National Cheng Kung University

Chapter 1

Fundamental of Electrical Drives

https://www.automationdirect.com/adc/overview/catalog/drives

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Department of Electrical Engineering

Overview of Electrical Drives

History of Electric Drives

Year

< 1950

Before semiconductor devices were introduced

- AC motors for fixed speed applications
- DC motors for variable speed applications

1960s

After semiconductor devices were introduced

- Variable frequency sources available – AC motors in variable speed applications
  - ✓ *Coupling between flux and torque control*
  - ✓ *Application limited to medium performance applications – fans, blowers, compressors – scalar control*
- High performance applications dominated by DC motors – tractions, elevators, servos, etc

1980s

After vector control drives were introduced

- AC motors used in high performance applications – elevators, tractions, servos
- AC motors favorable than DC motors – however control is complex hence expensive
- Cost of microprocessor/semiconductors decreasing –predicted 30 years later AC motors would take over DC motors

What is an AC Drive?

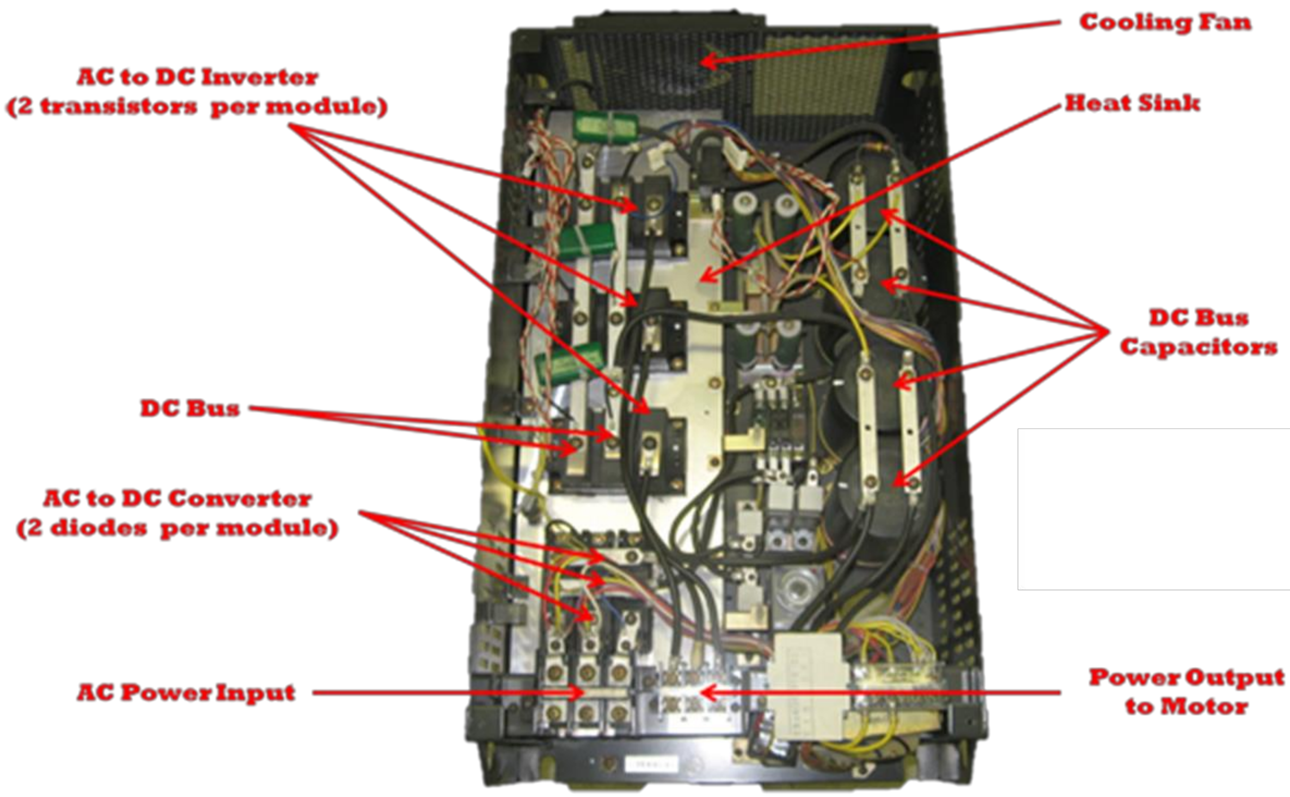
- **A variable-frequency drive (VFD);** also termed adjustable-frequency drive, “variable-voltage/variable-frequency (VVVF) drive”, variable speed drive, **AC drive**, micro drive or inverter drive) is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage.
- VFDs are made in a number of different low- and medium-voltage AC-AC and DC-AC topologies.

