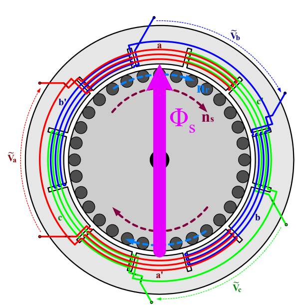
ECET 4530

Industrial Motor Control

Variable Frequency Drives

1

Induction Motor Operation



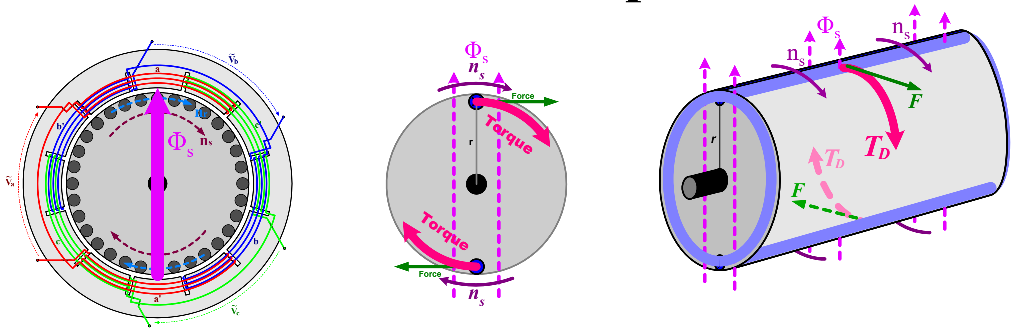
When a 3Φ Induction Motor is supplied by a balanced 3Φ source, its stator windings produce a net **magnetic field** (Φ_s) that passes through the rotor conductors and **rotates** directionally at a speed that is defined to be the **synchronous speed** of the motor.

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

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

2

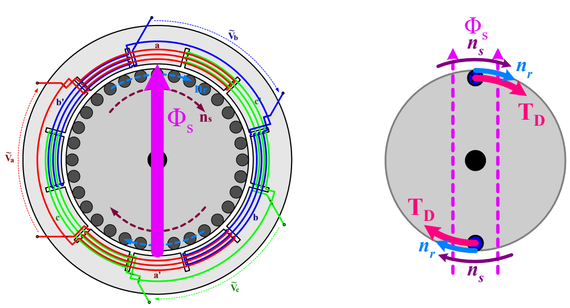
Induction Motor Operation

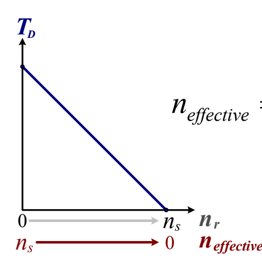


When the rotating stator field cuts across the rotor conductors, a force is developed upon those conductors, resulting in a net **torque** (***T_D***) being developed upon the rotor that tries to **accelerate the rotor** in the direction of the rotating field.

3

Induction Motor Operation



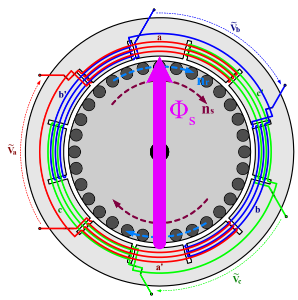


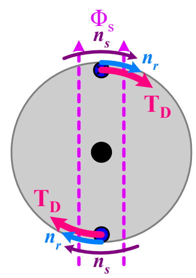
$$n_{effective} = n_s - n_r$$

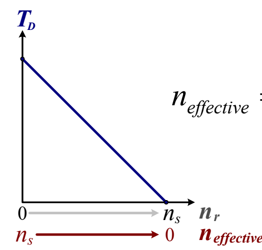
But as the rotor begins to rotate in the direction as the rotating stator field, the rate at which the field lines cut across the rotor conductors decreases, resulting in a decrease in the developed **torque** such that T_D is proportional to $n_{effective}$, the difference between the rotor speed, n_r, and the synchronous speed, n_s.

