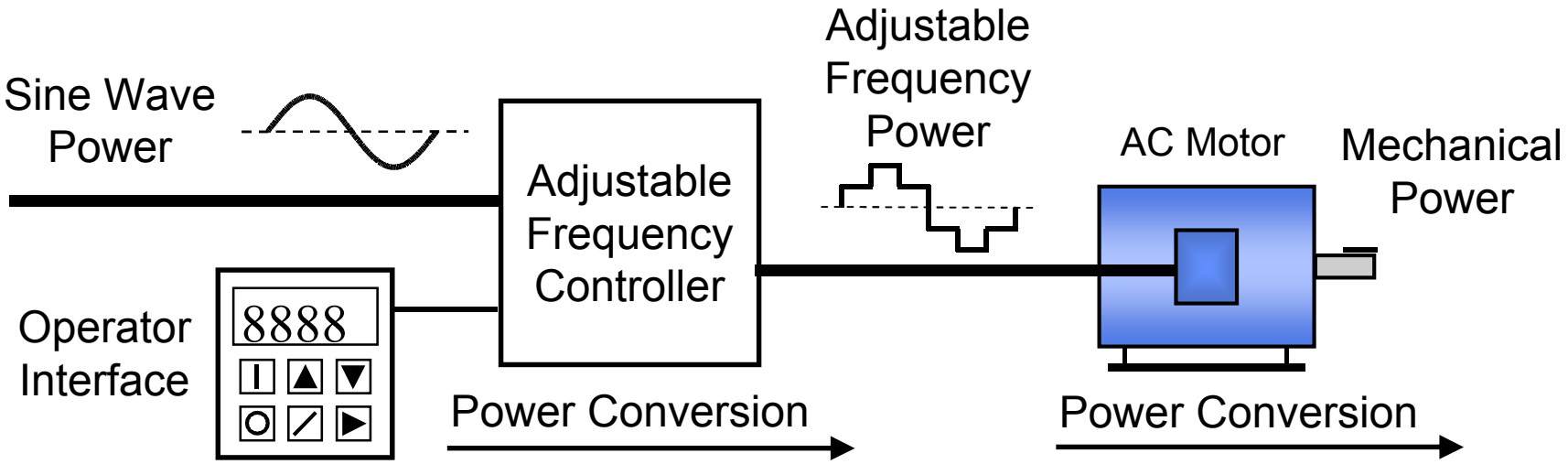
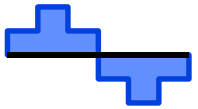
Principles of Adjustable Frequency Drives

What is an Adjustable Frequency Drive?

- An adjustable frequency drive is a system for controlling the speed of an AC motor by controlling the frequency of the power supplied to the motor.
- A basic adjustable frequency drive system consists of an ordinary three phase motor, an adjustable frequency controller and an operator interface.



Principles of Adjustable Frequency Drives



The Basic System Components

- The motor is usually a NEMA design B squirrel cage induction motor rated for 460 volt, three phase, 60 hz operation.
- The adjustable frequency controller is a solid state power conversion unit that receives 460 volt, three phase, 60 hz power and provides power to the motor which can be steplessly adjusted between 0 and 60 hz.
- The operator interface consists of a keypad or pushbuttons and a potentiometer for starting and stopping the motor and setting the operating speed.

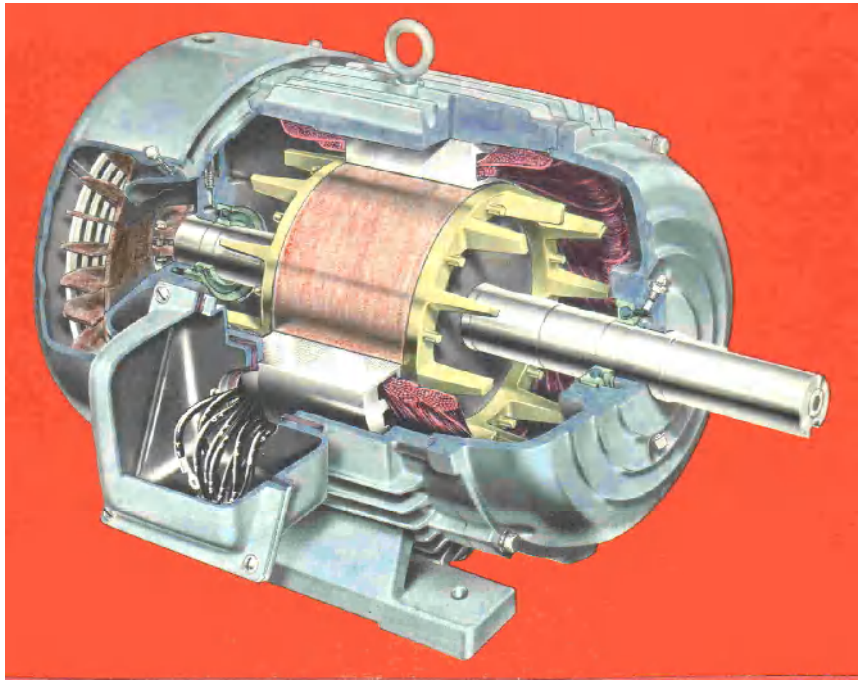
Standard AC Motor Operation

- AC Motor Construction.

A squirrel cage induction motor is a very simple machine.

Copper wire coils wound into slots in a stack of steel laminations form the stationary part of the motor called the stator.

A shaft and bearings support a solid rotor consisting of an aluminum "squirrel cage" cast into a stack of steel laminations.



