

# Variable Frequency Drives

## Introduction

### What Is a Variable Frequency Drive?

Adding a variable frequency drive (VFD) to a motor-driven system can offer potential energy savings in a system in which the loads vary with time. VFDs belong to a group of equipment called adjustable speed drives or variable speed drives. (Variable speed drives can be electrical or mechanical, whereas VFDs are electrical.) The operating speed of a motor connected to a VFD is varied by changing the frequency of the motor supply voltage. This allows continuous process speed control.

Motor-driven systems are often designed to handle peak loads that have a safety factor. This often leads to energy inefficiency in systems that operate for extended periods at reduced load. The ability to adjust motor speed enables closer matching of motor output to load and often results in energy savings.

### How Does a VFD Work?

Induction motors, the workhorses of industry, rotate at a fixed speed that is determined by the frequency of the supply voltage. Alternating current applied to the stator windings produces a magnetic field that rotates at synchronous speed. This speed may be calculated by dividing line frequency by the number of magnetic pole pairs in the motor winding. A four-pole motor, for example, has two pole pairs, and therefore the magnetic field will rotate  $60 \text{ Hz} / 2 = 30$  revolutions per second, or 1800 rpm. The rotor of an induction motor will attempt to follow this rotating magnetic field, and, under load, the rotor speed "slips" slightly behind the rotating field. This small slip speed generates an induced current, and the resulting magnetic field in the rotor produces torque.

Since an induction motor rotates near synchronous speed, the most effective and energy-efficient way to change the motor speed is to change the frequency of the applied voltage. VFDs convert the fixed-frequency supply voltage to a continuously variable frequency, thereby allowing adjustable motor speed.

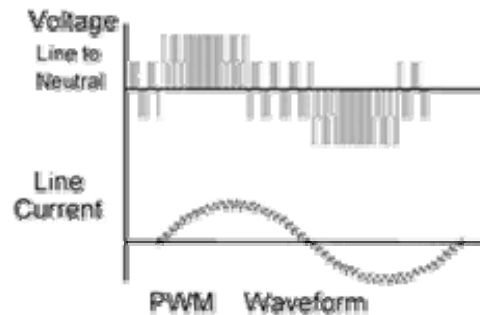
A VFD converts 60 Hz power, for example, to a new frequency in two stages: the rectifier stage and the inverter stage. The conversion process incorporates three functions:

- **Rectifier stage:** A full-wave, solid-state rectifier converts three-phase 60 Hz power from a standard 208, 460, 575 or higher utility supply to either fixed or adjustable DC voltage. The system may include transformers if higher supply voltages are used.
- **Inverter stage:** Electronic switches - power transistors or thyristors - switch the rectified DC on and off, and produce a current or voltage waveform at the desired new frequency. The amount of distortion depends on the design of the inverter and filter.
- **Control system:** An electronic circuit receives feedback information from the driven motor and adjusts the output voltage or frequency to the selected values. Usually the output voltage is regulated to produce a constant ratio of voltage to frequency (V/Hz). Controllers may incorporate many complex control functions.

Converting DC to variable frequency AC is accomplished using an inverter. Most currently available inverters use pulse width modulation (PWM) because the output current waveform closely approximates a sine wave. Power semiconductors switch DC voltage at high speed, producing a series of short-duration pulses of constant amplitude. Output voltage is varied by changing the width and polarity of the switched pulses. Output frequency is adjusted by changing the switching cycle time. The resulting current in an inductive motor simulates a sine wave of the desired output frequency (see Figure below). The high-speed switching of a PWM inverter results in less waveform distortion and, therefore, lower harmonic losses.

The availability of low-cost, high-speed switching power transistors has made PWM the dominant inverter type.

*Figure. Inverter's Pulse Width Modulation Output*



## Applications

Variable speed drives are used for two main reasons:

- to improve the efficiency of motor-driven equipment by matching speed to changing load requirements; or
- to allow accurate and continuous process control over a wide range of speeds.

