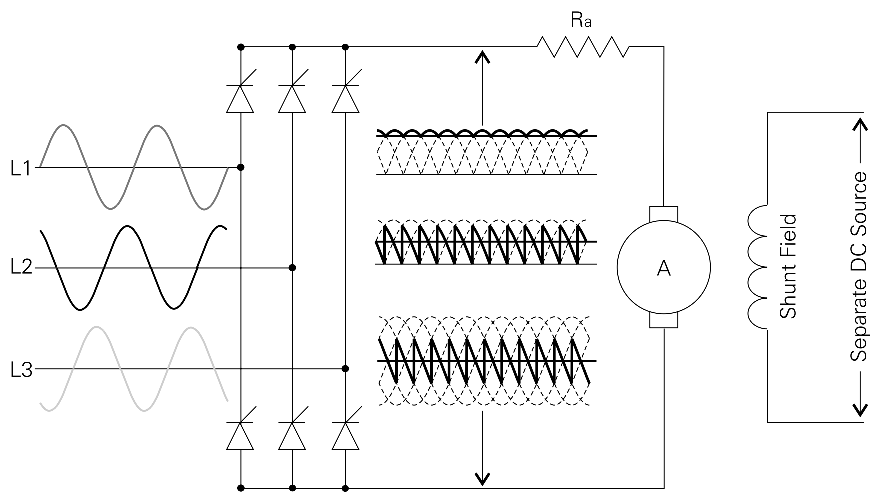
5. A thyristor is one type of device commonly used to convert ___________ .

   a. DC to AC
   b. AC to DC

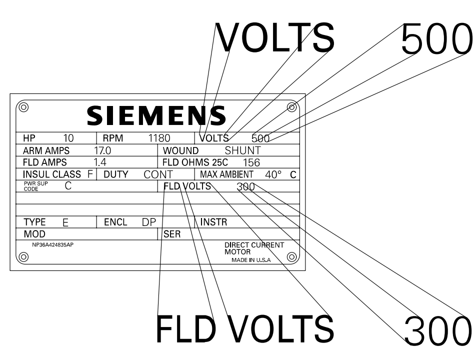
6. The approximate converted DC voltage of a six-pulse converter when the thyristors are gated at 30° is ___________ VDC.

Controlling a DC Motor

A thyristor bridge is a technique commonly used to control the speed of a DC motor by varying the DC voltage. Examples of how a DC rectifier bridge operates are given on the next few pages. Voltage values given in these examples are used for explanation only. The actual values for a given load, speed, and motor vary.

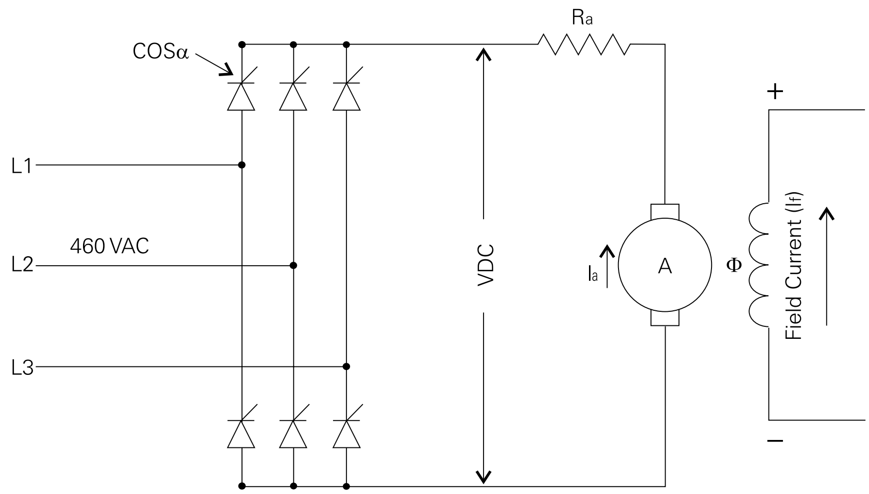


It is important to note that the voltage applied to a DC motor be no greater than the rated nameplate. Armature windings are commonly wound for 500 VDC. The control logic in the drive must be adjusted to limit available DC voltage to 0 - 500 VDC. Likewise, the shunt field must be limited to the motor's nameplate value.