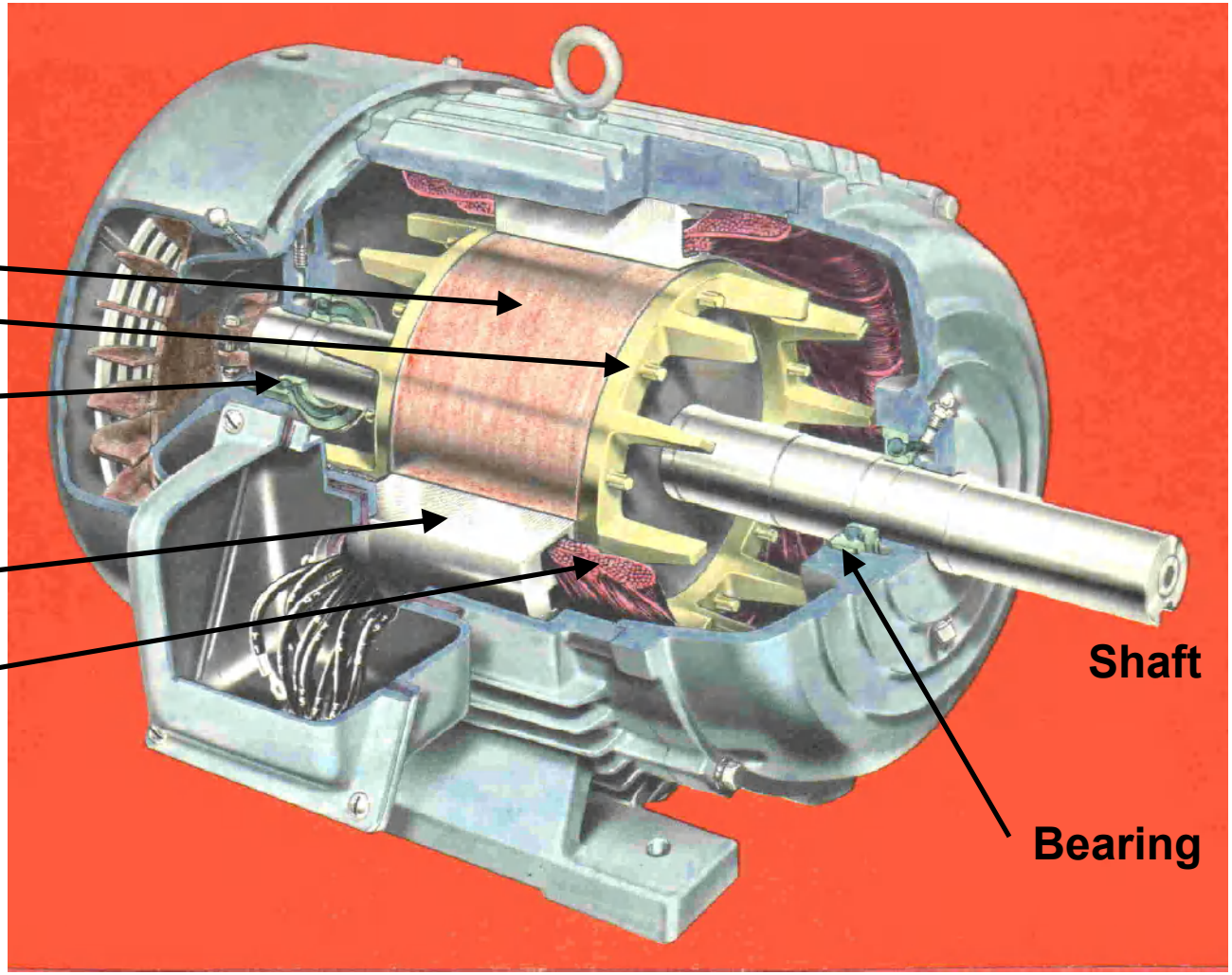
Principles of Adjustable Frequency Drives

AC Motor Construction

Rotor
- Iron
- Aluminum

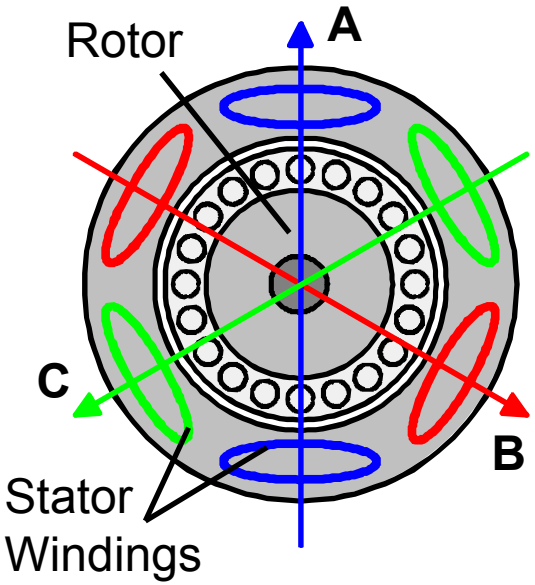
Bearing

Stator
- Iron
- Copper wire windings

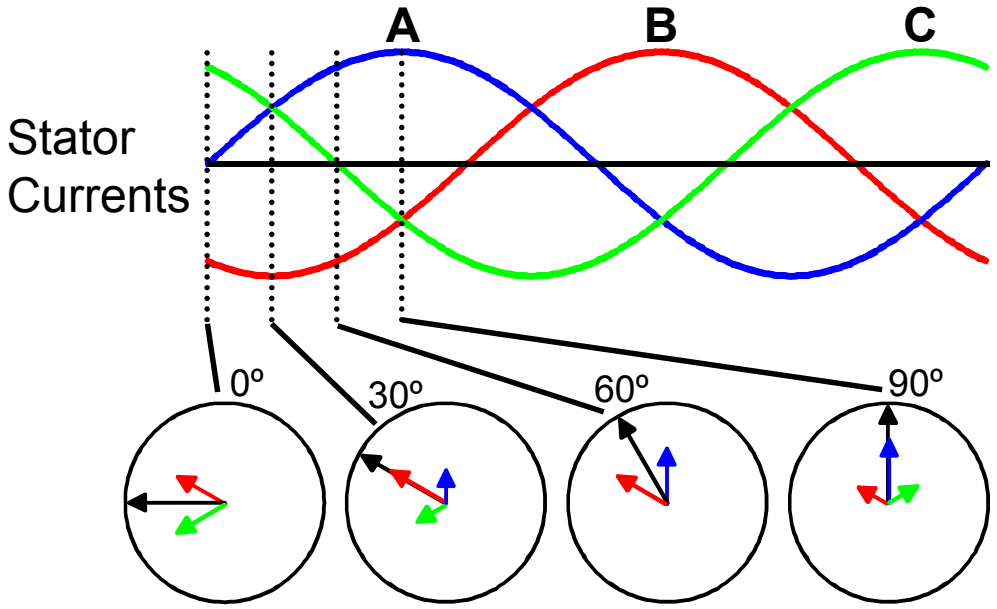


Standard AC Motor Operation

- Rotating Magnetic Field
  - The three phase stator windings in of induction motor stator produce a rotating magnetic field.



