



ECET 4530

Industrial Motor Control

Variable Frequency Drives



Electronic Motor Drives

Electronic motor drives are devices that control the speed, torque and/or rotational direction of electric motors.

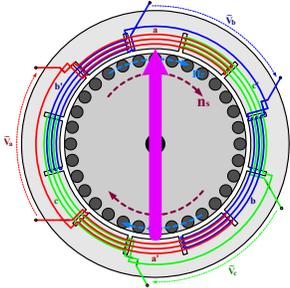
Electronic motor drives can be divided into two categories:

- **AC Motor Drives**
- **DC Motor Drives**

This presentation will focus on AC Motor Drives.



Synchronous Speed



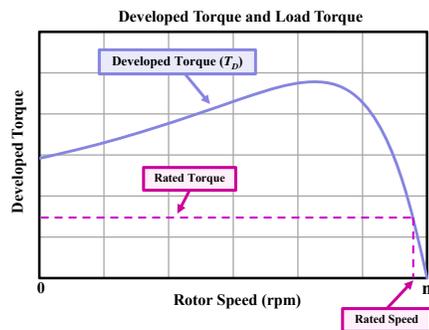
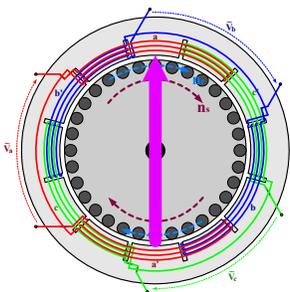
When a 3Φ Induction Motor is supplied by a balanced 3Φ source, its stator windings produce a net magnetic field that passes through the rotor region and rotates in direction at a speed that is defined as the synchronous speed of the motor.

The synchronous speed, n_s , is a function of both the source's electric frequency and the number of poles* of the machine:

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



Synchronous Speed



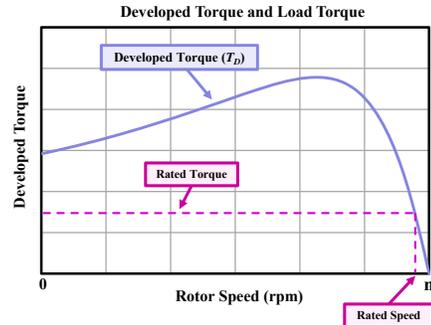
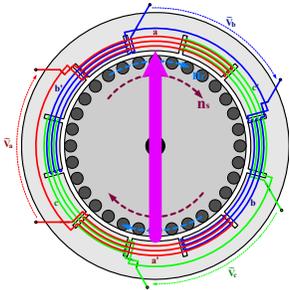
$$n_s = \frac{120 \cdot f_{elec}}{\# poles}$$

The rotating stator field develops a torque within the rotor that tries to accelerate the rotor up to synchronous speed.

But, when driving a load, the rotor will rotate at a speed that is less than, but typically within 5% of, synchronous speed.



Synchronous Speed



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

Although the supply voltage magnitude affects the magnitude of the developed torque, it is the supply voltage frequency that determines the synchronous speed of the motor.

Thus, it is the supply voltage frequency that has the greatest affect on the operational speed of the motor.

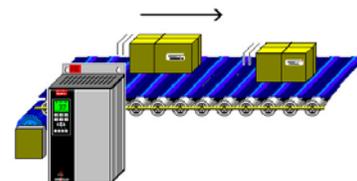


Variable Frequency Drives

A Variable Frequency Drive (VFD) is a type of motor drive that is used to control the rotational speed of an AC motor by varying the frequency of the electric power supplied to the motor.

VFDs are sometimes referred to by a variety of other names:

- Adjustable Speed Drives (ASDs)
- Variable Speed Drives
- AC Inverter Drives





Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Directional Control**
- **Soft-Starting / Torque Control**
- **Overcurrent Protection & Speed Limitations**
- **Improved Operational Efficiency**
- **Decreased Maintenance Costs**
- **High-Speed Operation**
- **Dynamic/Regenerative Braking**



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Directional Control**
 - forward and reverse operation provided simply by modifying its output waveforms (i.e. – reversing the phase-sequence of its output voltages)
 - does not require the use of electromechanical contactors to energize/de-energize the motor or to reverse the phase-sequence of the motor's supply



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Soft-Starting / Torque Control**
 - motor can be soft-started with reduced voltage magnitude/frequency and gradually accelerated to lessen the mechanical/electrical stresses on the motor, its mechanical load and its electrical supply