4

Induction Motor Operation







$$n_{effective} = n_s - n_r$$

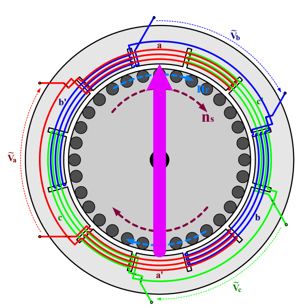
And since $\boldsymbol{n_{effective}}$ is zero when the rotor is rotating at synchronous speed, resulting in a developed torque $\boldsymbol{T_D = 0}$, the motor cannot accelerate beyond synchronous speed.

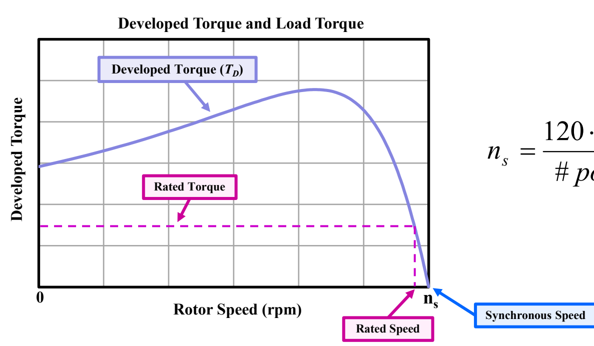
Thus, the motor "tries" to **accelerate up to its synchronous speed**.

The motor can only accelerate up to its synchronous speed under ideal no-load conditions.

5

Induction Motor Operation



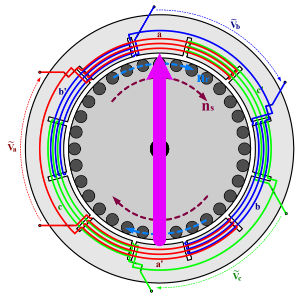


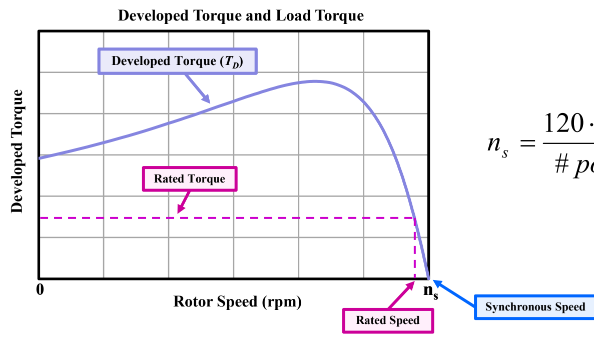
$$n_s = \frac{120 \cdot f_{elec}}{\# \, poles}$$

When driving rated load, the rotor of a "practical" induction motor will rotate at a speed, $\boldsymbol{n_{rated}}$,that is less than, but typically within 5% of, synchronous speed $\boldsymbol{n_s}$.

6

Induction Motor Operation



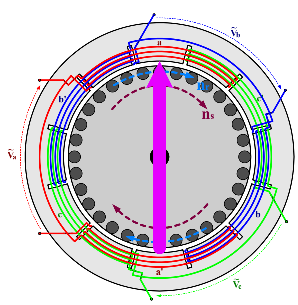


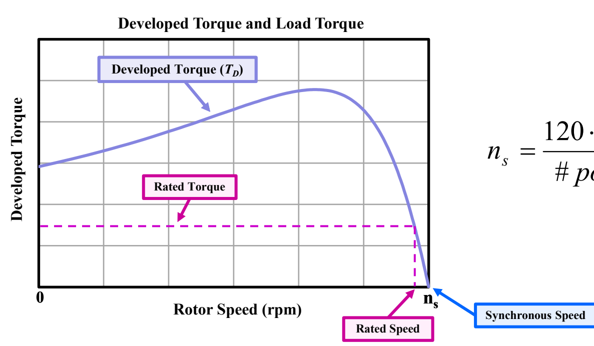
$$n_s = \frac{120 \cdot f_{elec}}{\# \, poles}$$

Although the supply voltage magnitude affects the height of the torque-speed curve and thus will have a slight effect on the rotor speed while driving a load, the motor will still try to rotate at a speed that is close to its synchronous speed regardless of the supply voltage magnitude.