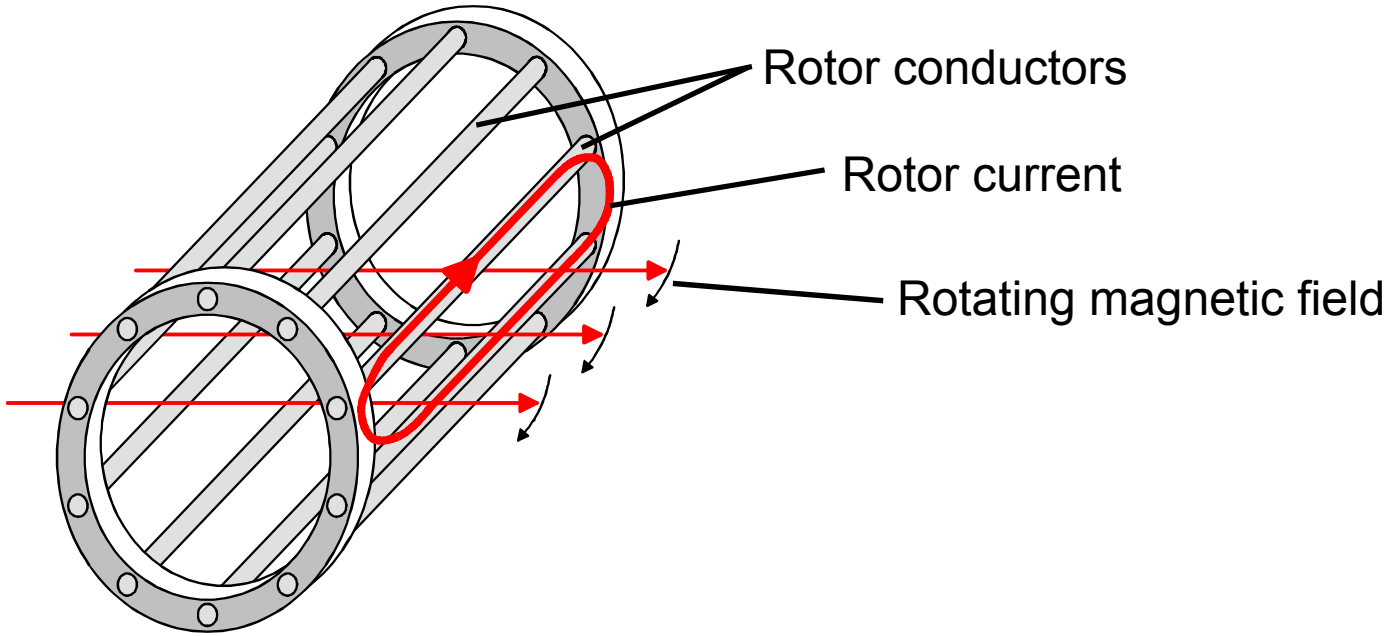
Motor Cross Section View



Sinusoidal A, B & C phase magnetic field vectors and the resulting constant amplitude rotating magnetic field vector

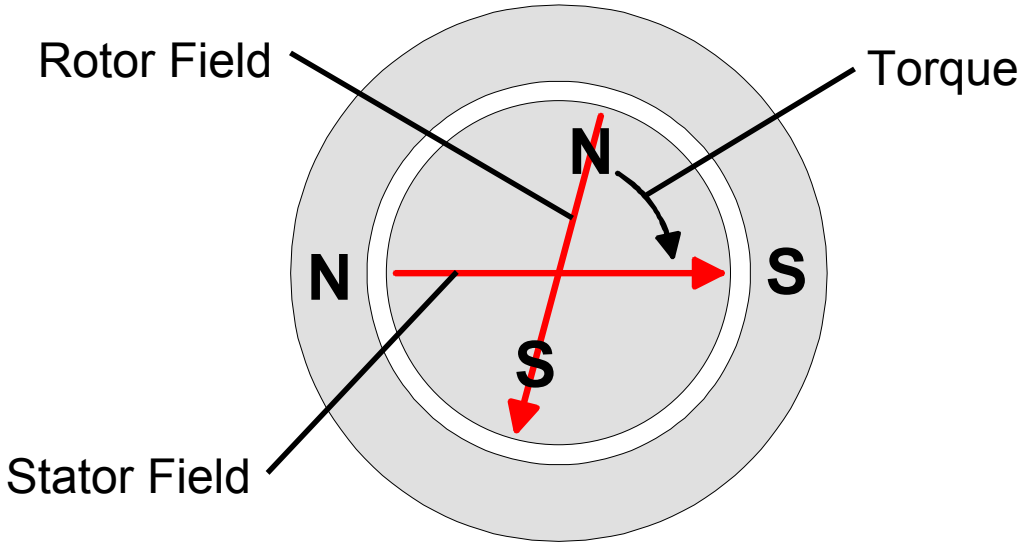
Standard AC Motor Operation

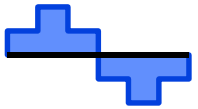
- Rotor Currents
  - The if operating speed of the rotor is different from the speed at which the stator field rotates, the field moves across the conductors comprising the rotor cage.
  - The moving field induces a current to flow in the rotor conductors.



Standard AC Motor Operation

- Rotor Field
  - The currents flowing in the rotor conductors produce a magnetic field that rotates at the same speed as the stator field and maintains an orientation at an angle with the stator field.
  - The magnetic force between these two rotating fields results in a torque applied to the rotor.





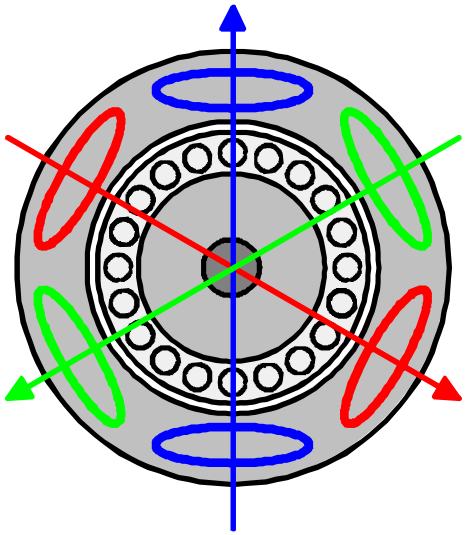
Standard AC Motor Operation

- Slip
  - The rotating speed of the stator field is called the motor's ***synchronous speed***.
  - The difference between the speed of the rotor and the motor's synchronous speed is called ***slip***.
  - Since current is induced in the rotor only when there is a difference between the operating speed of the rotor and the speed of the stator field, there is no rotor current and no torque produced when there is no slip.

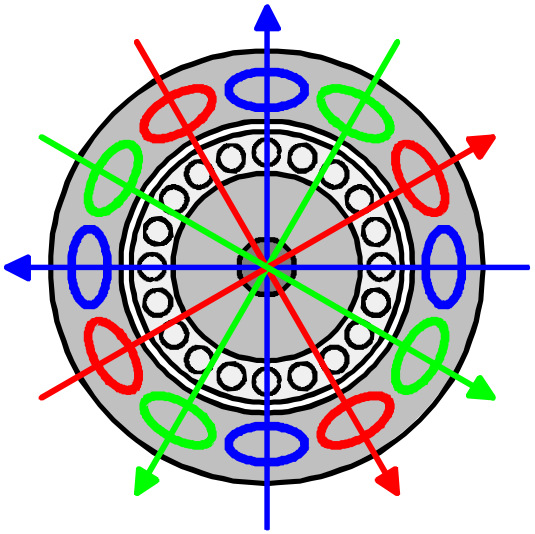
Motor Poles

- Motors can be constructed with any even number of ***poles***.
  - If a motor has two stator windings per phase, it is a two pole motor.
  - A four pole motor has four windings per phase.
  - Since a pair of windings is required to produce a magnetic field that passes through the rotor, a motor must have an even number of poles.