Basic Operation

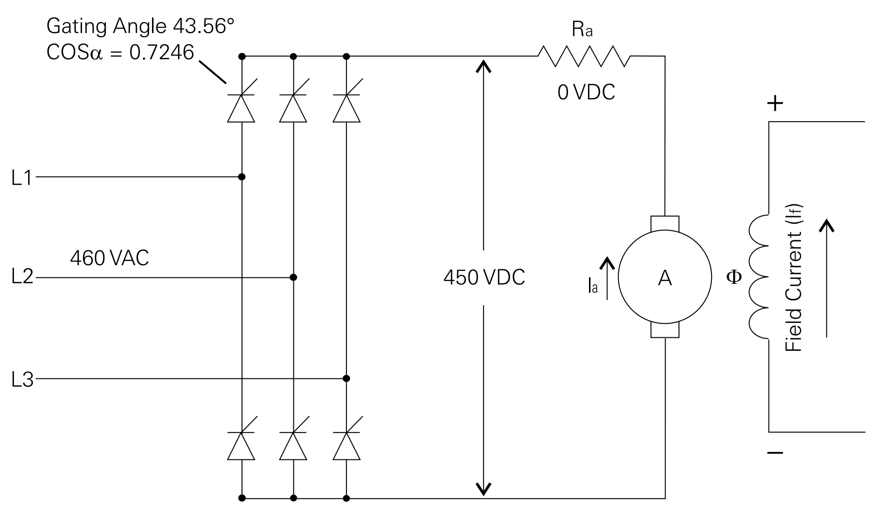
A DC drive supplies voltage to the motor to operate at a desired speed. The motor draws current from this power source in proportion to the torque (load) applied to the motor shaft.



100% Speed, 0% Load

In this example an unloaded motor connected to a DC drive is being operated at 100% speed. The amount of armature current (I_a) and unloaded motor needs to operate is negligible. For the purpose of explanation a value of 0 amps is used.

The DC drive will supply only the voltage required to operate the motor at 100% speed. We have already learned the amount of voltage is controlled by the gating angle (COSα) of the thyristors. In this example 450 VDC is sufficient. The motor accelerates until CEMF reaches a value of $V_a - I_aR_a$. Remember that $V_a = I_aR_a + \text{CEMF}$. In this example I_aR_a is 0, therefore CEMF will be approximately 450 VDC.



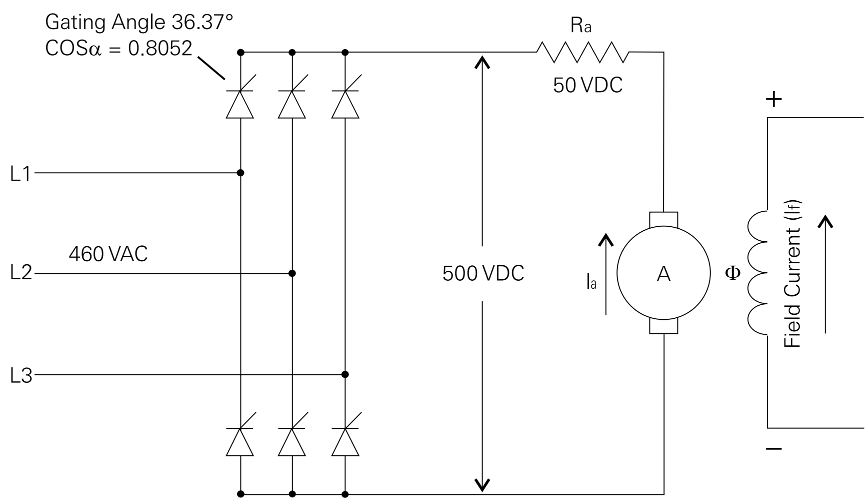
$V_a = 1.35 \times \text{VRMS} \times \text{COS}\alpha$
$V_a = 1.35 \times 460\text{ VAC} \times 0.7246$
$V_a = 450\text{ VDC}$