7

Induction Motor Operation





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

Thus, it is the supply voltage **frequency** that has the **greatest effect** on the operational speed of the motor, whether the motor is operating under load or under no-load conditions.

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Electric Motor Drives

An **Electric Motor Drive** is a device that **controls** the **speed**, **torque**, **acceleration**, **direction**, or other operational characteristic of an electric motor.

Although there are a variety motor drives available, they can generally be divided into two categories:

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

This presentation will focus on AC Motor Drives that are used to control the speed or other operational characteristics of three-phase induction motors.

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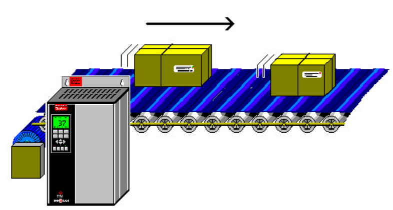
Variable Frequency Drives

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** (**ASD**s)
- **Variable Speed Drives**
- **AC Inverter Drives**



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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**

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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

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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 by raising the magnitude and frequency of the voltage to lessen the mechanical/electrical stresses on the motor, its mechanical load, and its electrical supply

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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

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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:

$$horsepower \equiv speed^3$$

10% Speed Decrease ➔ 27% Energy Savings

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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 the decreased stress during the initial startup and acceleration and, if applicable, the decreased stress resulting from lower-speed operation

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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 the frequency above its rated value, provided that rated power for the motor is not exceeded and that any other mechanical and electrical concerns are addressed

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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

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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 external resistors

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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

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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 that may include PLCs, multiple VFDs, and/or devices.

Note that complex motor control systems are typically controlled by Programmable Logic Controllers (PLCs).

PLCs will be covered in a separate presentation.

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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 **½Hp** and is configured to receive power from a 240V, 3Φ 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.

Further information regarding the use of the PF-40 will be provided during the laboratory sessions.

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VFD – Basic Operation

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

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

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VFD – Basic Operation

The 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

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VFD – Basic Operation

Energy Conversion Process in a VFD

Stage I Stage II

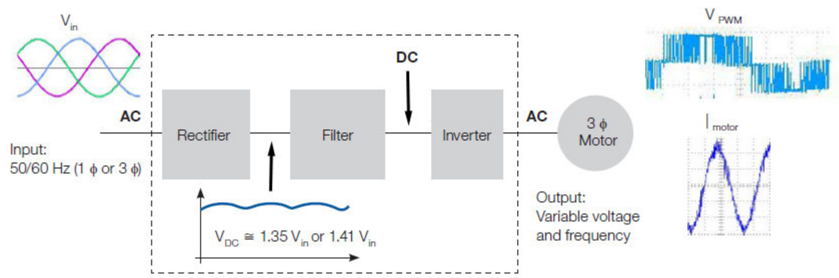

Figure taken from "Technical Guide – Induction motors fed by PWM frequency inverters" by WEG ©2009 – www.weg.net

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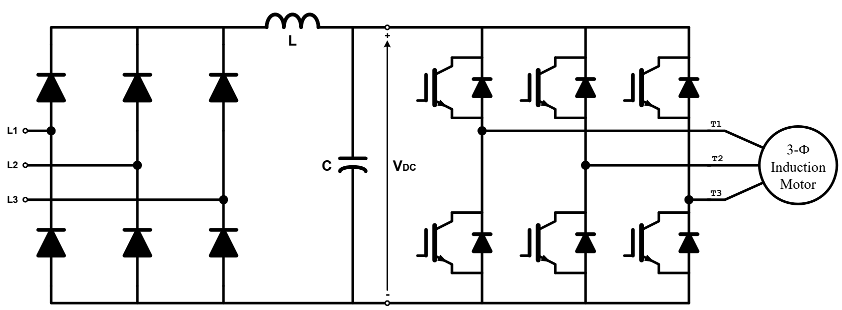
VFD – Basic Operation