Two Pole Motor



Four Pole Motor



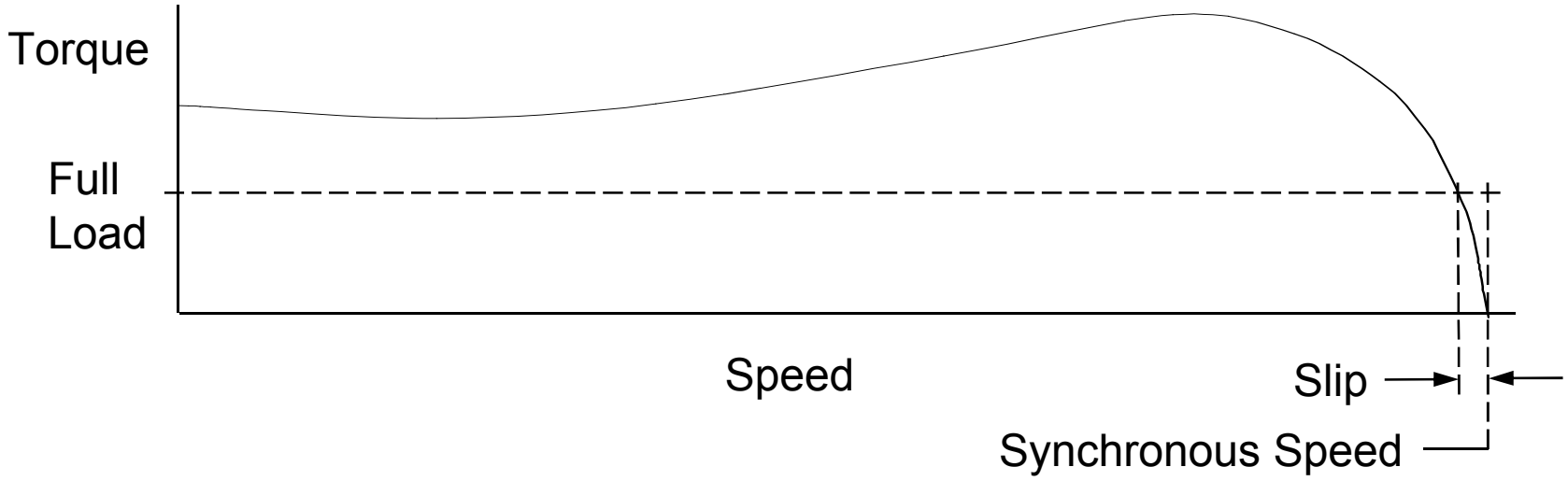
Motor Poles

- The motor's synchronous speed (RPM) is determined by the frequency (f) of the stator voltage and the number of poles (P) in the motor:

$$RPM = \frac{120 \times f}{P}$$

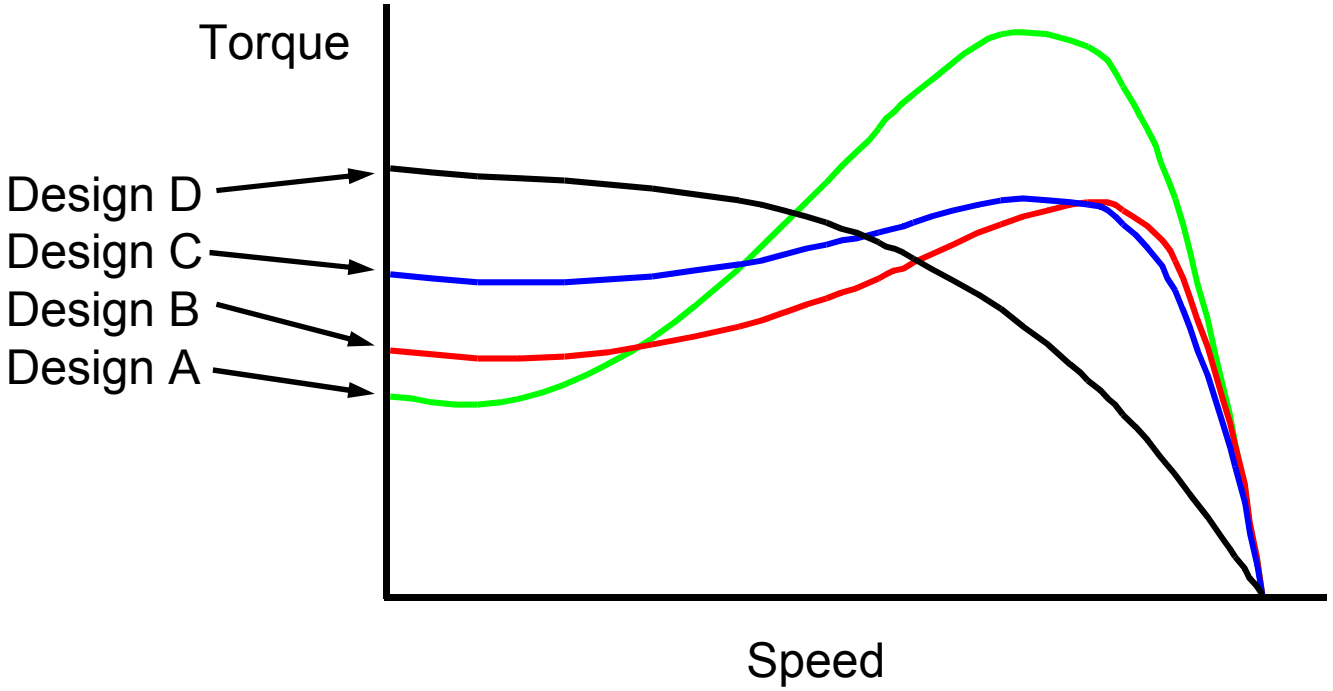
Standard AC Motor Operation

- Torque-Speed Curve
  - At the synchronous speed, the torque produced is zero.
  - In the normal operating region, from no load to full load, the torque produced is directly proportional to slip and the torque vs. speed relationship is fairly linear.