$V_a = I_aR_a + \text{CEMF}$
$V_a = 0 + 450$
$V_a = 450\text{ VDC}$

100% Speed, 100% Load

A fully loaded motor requires 100% of rated armature current at 100% speed. Current flowing through the armature circuit will cause a voltage drop across the armature resistance (R_a). Full voltage (500 VDC) must be applied to a fully loaded motor to operate at 100% speed. To accomplish this, thyristors are gated earlier in the sine wave (36.37°).

The DC drive will supply the voltage required to operate the motor at 100% speed. The motor accelerates until CEMF reaches a value of V_a - I_aR_a. Remember that $V_a = I_aR_a + CEMF$. In this example armature current (I_a) is 100% and R_a will drop some amount of voltage. If we assume that current and resistance is such that R_a drops 50 VDC, CEMF will be 450 VDC.



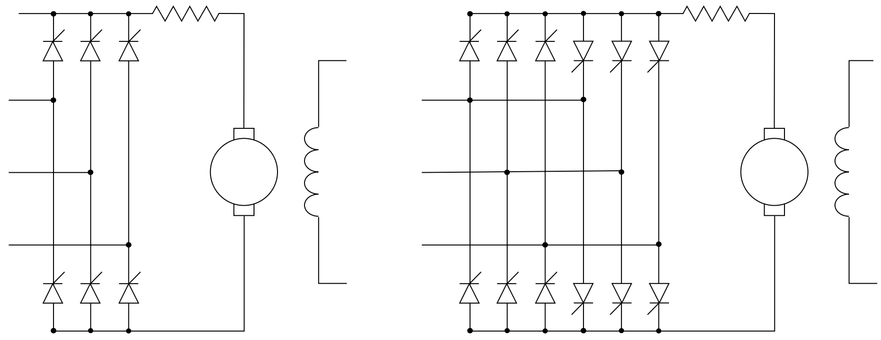
$V_a = 1.35 \times VRMS \times COS\alpha$
$V_a = 1.35 \times 460\,VAC \times 0.8052$
$V_a = 500\,VDC$

$V_a = I_aR_a + CEMF$
$V_a = 50 + 450$
$V_a = 500\,VDC$

1 Quad, 4 Quad

Up to this point we have only looked at a drive in single-quadrant operation. A single-quadrant DC drive will have six thyristors.

In the speed-torque chart there are four quadrants of operation according to direction of rotation and direction of torque. A four-quadrant DC drive will have twelve thyristors.