Simplified Schematic Drawing of VFD Power Circuitry



Constant-Frequency 3Φ AC Voltage → **Rectified and Filtered** → **DC Voltage** → **PWM Switching Scheme** → **Variable-Frequency 3Φ AC Voltage**

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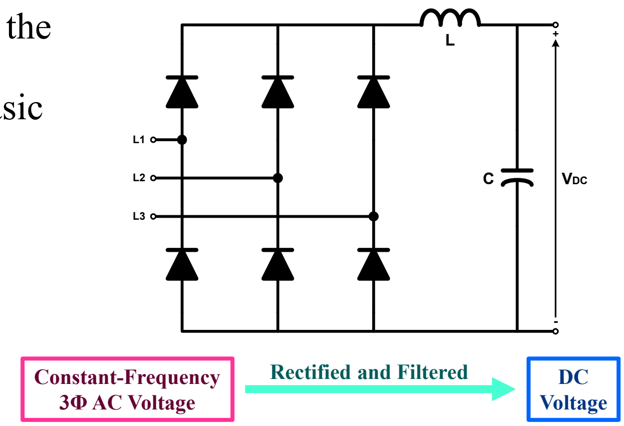
VFD Basic Operation – Stage I

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**



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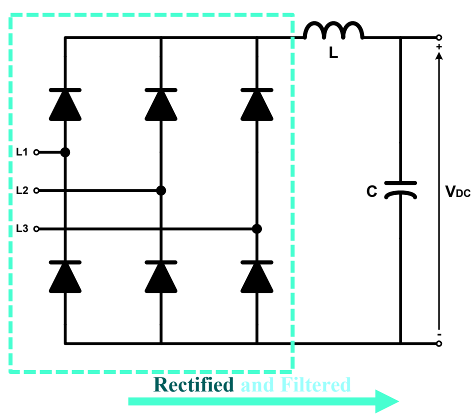
VFD Basic Operation – Stage I

A) Rectification of the 3Φ, 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.



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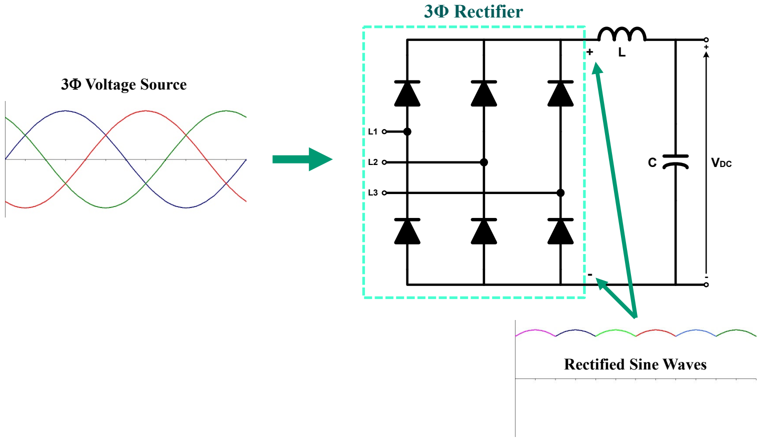
VFD Basic Operation – Stage I

A) Rectification of the 3Φ, Constant-*f* AC Waveforms



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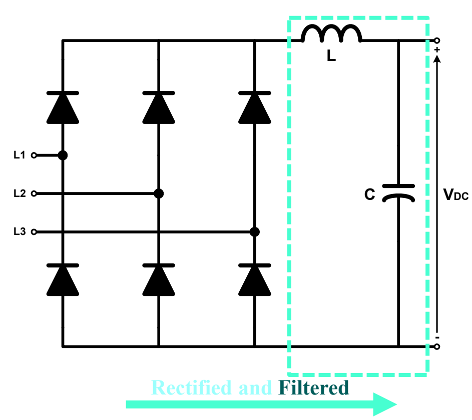
VFD Basic Operation – Stage I