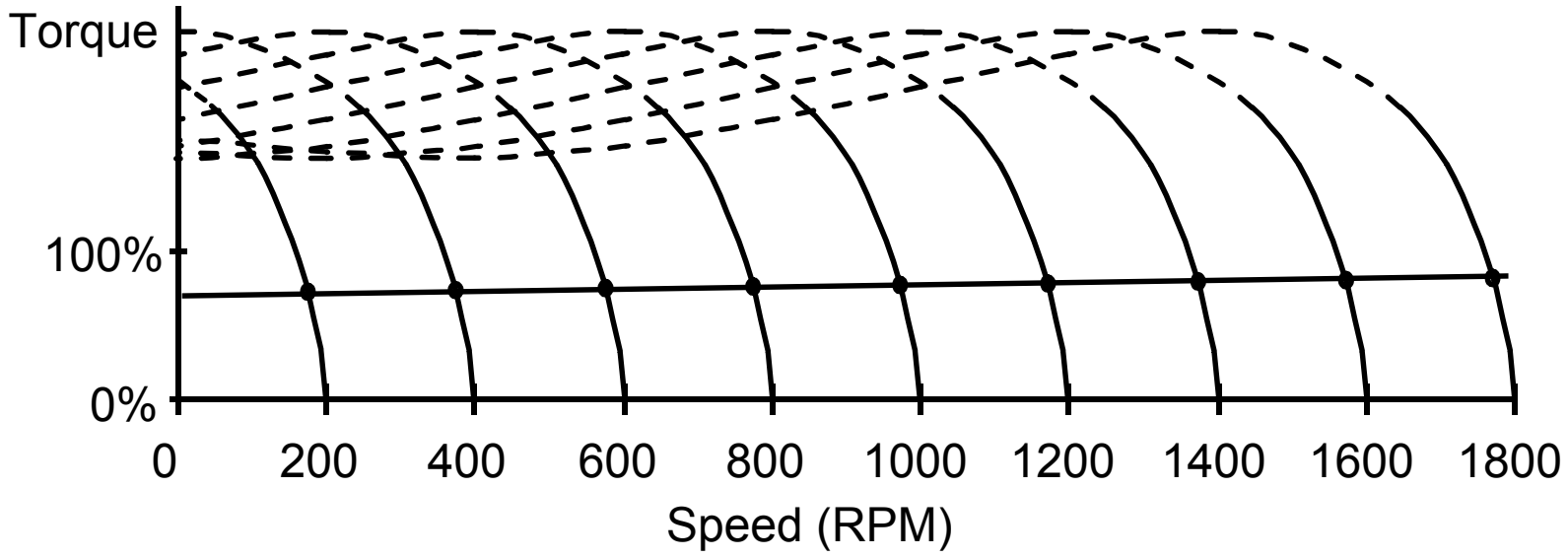
Standard AC Motor Operation

- Non-Standard Motors
  - We will consider a Design B motor to be a standard motor.
  - Other motor designs are not normally used for adjustable frequency drives.



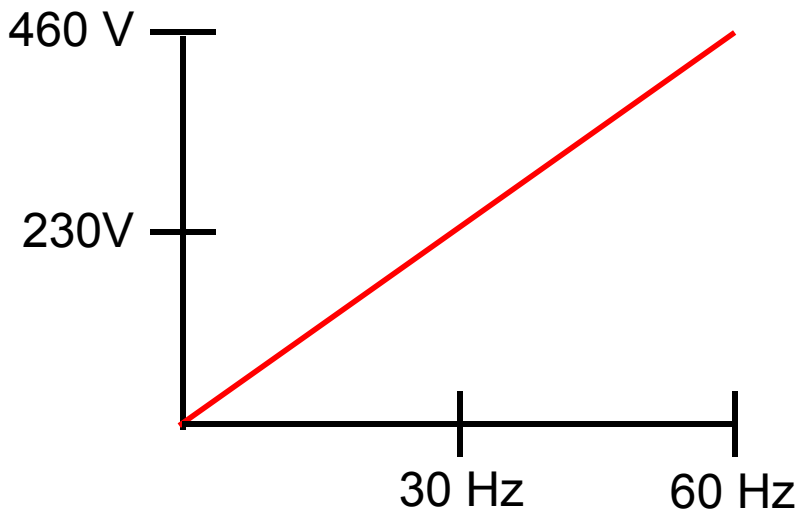
Adjustable Frequency Motor Operation

- Objective
  - Adjust the torque-speed curve throughout a wide range of operating speeds
  - Achieve performance at any speed that is comparable to fixed speed operation.



Adjustable Frequency Motor Operation

- Constant V/Hz Output
  - In order for a motor to have similar torque vs. speed characteristics over a range of operating frequencies, the applied voltage must be proportional to the applied frequency: $V = K \times f$, or $V/f = K$.

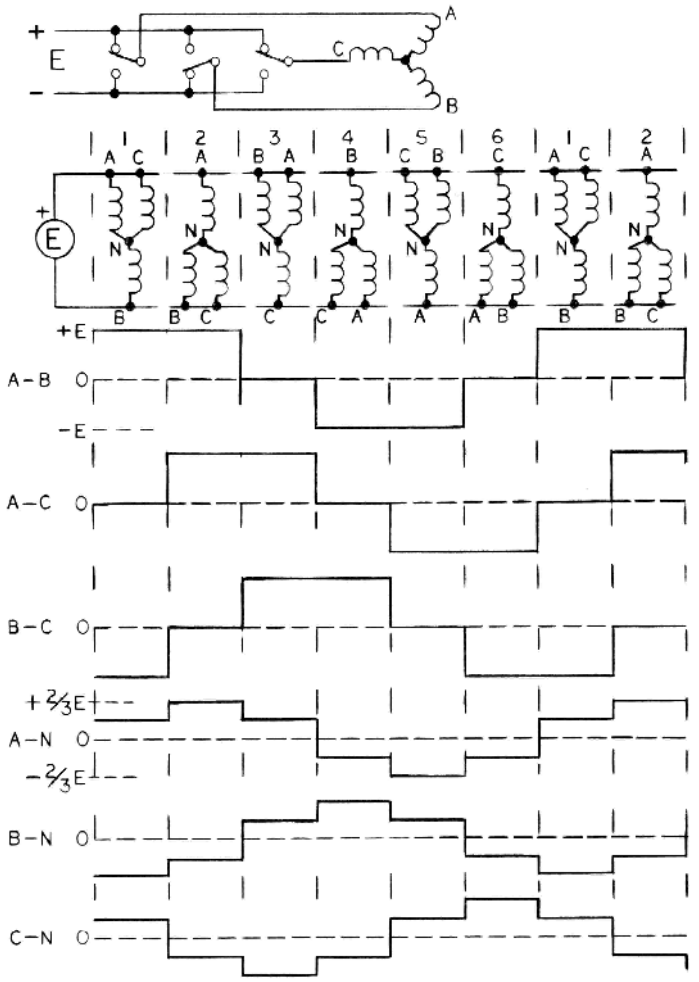


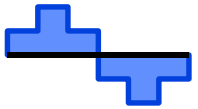
Adjustable Frequency Power Conversion

- Basic Inverter Switching Circuit

The basic inverter switching circuit consists of six switches that are switched in sequence to produce a stepped waveform.

Since there are six steps required to proceed through all of the combinations of switch configurations and six stair steps in the line to neutral voltage waveform, this is called a six-step waveform.



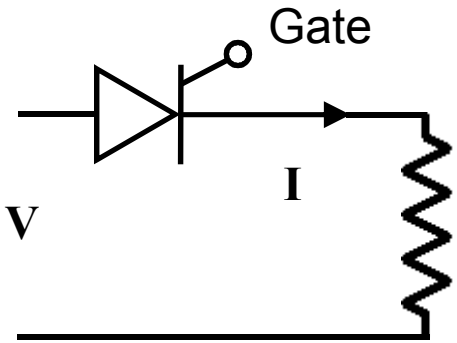


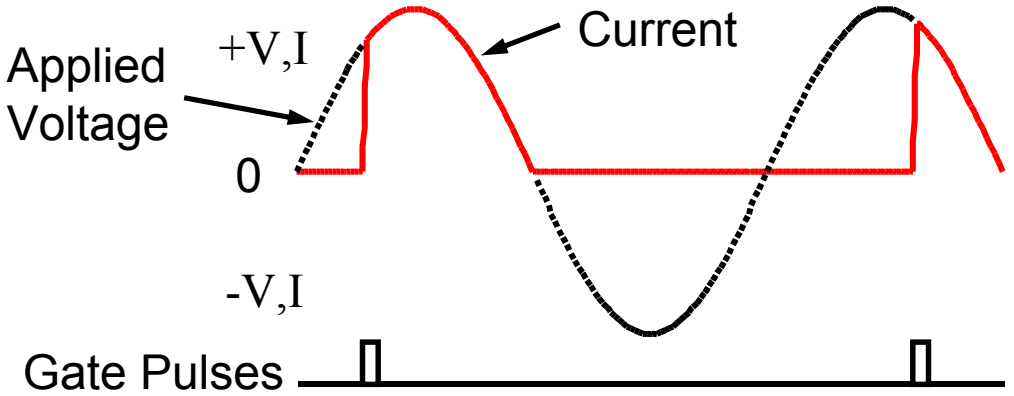
Adjustable Frequency Power Conversion

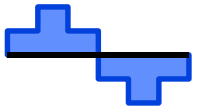
- Switching Devices
  - Thyristors
    - ≡ The transistor was invented in 1947, but early transistors did not have voltage and current ratings suitable for power converter applications.
    - ≡ The first solid state device suitable for power converter applications the thyristor or silicon controlled rectifier (SCR) which was introduced by General Electric in 1957.
    - ≡ The term thyristor is derived from the thyratron vacuum tube which has similar characteristics and had been used in motor control circuits since World War II.