Small variable-frequency drive

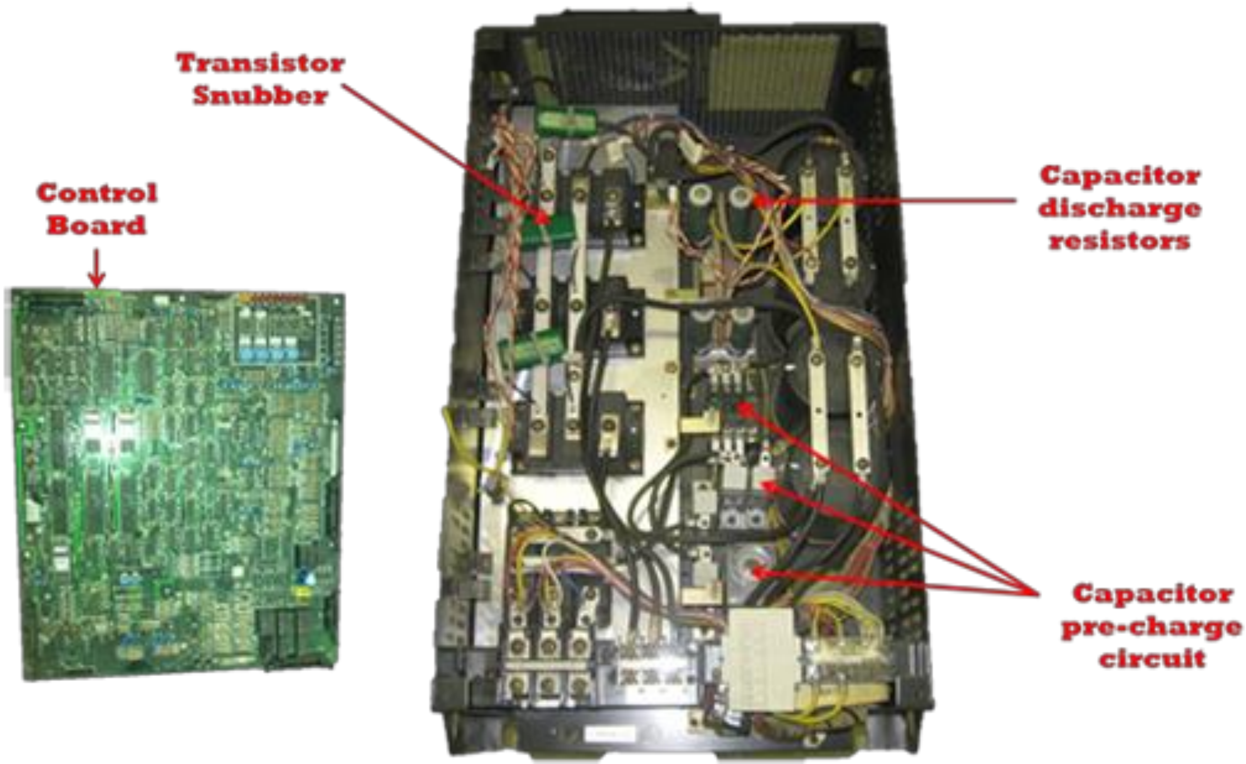
Inside of VFD (cover removed)