B) Filtering the Rectified AC Waveforms

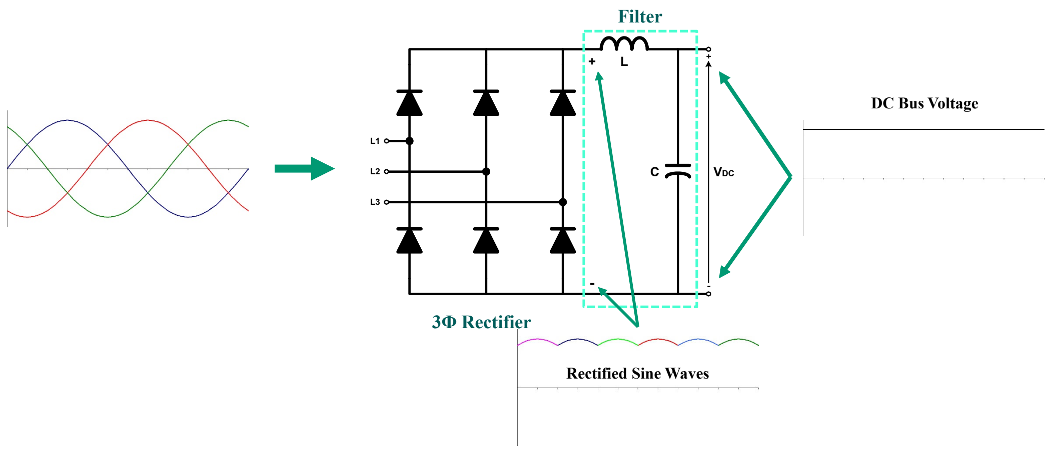
The rectified waveform is then **filtered** to smooth the output of the DC bus such that it is as close to DC as possible.



30

VFD Basic Operation – Stage I

B) Filtering the Rectified AC Waveforms



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VFD Basic Operation – Stage I

Conversion of the 3Φ, 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 1Φ source are typically smaller in size and thus are limited to low-power applications.

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VFD Basic Operation – Stage I

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

Also note that some VFDs that are designed to receive their power from a 3Φ source may be configured to instead receive their power from a 1Φ 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.

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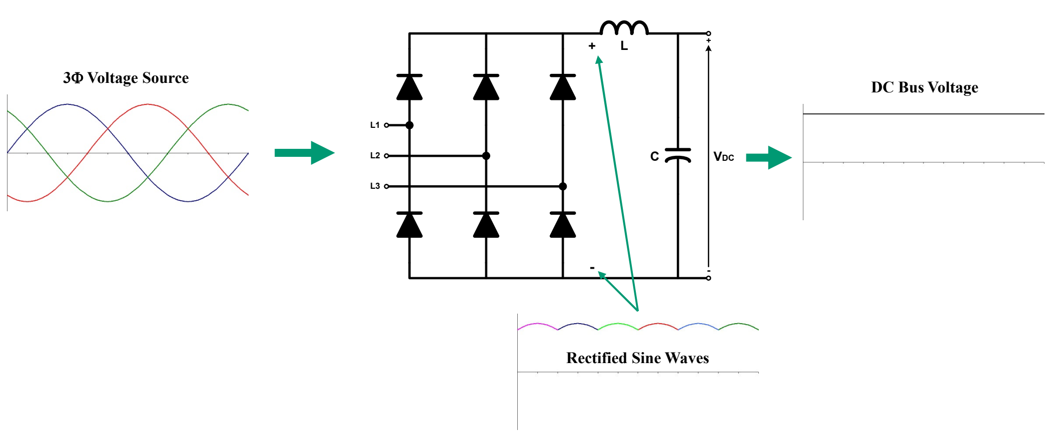
VFD Basic Operation – Stage I Summary