Adjustable Frequency Power Conversion

- Switching Devices
  - Thyristors
    - ≡ The thyristor passes current in only one direction like a rectifier but conducts only after a gate signal has been applied to turn the device on. Therefore it functions as a controlled rectifier.
    - ≡ The SCR can not be turned off by removing the gate signal. It must be turned off or commutated by reversing the applied voltage or diverting the current to another path.

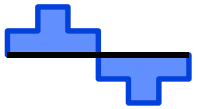






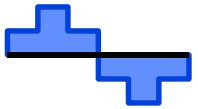
Adjustable Frequency Power Conversion

- Switching Devices
  - Power Transistors
    - ≡ In about 1980, power transistors began to become available in ratings and configurations that made them the preferred switching device for AF drive inverter circuits.



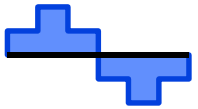
Adjustable Frequency Power Conversion

- Switching Devices
  - Gate Turn-Off Thyristors - GTOs
    - ≡ Although semiconductor manufacturer's efforts to develop GTOs date to the early days of SCRs, transistors displaced SCRs in most applications before GTOs became available in comparable ratings.
    - ≡ Transistors have generally remained the preferred switching device because transistorized inverters have been less expensive to manufacture because support circuitry such as base drives have been less expensive.



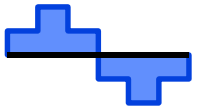
Adjustable Frequency Power Conversion

- Switching Devices
  - Insulated (or isolated) Gate Bipolar Transistors - IGBTs
    - ≡ IGBTs began to take over the AF drive switching device market in about 1988.
    - ≡ IGBTs have enabled substantial reductions in AF drive manufacturing cost.
    - ≡ The low gate current requirement of IGBTs eliminated the base drive circuitry and associated power supplies that had previously been required. This reduced the size and cost of the low voltage control circuitry by 50% or more.
    - ≡ Since IGBTs have very fast switching times, their switching losses are much less than ordinary bipolar transistors. This means that an IGBT drive has a smaller heatsink and cooling fan and the overall drive package is smaller.



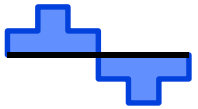
Adjustable Frequency Power Conversion

- Topologies
  - Several power circuit configurations or *topologies* have been used for adjustable frequency drive products.



Adjustable Frequency Power Conversion

- Topologies
  - Inverters and Cyclo Converters
    - ≡ A cyclo converter converts AC power directly into AC power at a different frequency. Cyclo converters have been used for some custom-engineered large drives, but they have never been marketed as a general-purpose product.
    - ≡ An inverter drive is comprised of two stages of power conversion, an AC to DC converter and a DC to AC inverter.

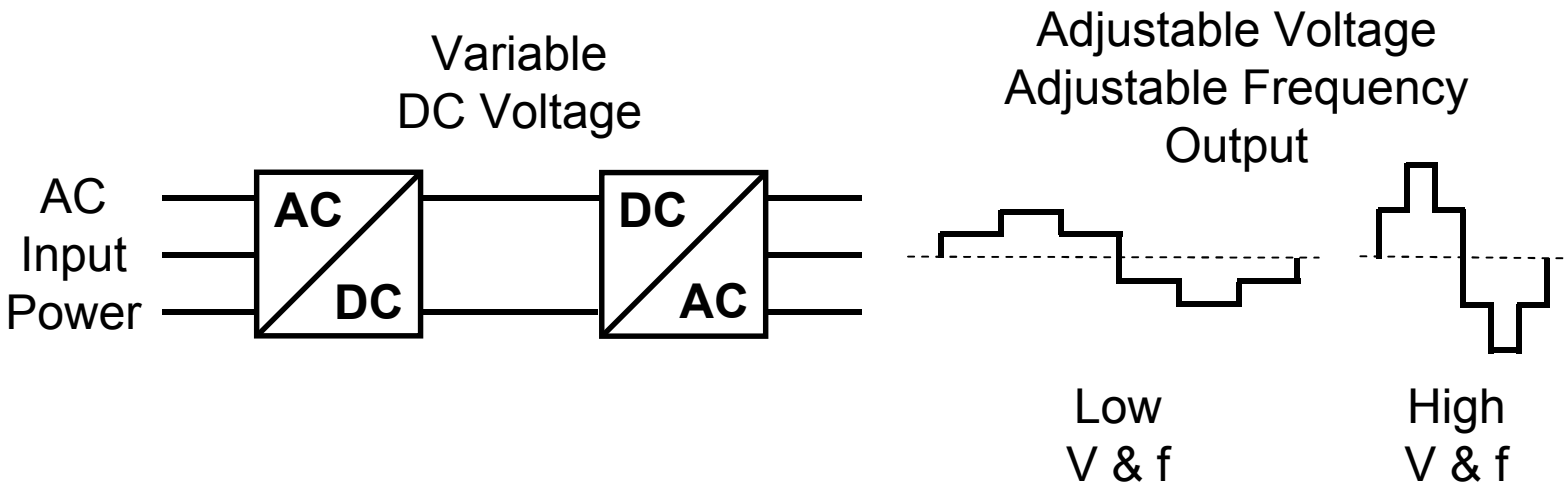


Adjustable Frequency Power Conversion

- Topologies
  - Voltage Source Input (VSI) and Current Source Input (CSI) Inverter Drives
    - ≡ In a VSI drive, the AC to DC power conversion stage, or input stage, is a fixed voltage source or an adjustable voltage source.
    - ≡ In a CSI drive, the input stage is an adjustable current source.