- https://en.wikipedia.org/wiki/Variable-frequency_drive

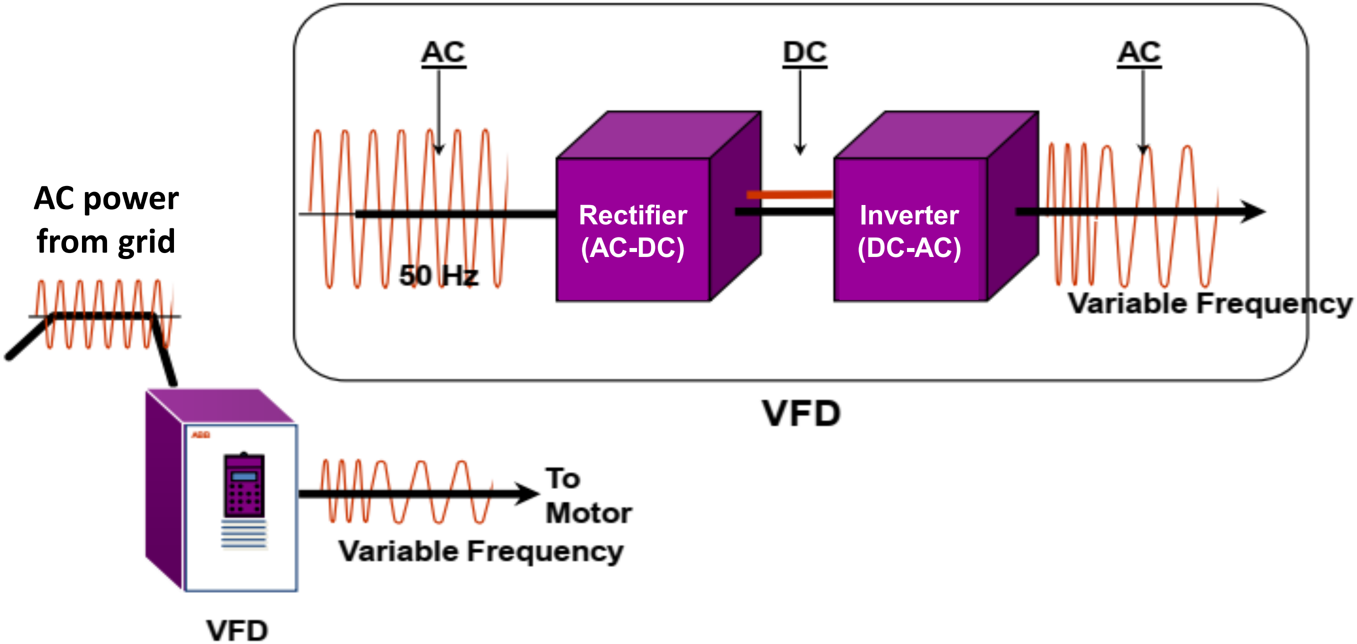
An Actual AC Drive (VFD)



An Actual AC Drive (VFD)