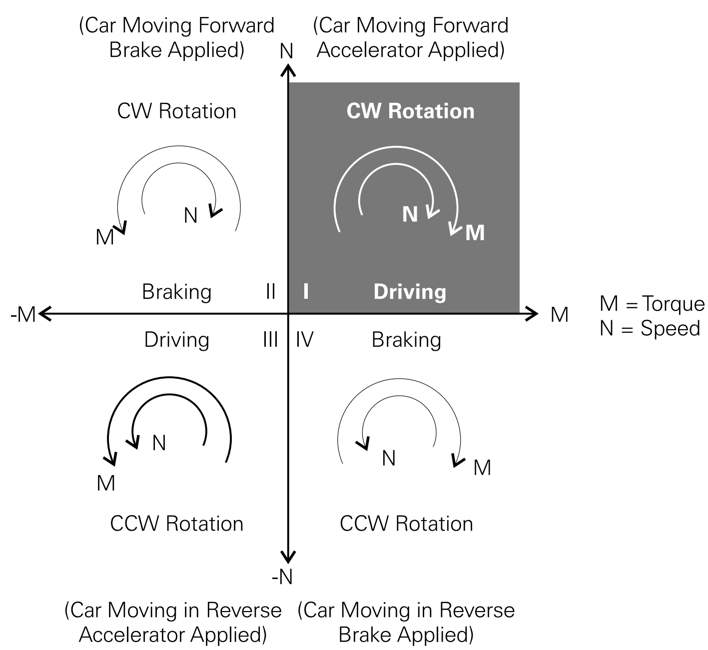


1 Quadrant - 6 SCRs

4 Quadrant - 12 SCRs

Single-Quadrant Operation

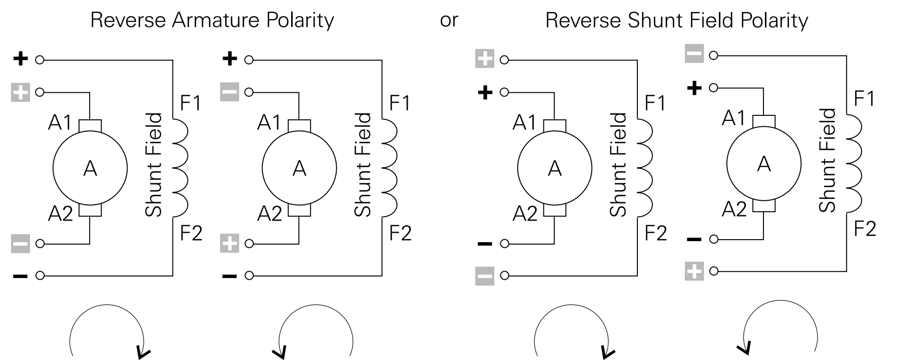
Single-quadrant drives only operate in quadrant I. Motor torque (M) is developed in the forward or clockwise (CW) direction to drive the motor at the desired speed (N). This is similar to driving a car forward on a flat surface from standstill to a desired speed. It takes more forward or motoring torque to accelerate the car from zero to the desired speed. Once the car is at desired speed your foot can be let off the accelerator a little. When the car comes to an incline a little more gas, controlled by the accelerator, maintains speed. To slow or stop a motor in single-quadrant operation the drive lets the motor coast.



Changing Direction of a DC Motor

There are two ways to change the direction a DC motor rotates.

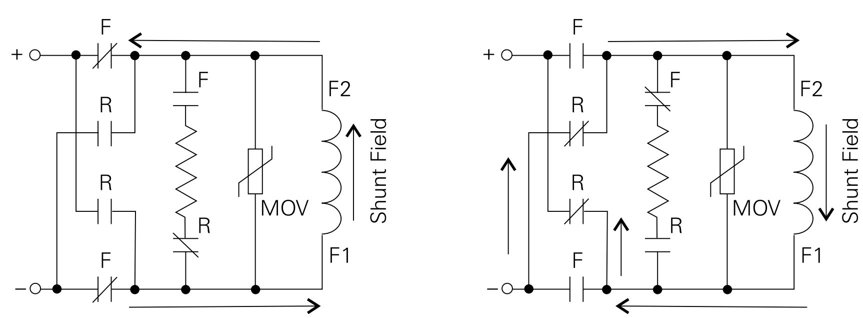
1. Reverse Armature Polarity
2. Reverse Field Polarity



Reversing in Single-Quadrant Operation

Field contactor reverse kits can be used to provide bidirectional rotation from a single-quadrant drive. To turn the motor in the forward direction the "F" contacts are closed, applying DC voltage in one polarity across the shunt field. Simply reversing the polarity of the field, by opening the "F" contacts and closing the "R" contacts, will reverse direction of a DC motor.

It is important to note that field reversal will only work when a quick reversal is not required. The field circuit is inductive and must be brought to 0 current before opening the contacts.