Motor-driven centrifugal pumps, fans and blowers offer the most dramatic energy-saving opportunities. Many of these operate for extended periods at reduced load with flow restricted or throttled. In these centrifugal machines, energy consumption is proportional to the cube of the flow rate. Even small reductions in speed and flow can result in significant energy savings. In these applications, significant energy and cost savings can be achieved by reducing the operating speed when the process flow requirements are lower.

In some applications, such as conveyers, machine tools and other production-line equipment, the benefits of accurate speed control are the primary consideration. VFDs can increase productivity, improve product quality and process control, and reduce maintenance and downtime. Decreasing cost and increasing reliability of power semiconductor electronics are reasons that VFDs are increasingly selected over DC motors or other adjustable speed drives for process speed control applications.

Motors and VFDs must be compatible. Consult the manufacturers of both the VFD and the motor to make sure that they will work together effectively. VFDs are frequently used with inverter-duty National Electrical Manufacturers Association (NEMA) design B squirrel cage induction motors. (Design B motors have both locked rotor torque and locked rotor current that are normal.) De-rating may be required for other types of motors. VFDs are not usually recommended for NEMA design D motors because of the potential for high harmonic current losses. (Design D motors are those that have high locked rotor torque and high slip.)

## Additional Benefits of VFDs

In addition to energy savings and better process control, VFDs can provide other benefits:

- A VFD may be used for control of process temperature, pressure or flow without the use of a separate controller. Suitable sensors and electronics are used to interface the driven equipment with the VFD.
- Maintenance costs can be lower, since lower operating speeds result in longer life for bearings and motors.
- Eliminating the throttling valves and dampers also does away with maintaining these devices and all associated controls.

- A soft starter for the motor is no longer required.
- Controlled ramp-up speed in a liquid system can eliminate water hammer problems.
- The ability of a VFD to limit torque to a user-selected level can protect driven equipment that cannot tolerate excessive torque.

### How Much Will I Save?

The potential energy savings from installing a VFD is illustrated in the following example. Here, a 40 hp motor is used in an HVAC system with a flow-control damper. The system operates 365 days a year with the load/time profile shown in Table below. The damper is removed and a VFD installed. The estimated annual energy savings realized from the use a VFD is shown in Table below.

Table : Potential Energy Savings From Replacing a Damper With a VFD

Airflow Volume (percent of maximum)	Daily Operating Time (hours)	Energy Consumed Using a Damper(kWh/year)	Energy Consumed Using a VFD(kWh/year)	Difference in Energy Consumption (kWh/year)
50%	2	18 500	4 800	13 700
60%	3	29 300	9 800	19 500
70%	6	61 700	26 800	34 900
80%	6	63 300	35 900	27 400
90%	4	44 200	32 600	11 600
100%	3	34 200	35 200	-1 000
<b>Total</b>	<b>24</b>	<b>251 200</b>	<b>145 100</b>	<b>106 100</b>

The above example shows a possible electrical energy saving of 106 100 kWh per year, resulting from replacement of the existing damper-control system with a VFD. Savings would be less if the existing flow-control system used variable inlet vanes. At energy rates of \$0.085/kWh, annual savings are \$9,018.

At an estimated cost of \$4,200 for the VFD and \$750 for line and load reactors, the simple payback period is approximately seven months. When installation costs are added, the payback increases to one year.

### Purchasing Tips

#### Analyse the System as a Whole

Since the process of converting incoming power from one frequency to another will result in some losses, energy savings must always come from optimizing the performance of the complete system. The first step in determining the energy savings potential of a system is to thoroughly analyse the operation of the entire system. Detailed knowledge of the equipment operation and process requirements are required in order to ensure energy savings.

The most promising candidates for realizing energy savings are systems for centrifugal fans, blowers and pumps that have been designed to meet peak loads but actually operate at reduced load for extended periods. The following discussion pertains to centrifugal systems, but the same principles can be applied to other systems. Evaluating the energy-saving potential of a centrifugal system should include the following steps:

1. Develop a complete understanding of the process requirements and the equipment to which the centrifugal machine supplies fluid.
2. Obtain complete engineering specifications and performance curves for the centrifugal machine.