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Overcurrent Protection & Speed Limitations**
 - current limits can be set to provide overload protection for the motor
 - (max and min) speed limits can also be placed upon the operational speed of the motor as required by the mechanical system



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Improved Operational Efficiency**
 - a large energy savings can be achieved in applications that allow the motor to run at reduced speed, such as with fans and blowers for which:

$$\text{horsepower} \equiv \text{speed}^3$$

10% Speed Decrease → 27% Energy Savings



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Decreased Maintenance Costs**
 - reduced maintenance/repair costs and increased motor lifespan resulting from decreased stress during startup and acceleration along with the decreased stress of lower-speed operation



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **High-Speed Operation**
 - **greater than rated speed operation possible by increasing frequency above its rated value provided that rated power is not exceeded and that other mechanical and electrical concerns are addressed**



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Dynamic / Regenerative Braking**
 - **an AC motor is transformed into an AC generator when it is rotating faster than its synchronous speed (which is set by the VFD's output frequency) such that the mechanical system's rotational energy is converted back into electrical energy, resulting in a magnetic braking force being applied to the shaft of the machine.**



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Dynamic Braking**
 - during dynamic braking, the generated electrical energy is dissipated as heat either in the rotor conductors or in a bank of eternal resistors



Advantages of VFD Systems

In addition to speed control, VFDs can provide many other advantages when used to control an AC motor:

- **Regenerative Braking**
 - during regenerative braking, the generated electrical energy is recovered and returned to the supply
 - regenerative braking requires more complicated circuitry than dynamic braking



Advantages of VFD Systems

VFDs are typically configurable, allowing the user to set different operational characteristics such as the rate at which the drive will accelerate or decelerate the AC motor.

Additionally, VFDs are often networkable, allowing them to be controlled remotely as an individual unit or as part of a complex motor control system involving multiple VFDs and/or devices.

Note that complex motor control systems are typically controlled by Programmable Logic Controllers (PLCs). PLCs are covered in a separate presentation.



VFD Operation

Although VFDs come from many different manufacturers in a wide variety of sizes and with a large variety of features, most VFDs are constructed using the same operational components to provide their primary function:

the conversion of a constant-frequency AC waveform into a variable frequency (and variable magnitude) AC waveform.



VFD Operation

Basic VFD operation occurs in two stages:

- I – The conversion electric energy provided by a constant-frequency AC source into a DC form that is typically stored in a set of capacitors that are connected across a DC bus
- II – The conversion of the electric energy stored on the DC bus back into AC energy that will be supplied to the VFD's electric motor in the form of a variable frequency (and magnitude) AC waveform



VFD Operation

Energy Conversion Process in a VFD

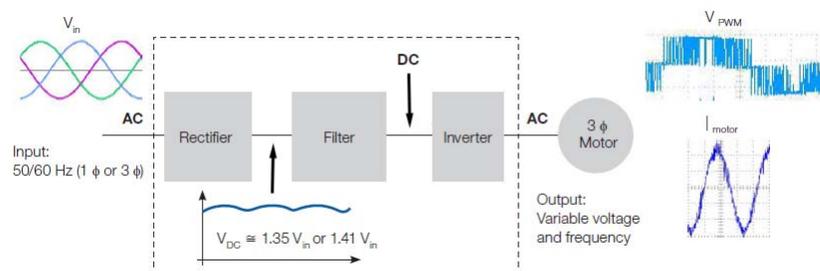
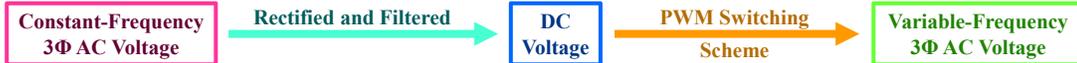
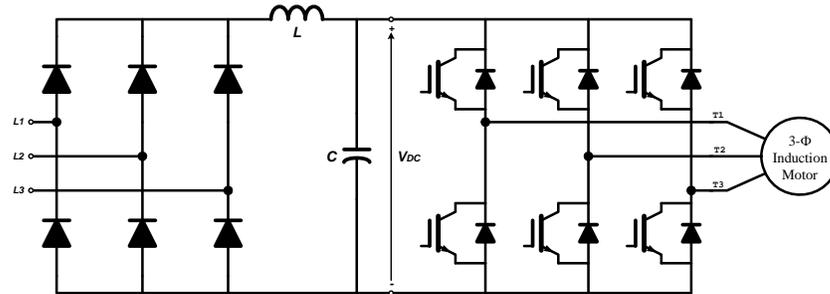