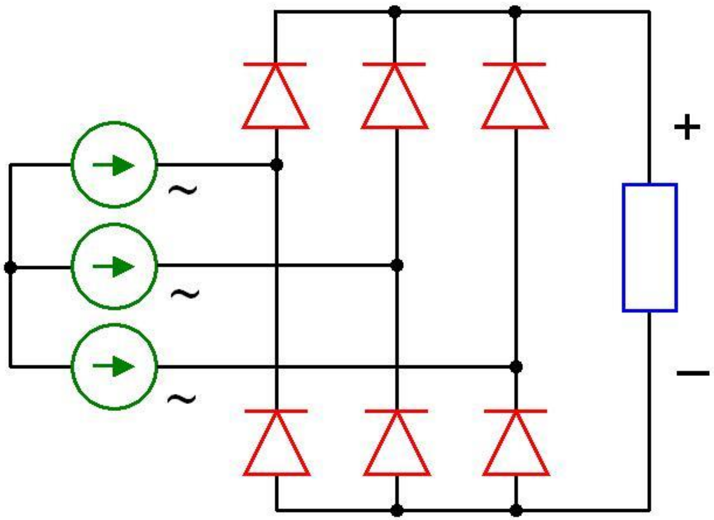
Principle of an AC Drive

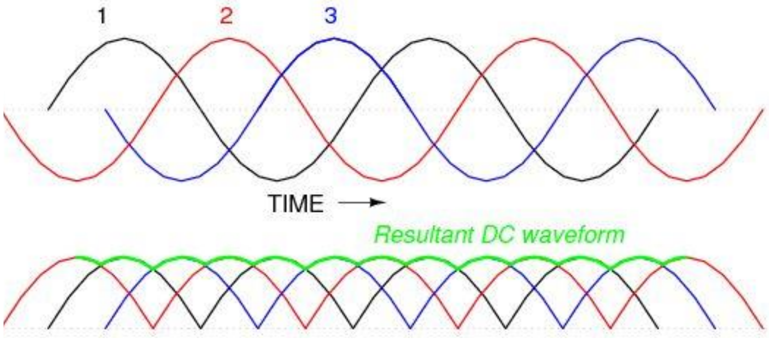


- First, the Converter (usually a diode rectifier) converts three-phase AC power (from grid or generator) to DC power.
- Next, the DC Bus stores and filters the DC power in a large bank of capacitors.
- Last, the Inverter (usually a set of six IGBTs) switches or inverts the DC power in a Pulse Width Modulated (PWM) AC waveform to the motor.