3. Obtain specifications for all components of the system, including dampers, valves, ducts or pipes, and heating or cooling coils.
4. Develop a load/time profile for the system. This step is critical for calculating accurate energy savings. For each component, list annual hours, all flow conditions and the input power to the centrifugal machine.
5. For each point in the above step, calculate the input power required by a VFD-driven motor and centrifugal machine delivering the same flow. Input shaft power can be determined from the centrifugal machine performance curves.
6. For each operating point, calculate the difference in power resulting from adding a VFD, and multiply each by the number of hours of annual operation. The difference is the energy savings resulting from installing a VFD.

The above process requires qualified staff with sufficient expertise with all components of the system, from VFD through to the process equipment.

Pump and fan affinity laws govern the relationship among speed, flow and input power. The laws state:

- Flow is proportional to speed
- Pressure increases with the square of the speed
- Power increases with the cube of the speed

When speed is reduced to 75 percent of design speed, flow decreases to 75 percent, outlet pressure decreases to 56 percent, and the input power requirement drops to 42 percent of full-speed values. For a similar flow reduction with a throttling valve or damper, the input power drops to only 80 percent. Note that pressure falls off more rapidly than flow.

### **VFD and Motor Selection**

Once you have verified the energy savings achievable using a VFD in your application, the following topics should be considered when selecting a motor and drive combination.

#### **Will the motor withstand the repetitive voltage stresses from use of a VFD?**

General-purpose induction motors are not designed for repetitive voltage overshoots that exceed line voltage plus 1000 volts. With a 230 VAC system, overshoots may not exceed this limit, but with a 575 VAC system, overshoots are likely. Repeated voltage stresses may lead to insulation breakdown and premature motor failure.

To use a VFD with an existing general-purpose motor, additional filtering and transient protection may be required. NEMA definite-purpose motors rated "Inverter Duty" are recommended for use with VFDs. These motors can withstand repetitive voltage spikes that are 3.1 times the rated RMS voltage.

#### **FAQs:**

*Should I use a motor that has a different pole count (i.e., six-pole instead of four-pole)?*

A VFD may be able to provide the required speeds with better performance using a motor that has a different number of poles. This can reduce the inventory of spares. The use of a bypass, however, may limit the number of choices of pole count. Be sure to discuss your options with the VFD manufacturer.

*Is motor cooling adequate for extended operation at very low speeds?*

Cooling often depends on motor speed, such as with totally enclosed fan-cooled (TEFC) motors. To meet constant torque loads, therefore, a motor should not be operated at less than 30 percent speed without additional cooling. Consider a larger motor, constant speed cooling or a totally enclosed non-ventilated (TENV) motor for these conditions. Motor thermal protection devices will prevent high-

temperature damage when motors operate continuously at very low speeds. With variable torque loads such as centrifugal machines, the rapidly decreasing power at low speed reduces cooling problems.

*Will harmonics affect nearby sensitive equipment?*

Additional line filtering is often required to reduce the propagation of harmonics and radio frequency interference (RFI) to other equipment. Short leads between the motor and the VFD help minimize RFI propagation. When leads are longer than 15 metres (50 feet), reactive filters are recommended. Motor leads should also be enclosed in a rigid conduit to reduce RFI.

*Is the VFD starting torque and acceleration/deceleration adequate for the load?*

The VFD breakaway torque is less than the motor locked rotor torque and is limited by the VFD maximum current rating. This current rating also limits the rate of load acceleration. Acceleration, deceleration and maximum current are user-programmable.

*Can a VFD be used for all types of loads?*

Yes. VFDs for use with constant torque loads should be rated for operation at 150 percent load for a period of one minute. Variable torque loads such as fans and pumps are easier to start, and therefore the VFD overload rating is lower. The drive should be matched to the load.

*Does the application have a high static pressure or head?*

Applications in which a minimum pressure must be maintained may not be suitable candidates for a VFD. For example, if high pressure is required even at low flow, it may not be possible to significantly reduce pump speed. When speed and flow reduce, so does pressure. For this application, other energy-saving strategies such as parallel pumps may offer more energy savings.

*What type of enclosure is required?*

Check the ratings of both the drive and its enclosure to make sure that they are suitable for the climate to which they will be exposed (i.e., outdoor weather protection).