Forward Direction (Quadrant I)

Reverse Direction (Quadrant III)

Stopping a Motor

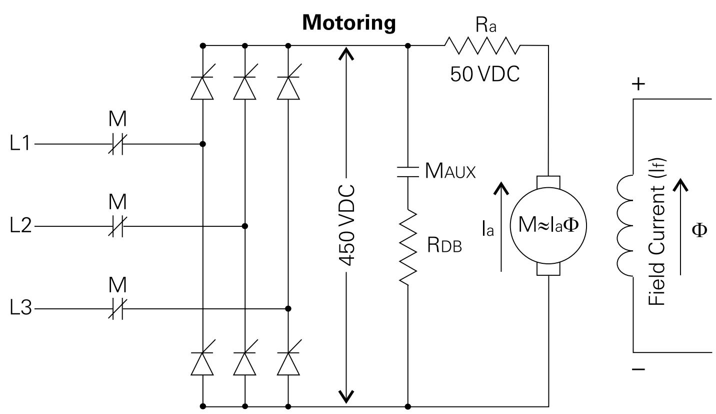
Stopping a motor in single-quadrant operation can be done by simply removing voltage to the motor and allowing the motor to coast to a stop. Alternatively, voltage can be reduced gradually until the motor is at a stop. The amount of time required to stop a motor depends on the inertia of the motor and connected load. The more inertia the longer the time.

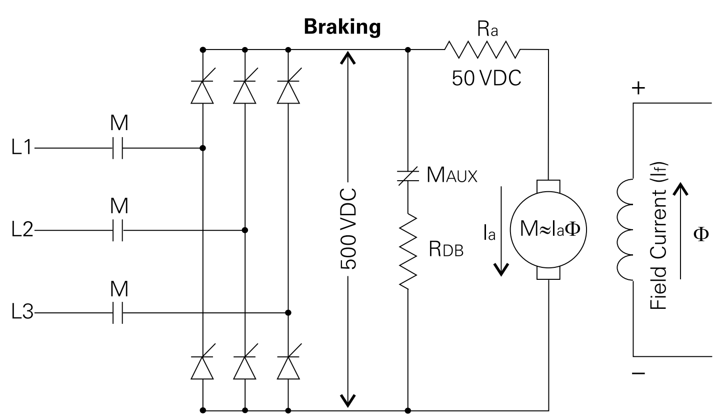
Dynamic Braking

Dynamic braking is often used on single quadrant drives as a means of stopping a motor quickly. Dynamic braking is not recommended for continuous or repetitive operation. Dynamic braking kits for use with Siemens SIMOREG® drives are typically designed to stop a load operating at base speed a maximum of three consecutive times. After three consecutive stops a waiting period of 15 minutes is required.

Dynamic braking develops stopping torque by using a contact (M_{AUX}) to connect a resistor (R_{db}) across the armature terminals after the drive controller turns off power to the motor. The field remains energized to supply stopping torque. This is because motor torque (M) depends on armature current (I_a) and field flux (Φ).

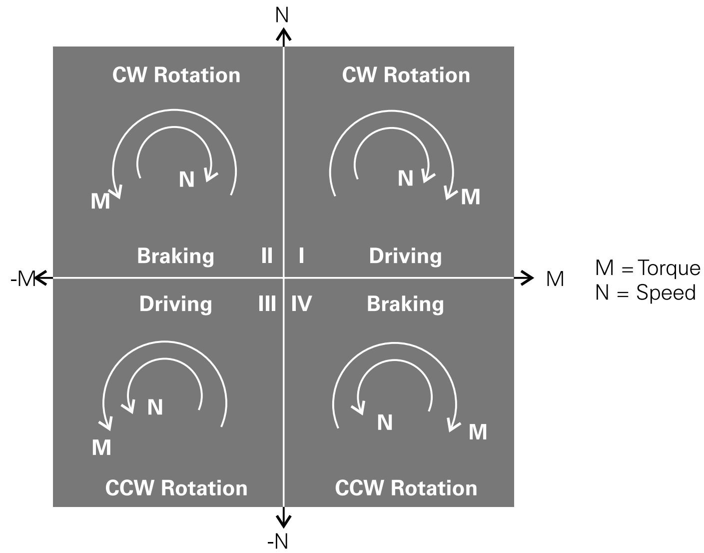
Armature current (I_a) reverses direction as the motor now acts like a generator. A reversal in armature current (I_a) results in a reversal of torque applied to the motor. Torque, now applied in the opposite direction, acts as a brake to the motor. Stored energy in the rotating motor is applied across the resistor and converted to heat. The resistor is sized to allow 150% current flow initially. Armature voltage decreases as the motor slows down, producing less current through the resistors. The motor is finally stopped due to frictional torque of the connected load.