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



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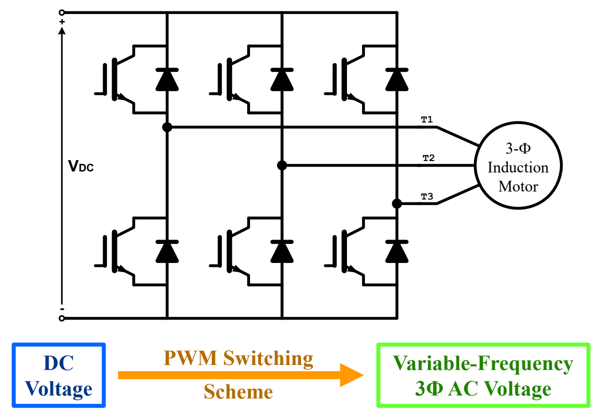
VFD Basic Operation – Stage II

Conversion of DC to a 3Φ, Variable-*f* set of AC Waveforms

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



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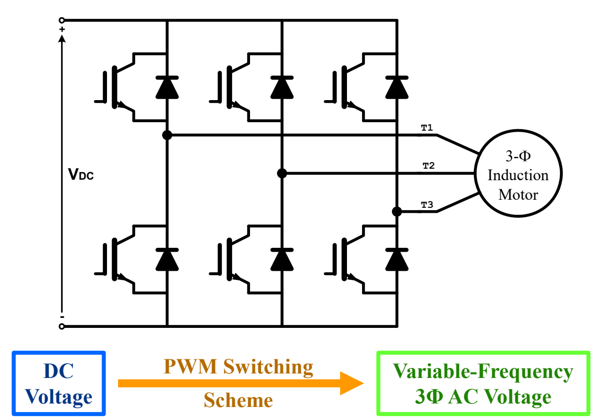
VFD Basic Operation – Stage II

Conversion of DC to a 3Φ, Variable-*f* set of AC Waveforms

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.



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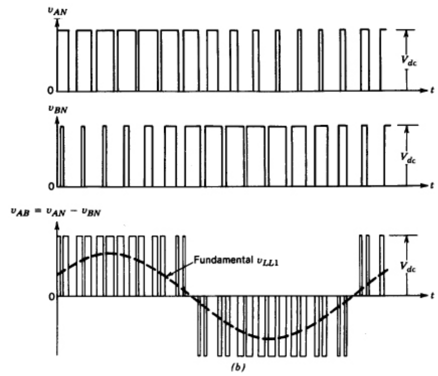
VFD Basic Operation – Stage II

Conversion of DC to a 3Φ, Variable-*f* set of AC Waveforms

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



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

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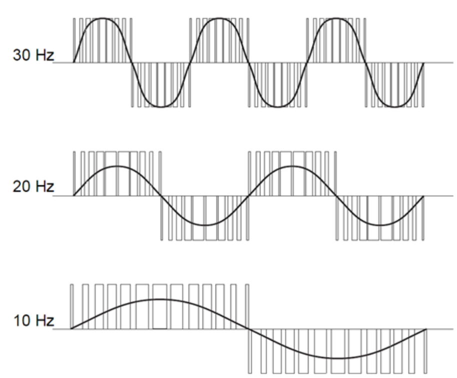
VFD Basic Operation – Stage II

Conversion of DC to a 3Φ, Variable-*f* set of AC Waveforms

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

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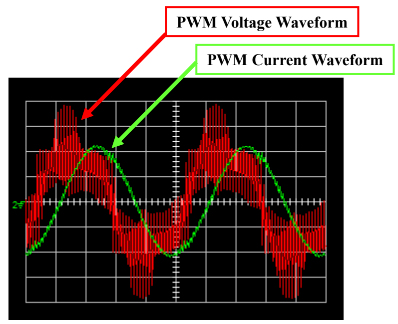
VFD Basic Operation – Stage II

Conversion of DC to a 3Φ, Variable-*f* set of AC Waveforms

The motor responds to the waveforms as if supplied by a single-frequency source, drawing **currents** that are relatively sinusoidal due to the natural filtering effect of the motor's highly-inductive stator coils, the reactances of which are proportional to the source frequency.