Principle of an AC Drive

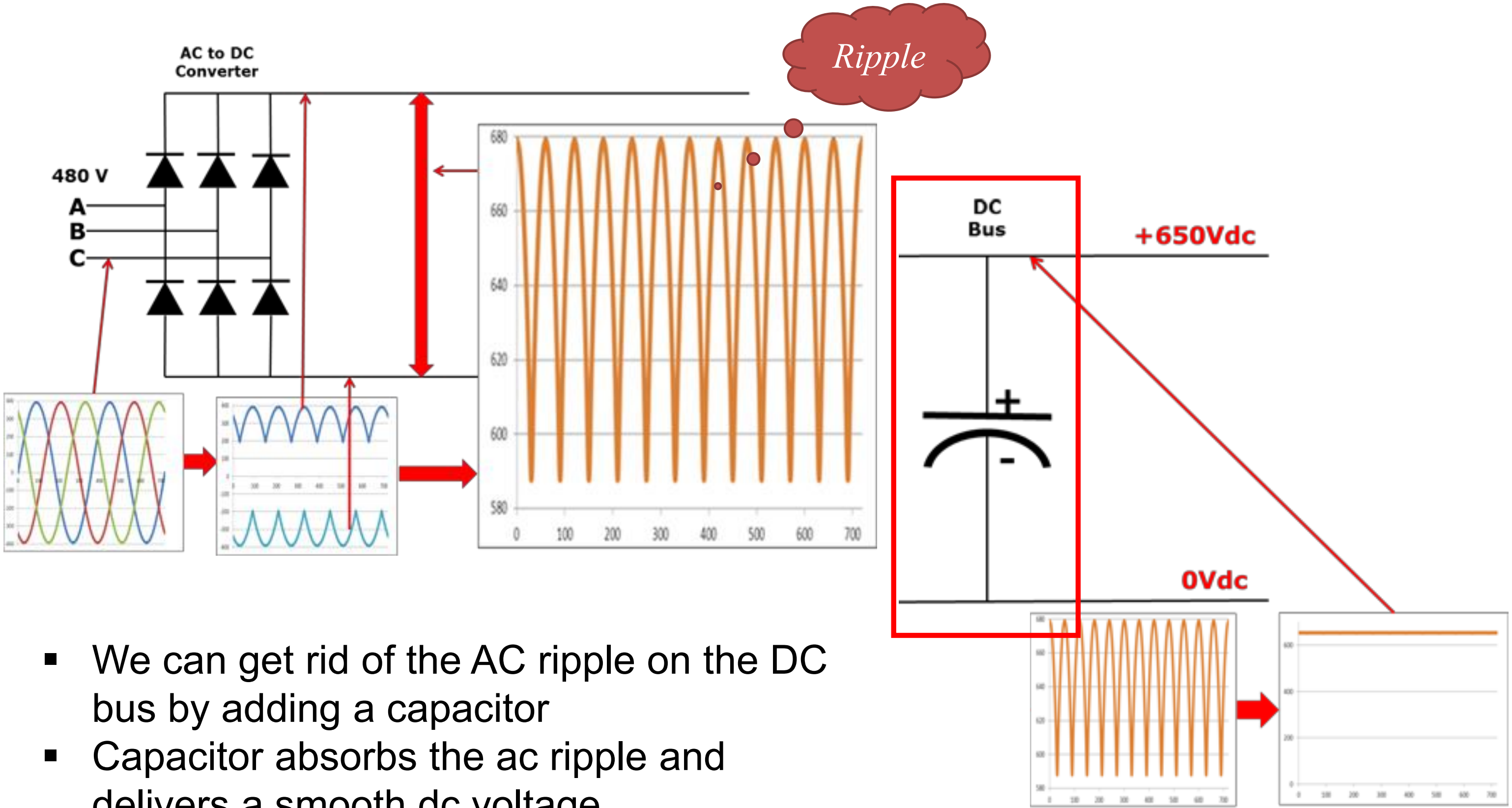
1st Stage: Rectifier





Principle of an AC Drive

2nd Stage: DC Bus

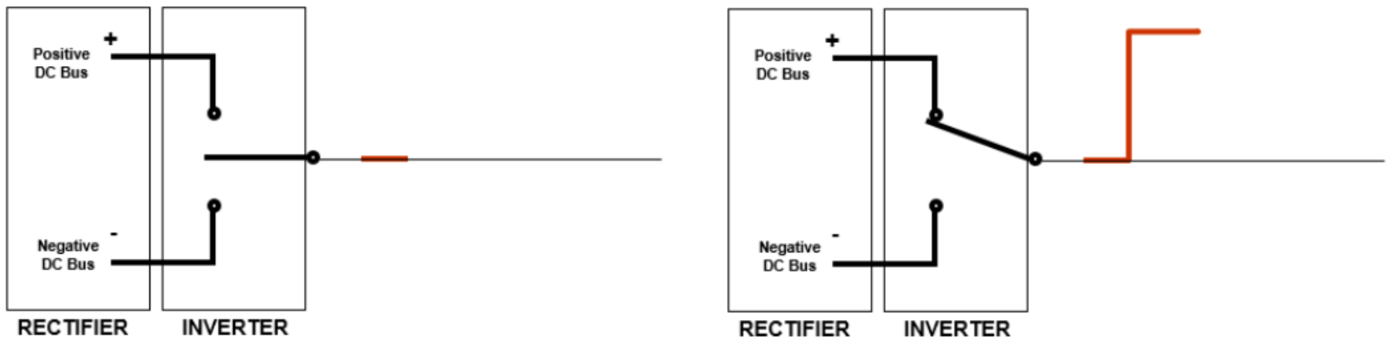


- We can get rid of the AC ripple on the DC bus by adding a capacitor
- Capacitor absorbs the ac ripple and delivers a smooth dc voltage.