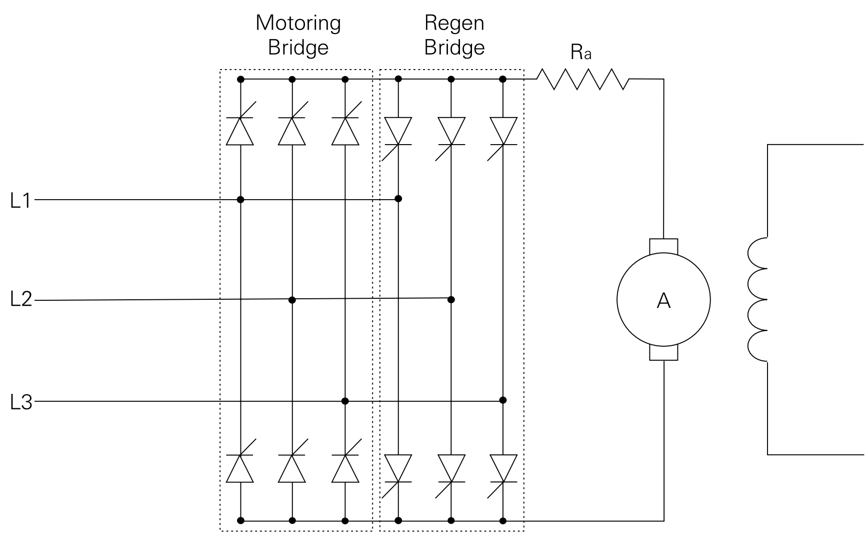
Four-Quadrant Operation

The dynamics of certain loads require four-quadrant operation. If motor voltage is suddenly reduced, negative torque is developed in the motor due to the inertia of the connected load. The motor acts like a generator by converting mechanical power from the shaft into electrical power which is returned to the drive. This is similar to driving a car downhill. The car's engine will act as a brake. Braking occurs in quadrants II and IV.