*Is speed control accuracy important for my application?*

Most VFDs incorporate a user-programmable, constant volts-to-frequency ratio over the operating frequency range of the drive. For more accurate speed control, a flux vector control strategy with either direct or indirect measurement of rotor flux may be required.

*Is direction of rotation affected?*

The phase sequence of the supply connection to the VFD does not affect the rotation direction of the drive. Changing the phase sequence between the drive and the motor will change the direction of rotation of the motor. Be sure to verify rotation before connecting the drive to the equipment. Some equipment may be damaged if rotation is reversed. If a bypass contactor is used with a VFD, be sure that the rotation direction is correct during bypass operation.

*Does the application require dynamic braking?*

Load braking is usually accomplished by switching in a power load resistor across the DC bus to dump excess energy. This is usually an optional feature that is available only with some drives.

*How many motors can be operated on a drive?*

More than one motor on a drive is common. All receive the same frequency, so they change speed in unison. Each motor must have its own overload protection.

*Do I require remote monitoring or flexible control and set-up software?*

You may need drive monitoring and set-up software with RS-485 multi-drop communication. RS-485 allows monitoring and control of several drives from a remote location.

*Do I need bypass switching?*

Bypass switches are sometimes used so that a motor can operate when connected directly to the utility power supply. This enables operation of the motor when the drive is out of service.

### Exactly what is an AC drive?

The word "drive" is used loosely in the industry. It seems that people involved primarily in the world of gear boxes and pulleys refer to any collection of mechanical and electro-mechanical components, which when connected together will move a load, as a "drive". When speaking to these people, an AC drive may be considered by them as the variable frequency inverter and motor combination. It may even include the motor's pulley - I am not sure.

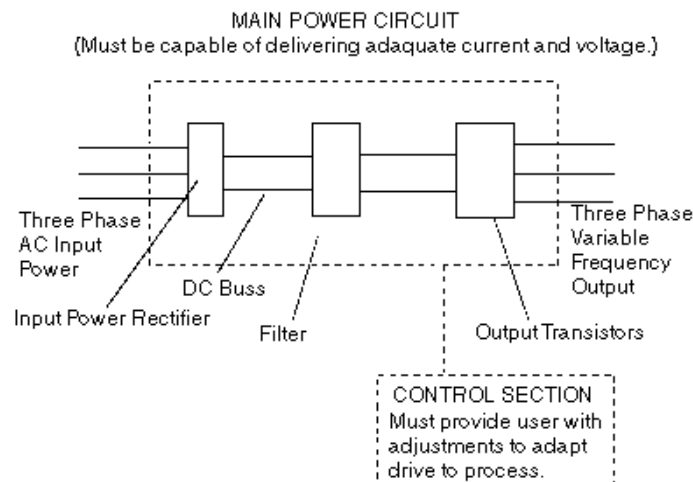
People in the electrical field and electrical suppliers usually refer to a variable frequency inverter unit alone, or an SCR power module alone (when discussing DC drives) as the "drive" and the motor as the "motor".

Manufacturers of variable frequency drives (VFD) used to refer to the drive as just that, a "variable frequency drive". More manufacturers are referring to their drive as an "adjustable speed AC drive". To make matters worse when a motor is included in the package it may be referred to as an "adjustable speed AC drive system".

A variable frequency drive is an adjustable speed drive. Adjustable speed drives include all types; mechanical and electrical. Now is it clear? Don't worry about it. It's not clear to anyone. As you read on, when I refer to the "drive" I am referring to the variable frequency inverter alone.

### A little about AC drives

The main power components of an AC drive, have to be able to supply the required level of current and voltage in a form the motor can use. The controls have to be able to provide the user with necessary adjustments such as minimum and maximum speed settings, so that the drive can be adapted to the user's process. Spare parts have to be available and the repair manual has to be readable. It's nice if the drive can shut itself down when detecting either an internal or an external problem. It's also nice if the drive components are all packaged in a single enclosure to aid in installation but that's about it.



The paradox facing drive manufacturers today is that as they make their drives easier to use, the amount of training with which they must provide their users increases. This is because as drives become easier to use they are purchased more and more by people of less and less technical capability. As less technical people get involved in drive purchases the number of misapplications goes way up. I call this phenomenon the "dumb trap". (When manufactures discover this phenomenon they simultaneously discover how dumb they've been. Some have not yet discovered it.)