$$X_s = \omega \cdot L_s = 2\pi \cdot f \cdot L_s$$



Voltage and Current Waveforms for one phase of a three-phase VFD

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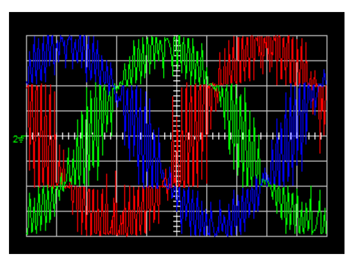
PF40 Operation – Stage II

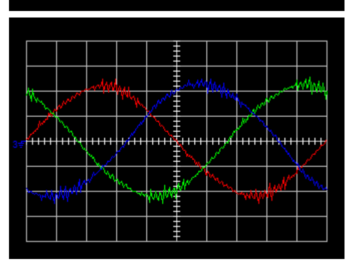
Conversion of DC to a 3Φ, Variable-*f* set of AC Waveforms

Shown to the right are the actual 3Φ **voltages** and **currents** supplied to a motor by one of the PF40 VFDs that are present in the Q-215 lab when the VFD is set to supply the motor at a frequency of 60Hz.

Although the voltage waveforms look quite distorted due to the relatively-large, high-frequency harmonics that are present in the waveforms due to the nature of the switching circuit in the output stage of the VFD, the current waveforms appear much closer to ideal sine waves because of the natural filtering that occurs within the motor.



Three-Phase Voltages at 60 Hz



Three-Phase Currents at 60 Hz

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VFD Operational Considerations

Note that the **torque** developed by an AC Induction motor and the magnitude of the **currents** drawn by the motor at a specific speed are directly affected by the magnitude of the supply voltages.

Thus, VFDs are often configured to vary both the frequency and the shape (magnitude) of the supply voltages in order to result in a desired set of operational characteristics for its supplied motor.

For example, the **volts per hertz ratio** ($^{V}/_{Hz}$) can be held constant in order to deliver relatively-**constant developed torque** by the motor as the frequency is varied.

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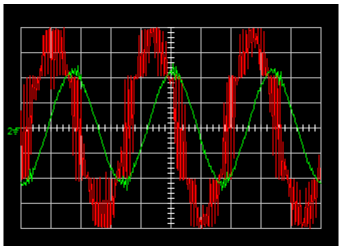
PF40 Operation – Stage II

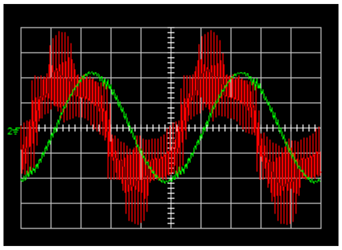
Conversion of DC to a 3Φ, Variable-*f* set of AC Waveforms

Shown to the right are images that compare the voltages and currents supplied to a motor a at frequencies of 60Hz & 40Hz.

Note that this VFD is configured to vary the shape of the output voltages in order to maintain **constant current magnitude** in the motor at the various operational frequencies.



Single-Phase Voltage & Current at 60 Hz



Single-Phase Voltage & Current at 40 Hz

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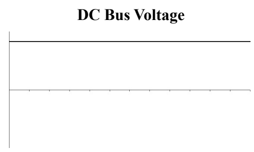
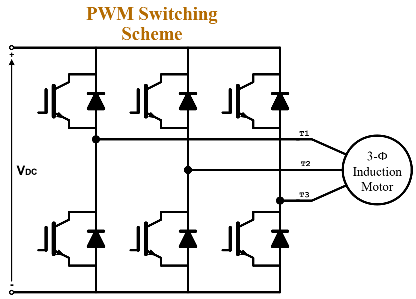
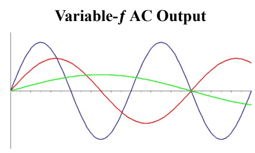
VFD Basic Operation – Stage II Summary

Conversion of DC to a 3Φ, Variable-*f*, AC Waveform







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

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