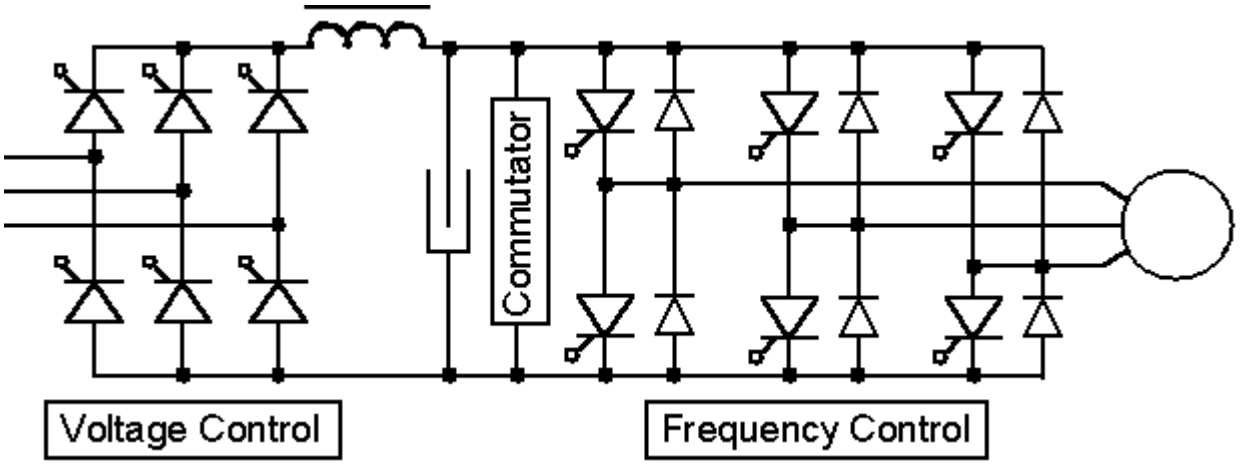
Adjustable Frequency Power Conversion

- Topologies
  - Variable Voltage Input (VVI) Inverter Drives
    - ≡ The first inverter drives used an adjustable voltage AC to DC converter as the input power conversion stage.
    - ≡ The output voltage of the first stage determined the amplitude of the output waveform while the inverter stage determined the output frequency.



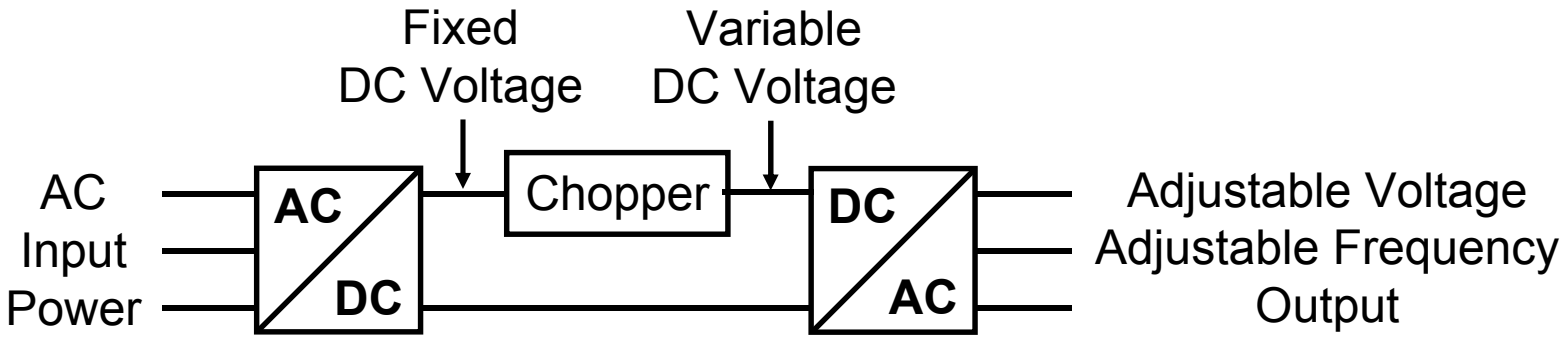
Adjustable Frequency Power Conversion

- Topologies
  - VVI Drive Power Circuit
    - ≡ The VVI converter is an SCR converter similar to the converter used in a DC drive.
    - ≡ An L-C filter is used between the converter and inverter.
    - ≡ The inverter uses either transistors or SCRs with a commutator circuit.
    - ≡ Back diodes in the inverter circuit carry the motor's reactive current.



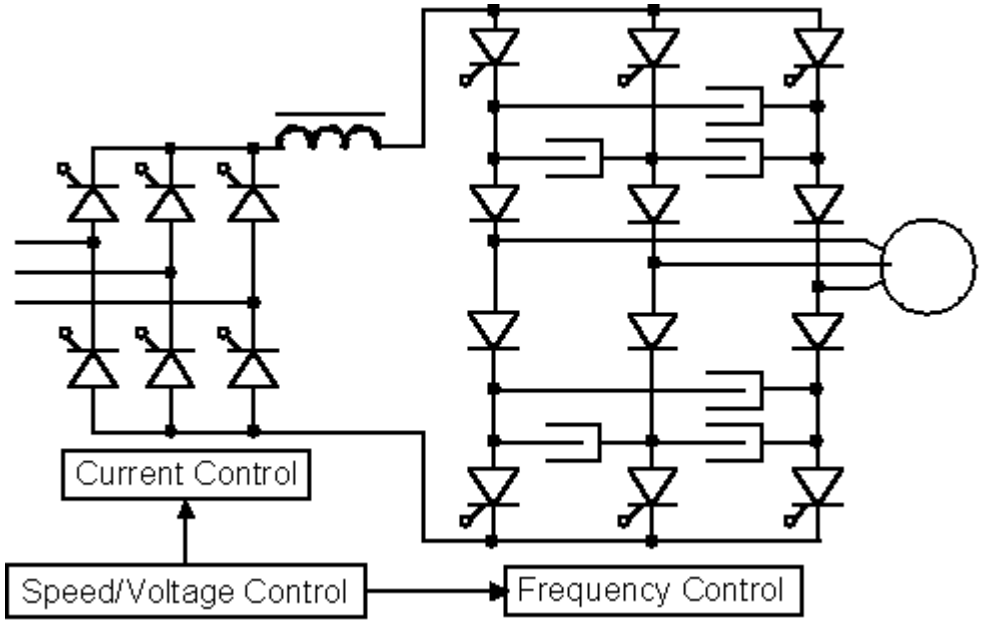
Adjustable Frequency Power Conversion

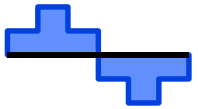
- Topologies
  - Chopper VVI Drive
    - ≡ A chopper VVI drive has a rectifier to convert the AC input to a fixed DC voltage.
    - ≡ A chopper is used to convert the fixed DC to and adjustable DC voltage input to the inverter.
    - ≡ This design has been used in a product design in which the chopper served to commutate the inverter SCRs as well as control the DC voltage input to the inverter.



Adjustable Frequency Power Conversion

- Topologies
  - Current Source Drives
    - ≡ Current source drives use an SCR converter as the first stage, similar to a VVI drive, but the DC filter section consists of a large inductor and no capacitor.