Use to eliminate the ripples

Principle of an AC Drive

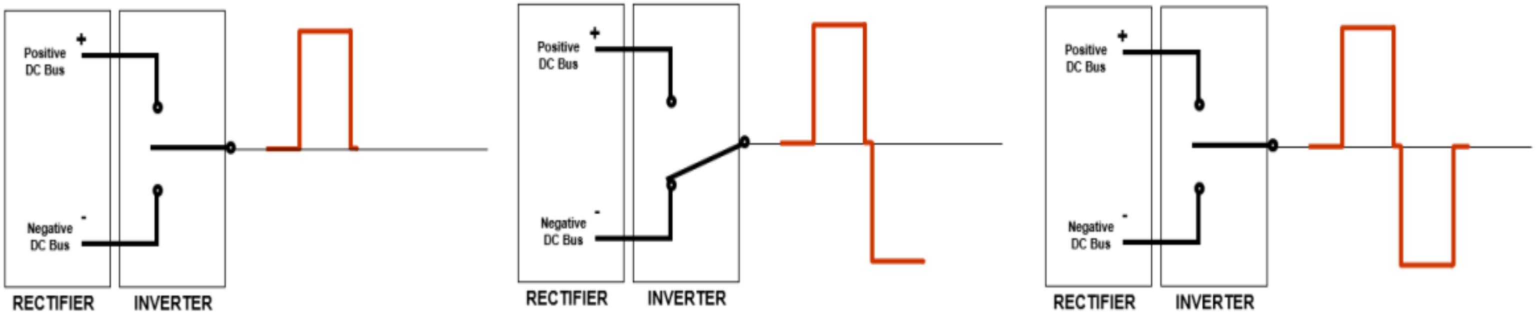
3rd Stage: Switching Sequence for converting DC to AC



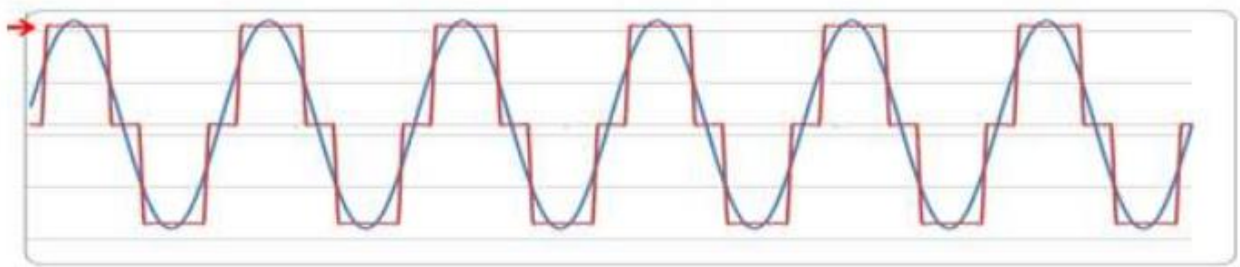
- When we close one of the top switches in the inverter, that phase of the motor is connected to the positive dc bus and the voltage on that phase becomes positive