Figure taken from "Technical Guide – Induction motors fed by PWM frequency inverters" by WEG ©2009 – www.weg.net



VFD Operation

Simplified Schematic Drawing of VFD Power Circuitry

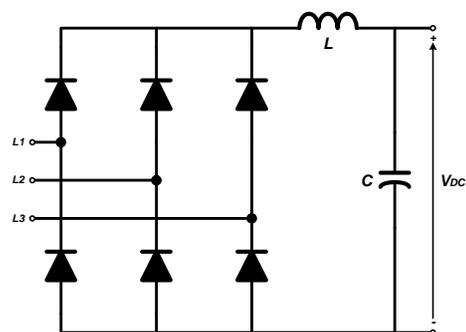


VFD Operation

Stage I – Conversion of the 3Φ, Constant-*f* AC Waveforms to DC

The circuitry used to convert the supply voltage waveforms from AC to DC has two basic components:

- Rectifier
- Filter



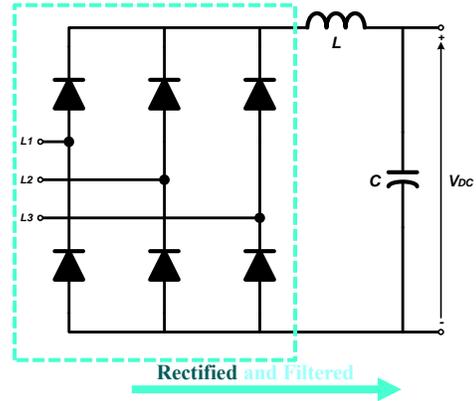


VFD Operation

Stage Ia – Rectification of the 3 Φ , Constant- f AC Waveforms

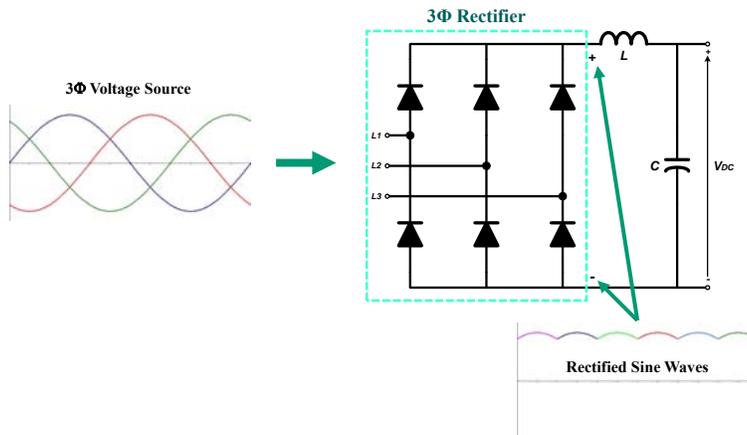
The AC power is first converted to a form that resembles DC using a rectifier or converter bridge.

A full-wave rectifier is typically used for this task.



VFD Operation

Stage Ia – Rectification of the 3 Φ , Constant- f AC Waveforms

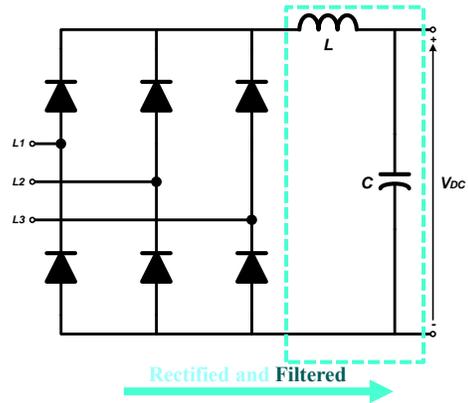




VFD Operation

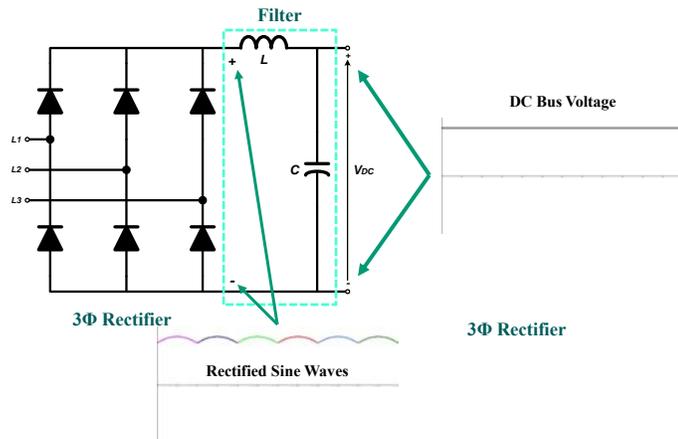
Stage Ib – Filtering the Rectified AC Waveforms

The rectified waveform is then filtered to smooth the output of the DC bus such that it is as close to DC as possible.