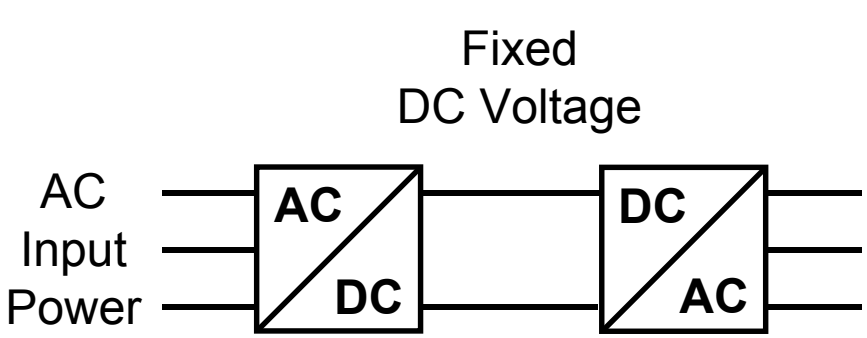


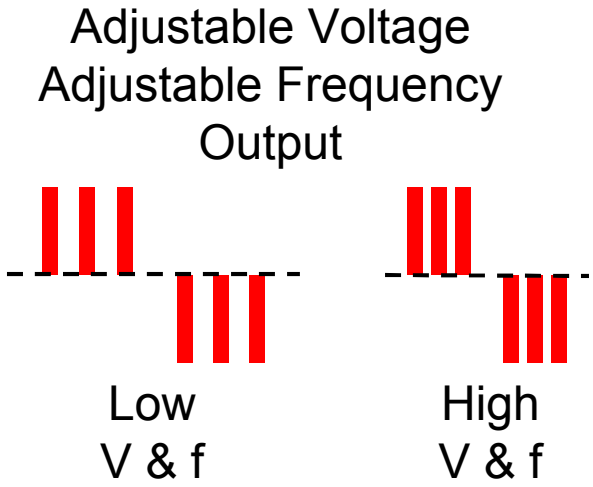
Adjustable Frequency Power Conversion

- Topologies
  - Current Source Drives
    - ≡ The inductance of the filter section and the configuration of the converter's regulator circuit cause the CSI input stage to function as an adjustable current source.
    - ≡ The inverter's regulator is either a speed regulator or an output voltage regulator.Since the CSI inverter circuit functions as a current steering circuit rather than as a voltage switching circuit, an output SCRs is turned off by turning on the next SCR in the sequence and diverting the current to that path.
    - ≡ This eliminates the separate commutation circuit that is used in VSI inverters.
    - ≡ This simplification of the inverter switching circuit seems to have been the primary factor that made the CSI inverter a viable product.
    - ≡ The CSI design has not been used in products with transistors in the inverter stage.

Adjustable Frequency Power Conversion

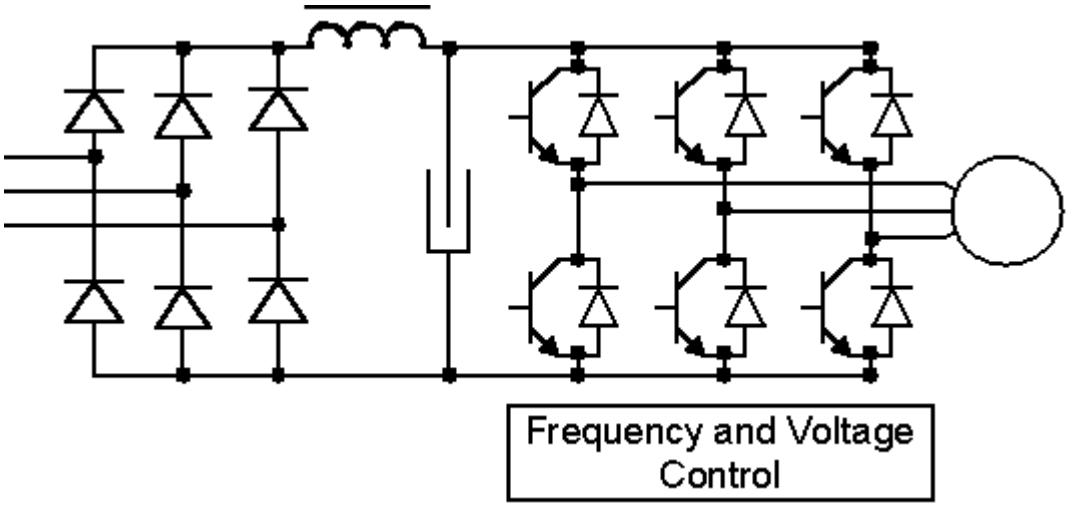
- Topologies
  - Pulse Width Modulated (PWM) Drives
    - ≡ In a PWM drive, a rectifier provides a fixed DC voltage to the inverter stage.
    - ≡ The inverter controls both the voltage and the frequency of the output waveform.
    - ≡ The output voltage is controlled by dividing the basic 6-step waveform into a series of narrow voltage pulses and modulating the width of the pulses.

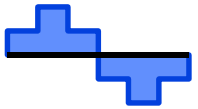




Adjustable Frequency Power Conversion

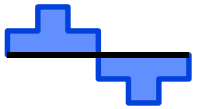
- Topologies
  - Pulse Width Modulated (PWM) Drives
    - ≡ Since the PWM drive uses a diode rectifier as the input power conversion stage, no gate control circuitry is required in that section.
    - ≡ Since the output of a diode rectifier requires less filtering than an SCR converter, the filter uses little or no inductance.





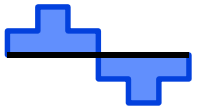
Adjustable Frequency Power Conversion

- Topologies
  - Pulse Width Modulated (PWM) Drives
    - ≡ The PWM output waveform is more complicated to generate than the 6-step waveform, but the cost of that complexity is "only a few lines of code" in the microprocessor.
    - ≡ The use of fast switching IGBT transistors has resulted in PWM drives that are much more efficient and compact than the older topologies.



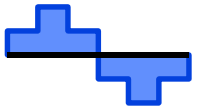
Adjustable Frequency Power Conversion

- Topologies
  - PWM Historical Note
    - ≡ PWM products that used SCRs in the inverter stage were on the market from the late 1960's through the late 1970's.
    - ≡ These designs were produced in anticipation of improved switching devices and advances in integrated circuit technologies.
    - ≡ These advances did not materialize in the time frame or in the way that was originally anticipated, but the early expectations where ultimately fulfilled probably more thoroughly than most people had anticipated.



Adjustable Frequency Power Conversion

- Topologies
  - Other Topologies
    - ≡ Some AF drive products have used inverter circuits that employ more than 3 switches to improve the output waveform or control the output voltage by adding voltage vectors from two or more 3-phase inverter circuits.
    - ≡ Many other topologies have been described in the literature but most have not had substantial implementation in products.
    - ≡ Topologies that have not been manufactured are not necessarily unimportant. In 1979, Exxon purchased Reliance Electric allegedly for the purpose of gaining access to manufacturing facilities for an AF drive topology called the Alternating Current Synthesizer (ACS). Exxon never manufactured the ACS and ultimately sold Reliance.



Adjustable Frequency Drive Control Strategies

- V/Hz Control
  - The drive simply sets the output voltage and frequency.
  - Some performance may be provided by automatically adjusting the output based on a simple estimate of the motor load.
- Sensorless Vector Control
  - Performance is improved by regulating the output based on a mathematical determination of motor characteristics and operating conditions.
  - Operating conditions are estimated from measurements of electrical parameters.
- Vector Control with Encoder Feedback
  - Performance is optimized by regulating the output based on shaft speed and position feedback from an encoder.