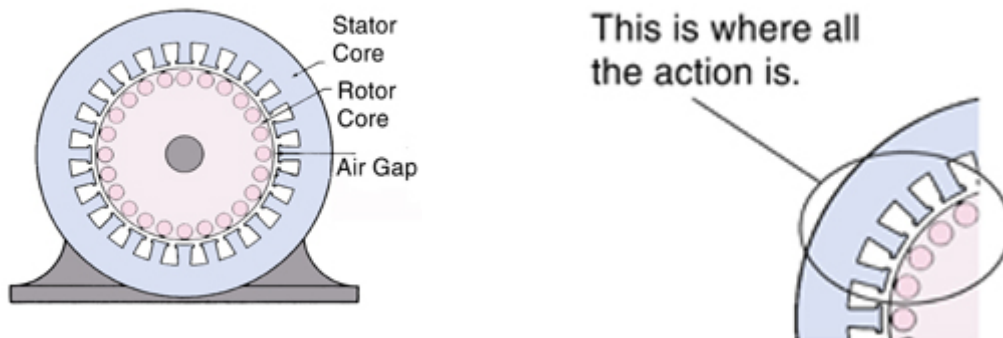
### Ambiguous Motor Theory

The real action in an AC variable frequency drive system is in the motor. This is really where it all happens.

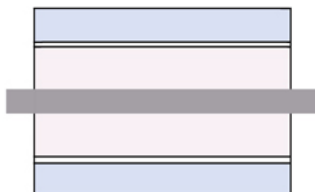
To be an AC drive application Wizard (which is several levels higher then Guru) one must understand how motors use electric power. It is essential. I cannot emphasize the importance of this.

All loads moved by electric motors are really moved by magnetism. The purpose of every component in a motor is to help harness, control, and use magnetic force. When applying an AC drive system it helps to remember you are actually applying magnets to move a load. To move a load fast does not require more magnets, you just move the magnets fast. To move a heavier load or to decrease acceleration time (accelerate faster) more magnets (more torque) are needed. This is the basis for all motor applications.

Where does the real action happen in a AC drive system?



Above is a cross-sectional view a motor rotor and field magnetic core. Looking from the side would look something like a looking at a can:



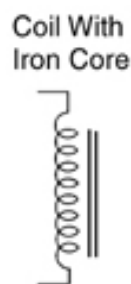
We can add magnets (and torque) to our drive system by using a motor with a core that is either longer, larger in cross-sectional diameter, or some combination of both.

## A Side Note About Fishing, Electro-magnets, Current, and Magnetic Conductivity

When we go fishing we put bait on a hook and throw it in water knowing that according to generally accepted theory, a hungry fish will sooner or later, bite. Well the truth is we don't know why the fish bite. No one to date, has talked to a fish (well maybe a few people talk to fish). The fact the we get hungry and therefore fish must too, seems like a safe assumption. But it doesn't really matter because we do know that putting bait on a hook will get fish into the boat.

Magnetism and electricity are the same way. We have some well accepted theories that we can use to explain how magnets can move our load but no one really knows what magnetism and electricity are (regardless of what they say). When it comes to using magnetic force to move our load, how it works just doesn't matter. We do know that it works. We have even noticed a few peculiar things.

We have noticed that when you wrap a coil of wire around a piece of iron and apply electric current the piece of iron becomes magnetic. We call this an electro-magnet.

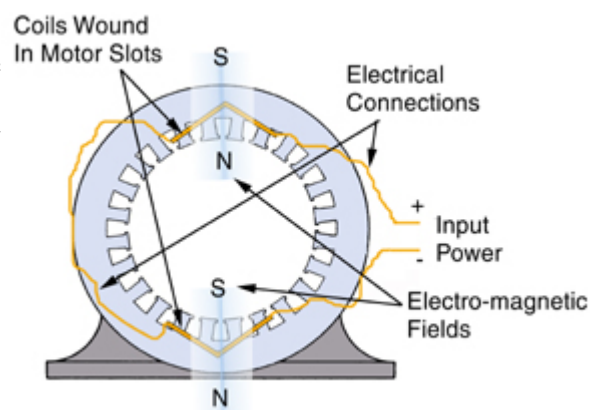


We have noticed a lot of things about electro-magnets that are very important to the drive application wizard:

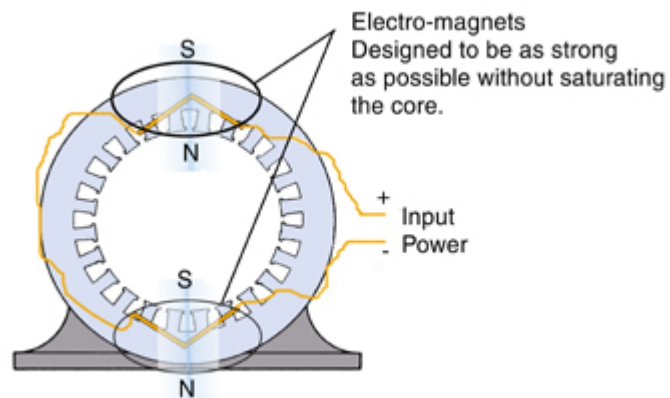
- After we apply the electric current, the magnet field grows at a finite rate to a finite size.
- After voltage is applied and full current is reached, which always takes a little time, the field quits growing and becomes a constant size. If we increase the applied voltage the field grows and becomes stronger, decrease the voltage and the field weakens and shrinks.
- When we remove electric power to the coil the field does not just disappear. It just decreases in size until it does disappear. It collapses over time so to speak.
- The more current our coil draws (which we can force by increasing the applied voltage level ) the stronger and larger our magnetic field becomes. I know I said it twice. It's that important.
- When we increase voltage to our electro-magnet, current will increase directly proportional up to a point. After that point current increases exponentially. **THIS IS IMPORTANT!** Generally accepted theory says that the iron core or any material, can only conduct a limited amount of magnetic flux. Once that point is reached current can become very high with a very small increase in voltage. This is called magnetic saturation and is sometimes seen in motor applications. Motor life becomes very short when the core reaches saturation - about 15 seconds in some cases. We will look at this and some of the causes later.
- Some energy is consumed by simply magnetizing the iron core. Different materials consume different amounts of energy. This is usually considered an energy loss.
- Some energy is converted into heat within the iron core. Different materials convert different amounts of energy. This is also usually considered an energy loss.
- Once a core is magnetized, demagnetization and reverse polarity re-magnetization consumes more energy and takes quite a long time, relatively speaking. (Remember, an existing field has to collapse over time.) The amount of this loss is proportional to the frequency of polarization reversals. This happens 120 times per second when operating an AC motor at 60 hertz. We will touch on the importance of this later. (Are you beginning to see where all this is going?)

## The Magnets Within the Motor and Torque

Motors are designed so that the electro-magnets are made as strong as possible with acceptable risk of core saturation. This will maximize the torque capability of the motor but also means that during normal operation every motor may at some point, operate close to saturation. How close a motor runs to saturation depends upon the amount and type of core material used. So naturally, this point varies from manufacturer to manufacturer. There really is a difference in motors and you get what you pay for.



When the voltage applied to a motor is increased current to the electro-magnets increases resulting in higher field strength and increased motor torque output. This is a commonly used technique, especially in AC drive applications. It is a very good way to gain torque capability when needed. This technique can cause higher than normal motor heating resulting in reduced motor life. Close monitoring of the motor is required. Avoid saturating the core.



The motor above is shown with two field coils, one for each magnetic pole. In the industry this would be called a "two pole motor". For simplicity, only one phase is shown. In reality, a 3-phase, two pole motor requires six coils, evenly spaced around the core - a minimum of two coils is required, to generate two electro-magnetic poles, for each of the three phases..