VFD Operation

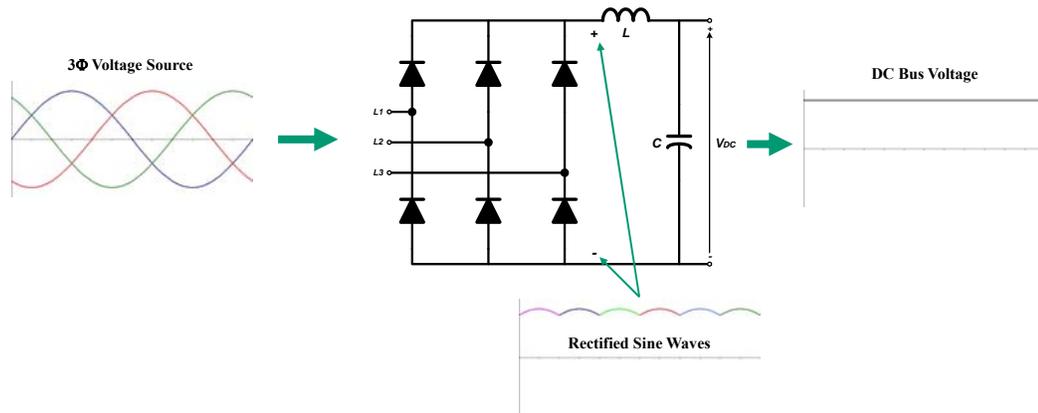
Stage Ib – Filtering the Rectified AC Waveforms





VFD Operation

Stage I – Conversion of the 3 Φ , Constant- f AC Waveforms to DC



VFD Operation

Stage I – Conversion of the 3 Φ , Constant- f AC Waveforms to DC

Note that some VFDs are designed to receive their power from a single-phase AC source instead of a three-phase AC source.

Drives designed to operate from a 1 Φ source are typically smaller in size and thus are limited to low-power applications.



VFD Operation

Stage I – Conversion of the 3 Φ , Constant- f AC Waveforms to DC

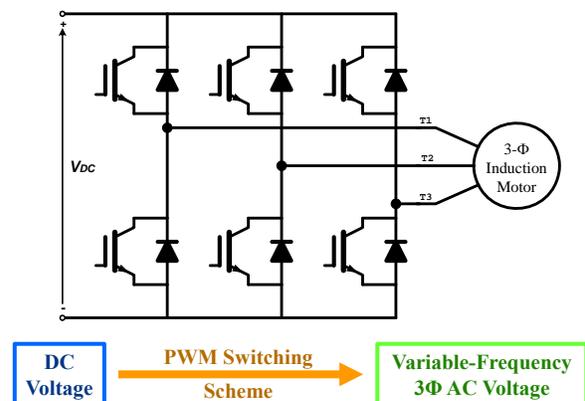
Also note that some VFDs that are designed to receive their power from a 3 Φ source may be configured to instead receive their power from a 1 Φ source provided that the drive is de-rated to prevent drawing too much current into the one operational phase of its three-phase rectifier circuit.



VFD Operation

Stage II – Conversion of DC to a 3 Φ , Variable- f , AC Waveform

A three-phase inverter is used to convert the DC energy back into a form that can be used to supply the AC motor.

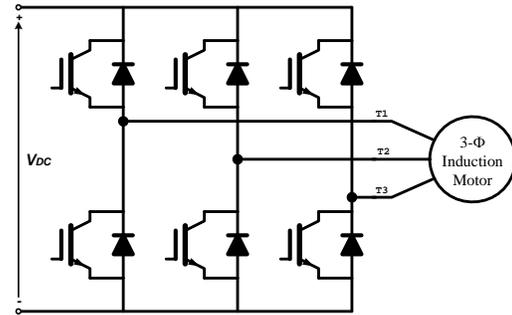




VFD Operation

Stage II – Conversion of DC to a 3 Φ , Variable- f , AC Waveform

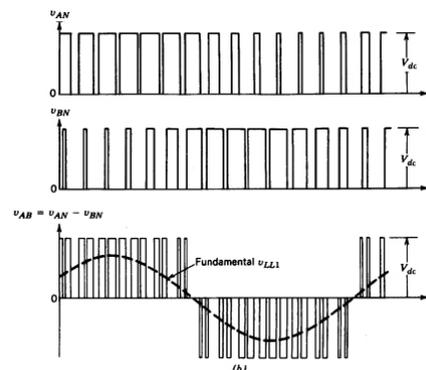
The inverter typically utilizes a set of Insulated Gate Bipolar Transistors (IGBTs) that are switched on and off using a Pulse Width Modulation (PWM) switching pattern.