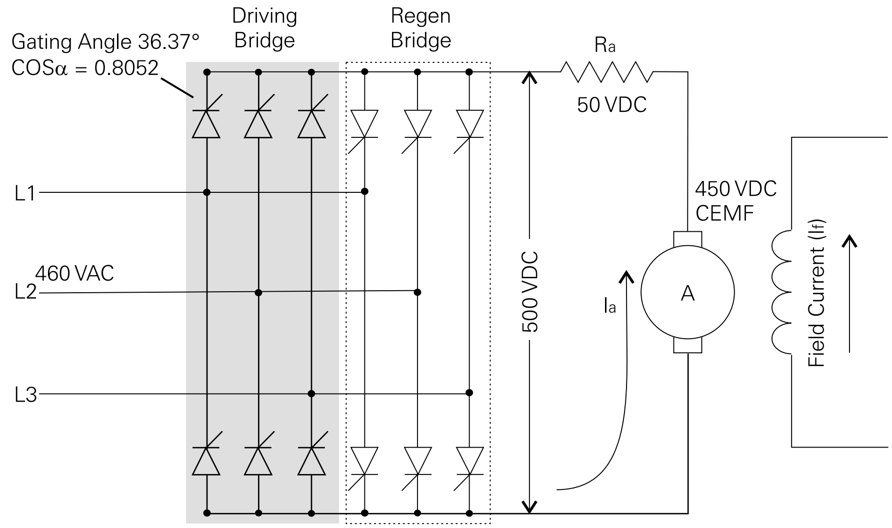
Regen

In order for a drive to operate in all four quadrants a means must exist to deal with the electrical energy returned by the motor. Electrical energy returned by the motor tends to drive the DC voltage up, resulting in excess voltage that can cause damage. One method of getting four-quadrant operation from a DC drive is to add a second bridge connected in reverse of the main bridge. The main bridge drives the motor. The second bridge returns excess energy from the motor to the AC line. This process is commonly referred to as regen. This configuration is also referred to as a 4-Quad design.



Motoring

The motor receives power from the incoming line. In this example the motor is operating at full speed (500 VDC).

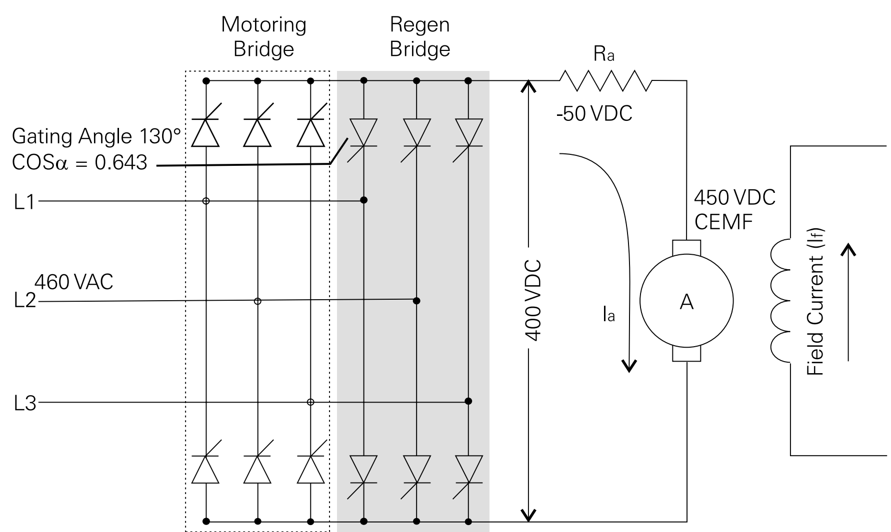


$V_a = 1.35 \times VRMS \times COS\alpha$
$V_a = 1.35 \times 460\ VAC \times 0.8052$
$V_a = 500\ VDC$

$V_a = I_aR_a + CEMF$
$V_a = 50 + 450$
$V_a = 500\ VDC$

100% Speed, -100% Load

When the motor is required to stop quickly, the motoring bridge shuts off and the regen bridge turns on. Due to the initial inertia of the connected load the motor acts like a generator, converting mechanical power at the shaft into electrical power which is returned to the AC line. The I_aR_a voltage drop (-50 VDC) is of opposite polarity then when the drive was supplying motoring power. The control logic is gating thyristors in the regen bridge at an angle of 130° and the resultant DC voltage on the bridge is 400 VDC, in the opposite polarity. Because the regen bridge is of opposite polarity, the voltage applied to the motor acts like an electrical brake for the connected load.