### A coil-ectomy

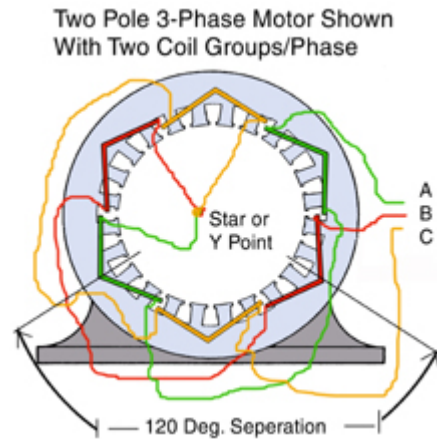
The most widely used AC motor in industry is the 5 horsepower, 1800 RPM, 60 Hz, 3-phase AC motor. (I can't prove this but it might be true.) In order for a motor to run 1800 RPM at 60 Hz it would have to be wound with four magnetic poles.

Important Motor Formula

$$\text{Synchronous RPM} = \frac{\text{Hertz} \times 120}{\text{Number of Poles}}$$

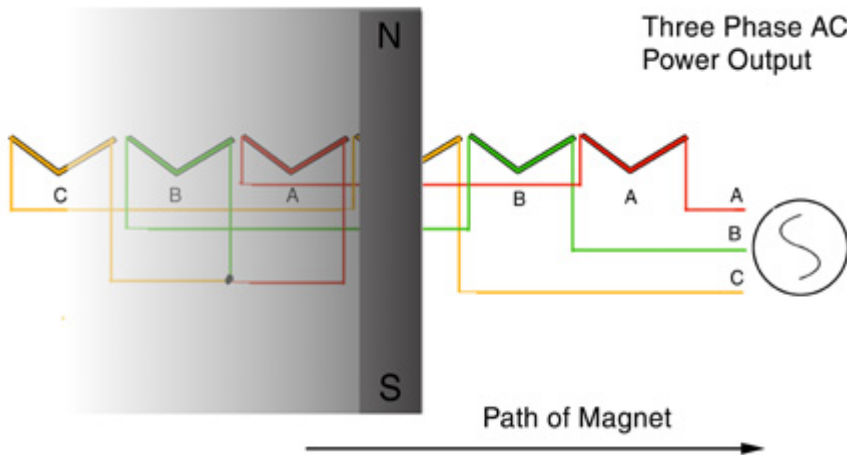
"Synchronous RPM" is the RPM the motor would run if the rotor did not slip. All AC induction motors slip. An AC motor referred to, in the industry, as an 1800 RPM motor will be name-plated with a speed of something less, usually around 1735 RPM. This is a typical RPM rating but can be higher or lower. The difference between the synchronous and the actual RPM is called "slip". Adjusting slip is an important technique in AC drive applications.

$$\begin{aligned} \text{Synchronous RPM} &= \frac{60 \text{ HZ} \times 120}{2 \text{ Poles}} \\ &= 3600 \end{aligned}$$



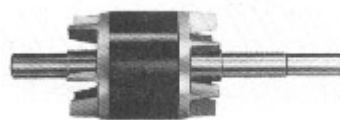
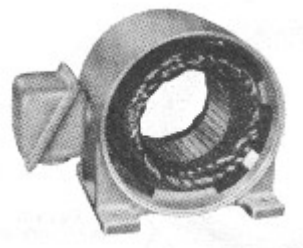
### AC Generator

If a magnet is passed along the coils, an electric current is generated in each of the three phases. In fact, there is little difference between AC generator and motor field windings.



### Induction Motors:

The most common electric motor found in industrial and commercial application is the AC induction motor. Induction motors work by electrically *inducing* an electro-magnetic pole into the rotor. The magnetic field that surrounds the rotor appears to rotate which has the effect of pulling the rotor in the direction of rotation. The speed of the rotation is determined by the frequency of the applied alternating current - change the frequency and the rotor speed is changed. This is the function of the variable frequency drive (VFD or AC drive).



### The Stator (Stationary Part)

The rotating magnetic field is produced by the coil windings when AC power is applied.

### The Rotor

Sometimes called a squirrel-cage rotor because if all of the magnetic iron were removed what would remain would be an aluminum cage that looks like a rodent exercise cage.

#### **Reference:**

[www.oeenrcan.gc.ca](http://www.oeenrcan.gc.ca)

[http://www.drivesys.com/ac\\_drives.html](http://www.drivesys.com/ac_drives.html)