VFD Operation

Stage II – Conversion of DC to a 3 Φ , Variable- f , AC Waveform

The PWM switching pattern produces a set of periodic waveforms having fundamental frequencies equal to that of the desired output frequency.



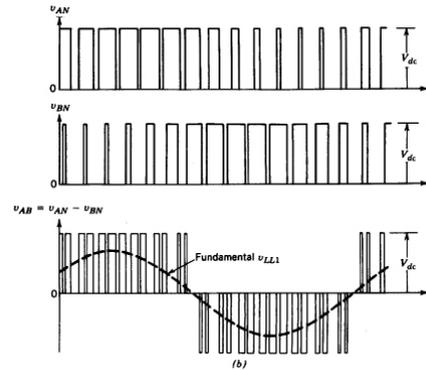
Note – only one phase of the three phase output is shown in the figure



VFD Operation

Stage II – Conversion of DC to a 3 Φ , Variable- f , AC Waveform

The motor responds to the waveforms as if it was supplied by a three-phase source, drawing currents that are relatively sinusoidal due to the natural filtering effect of the highly-inductive stator coils in the AC motor.



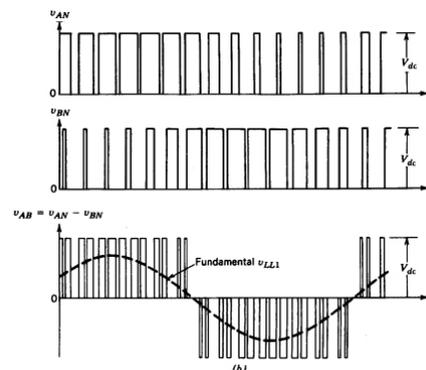
Note – only one phase of the three phase output is shown in the figure



VFD Operation

Stage II – Conversion of DC to a 3 Φ , Variable- f , AC Waveform

The magnitude and frequency of the output waveform is varied by manipulating the rate and the length of time during which each IGBT is turned on.

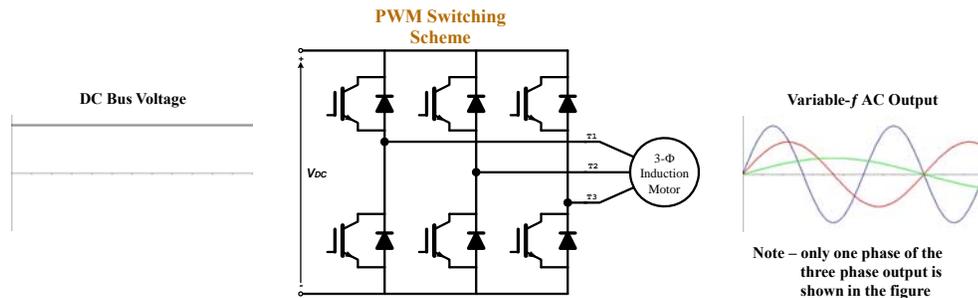


Note – only one phase of the three phase output is shown in the figure



VFD Operation

Stage II – Conversion of DC to a 3 Φ , Variable- f , AC Waveform



VFD Operational Considerations

Due to the operational characteristics of AC motors, the magnitude of the supply voltage must be varied proportionally to the frequency of the supply voltage in order for the motor to deliver (constant) rated torque at different motor speeds.

In other words, the volts per hertz (V/Hz) ratio must be held constant in order to deliver constant torque.



VFD Operational Considerations

Note that the volts per hertz ratio ($V/_{Hz}$) can be changed in order to vary the amount of torque delivered by the motor.

Also note that the volts per hertz ratio ($V/_{Hz}$) is often adjusted during startup and during low-frequency operation in order to optimize the performance of the motor.



PowerFlex 40

The PowerFlex 40 (PF-40) is a type of VFD that is manufactured by Allen-Bradley.

The version of the PF-40 available in the Q-215 lab is rated at $\frac{1}{2}$ Hp and is configured to receive power from a 240V, 3 Φ supply.

It can be configured for local operation using its built-in keypad or for remote operation across an Ethernet network via its communications module.