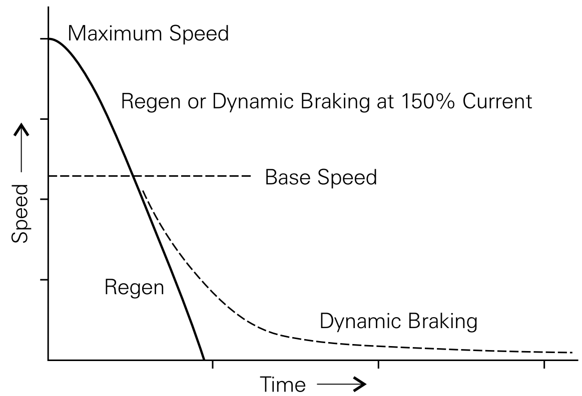
$V_a = 1.35 \times VRMS \times COS\alpha$
$V_a = 1.35 \times 460\ VAC \times 0.643$
$V_a = 400\ VDC$

$V_a = I_aR_a + CEMF$
$V_a = -50 + 450$
$V_a = 400\ VDC$

Regen vs. Dynamic Braking

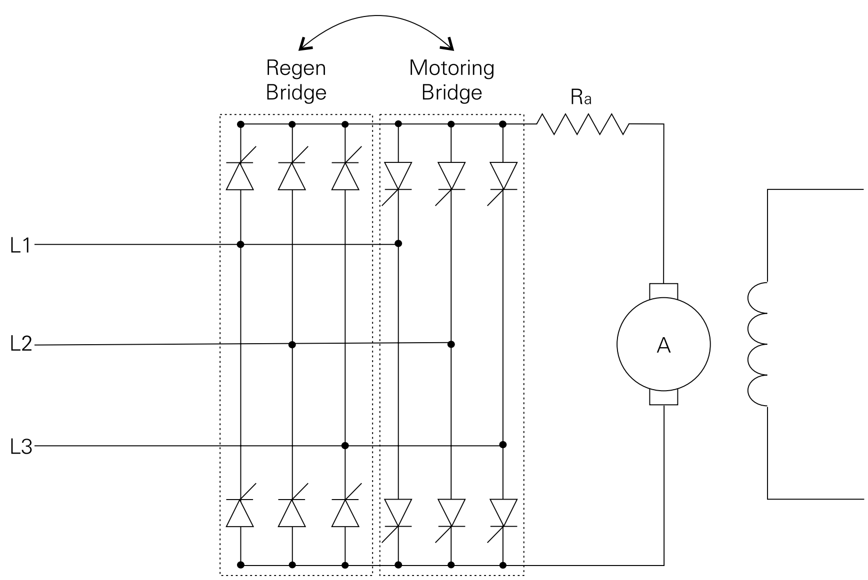
Regen and dynamic braking provide the same amount of braking power to slow a motor from maximum speed in field weakening to base speed. This is because field strength increases until the motor reaches base speed. However, from base speed to stop, regen is capable of slowing a motor at a faster rate. In addition, regen can develop torque at zero speed to bring the motor to a complete stop.

Another advantage of regen is that regen braking is not limited in duty cycle and cool-down periods. Applications that require frequent braking or have overhauling loads should consider four quadrant operation with regen braking.



Reversing

A four-quadrant drive can easily reverse the direction of rotation of a DC motor simply by applying armature voltage in the opposite polarity. This is accomplished by using what was the regen bridge to motor. The bridge that was used to drive the motor in the forward direction becomes the regen bridge.



Review 5

1. When torque is developed in the forward direction and the armature is turning in the forward direction, the motor is operating in quadrant ___________ .

2. When the armature is turning in the forward direction but torque is developed in the reverse direction, the motor is operating in quadrant ___________ .

3. The direction of rotation of a DC motor, operated from a 6-pulse converter, can be reversed by reversing the polarity of the DC voltage applied to the ___________ field.

4. ___________ ___________ is a method used to stop a motor quickly by applying a resistor to the armature.

5. Which of the following is an advantage of a 4-quad converter?

   a. Instead of being dissipated in heat, excess energy is returned to the supply line.
   b. From base speed to zero speed a 4-quad converter will stop a motor faster than a 1-quad converter.
   c. A 4-quad converter can reverse motor direction by simply applying voltage in the opposite polarity across the armature.
   d. all of the above.