Principle of an AC Drive

3rd Stage: Switching Sequence for converting DC to AC

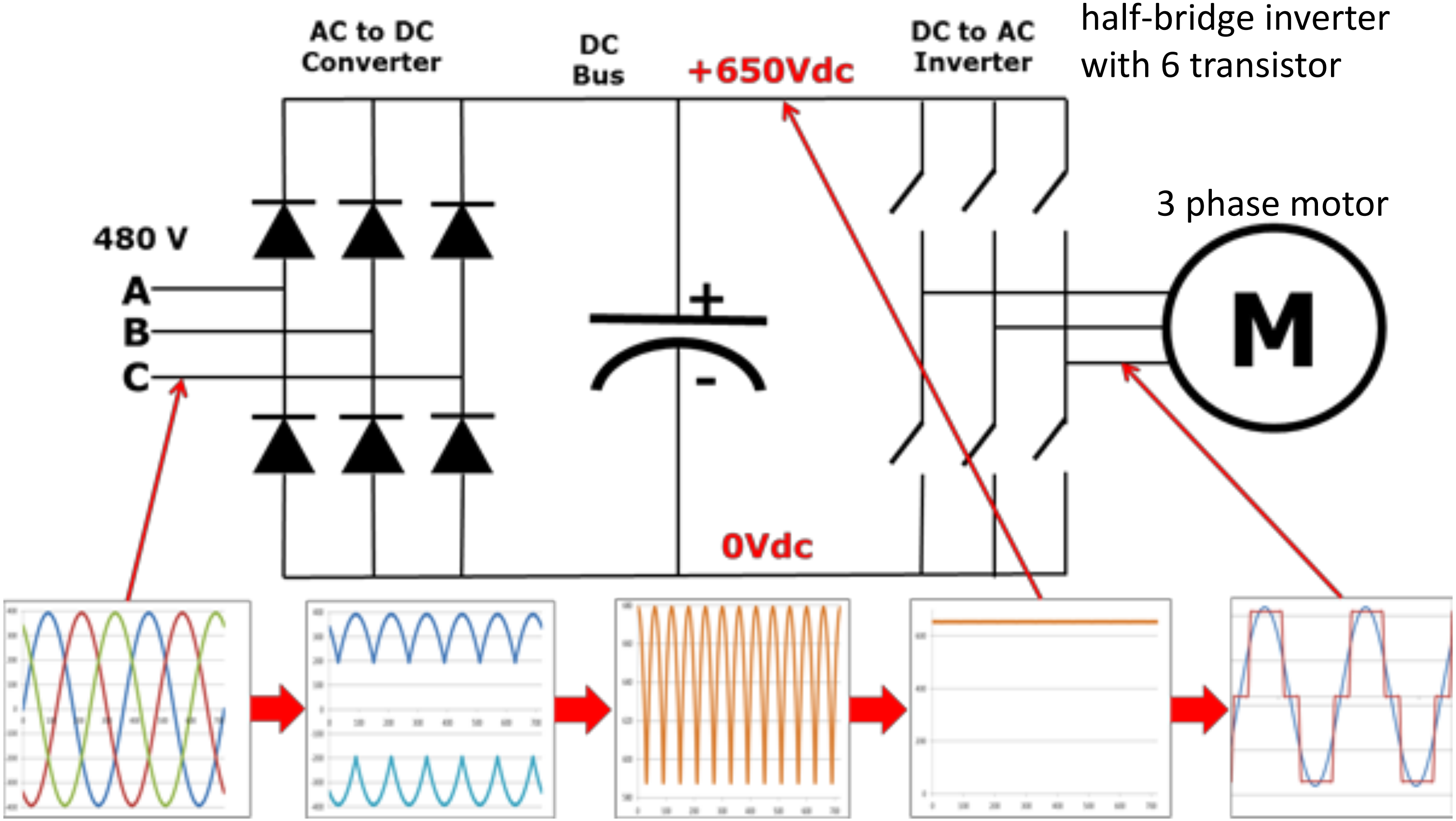


- When we close one of the bottom switches in the converter, that phase is connected to the negative dc bus and becomes negative. Thus, we can make any phase on the motor become positive or negative at will and can thus generate any frequency that we want. So, we can make any phase be positive, negative, or zero.



Principle of an AC Drive

This is a 3-phase half-bridge inverter with 6 transistor

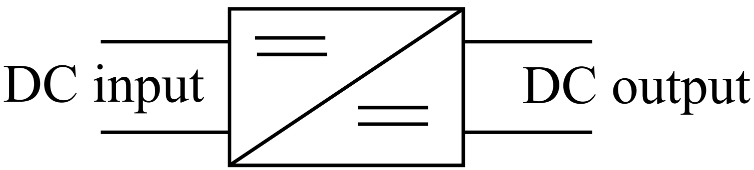


- https://www.vfds.com/blog/what-is-a-vfd

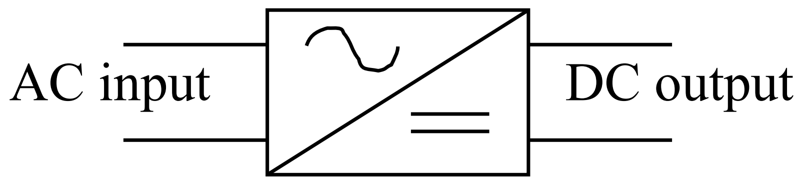
Power Electronic Devices for Motor Drives

Power Electronic Converters for Motor Drives

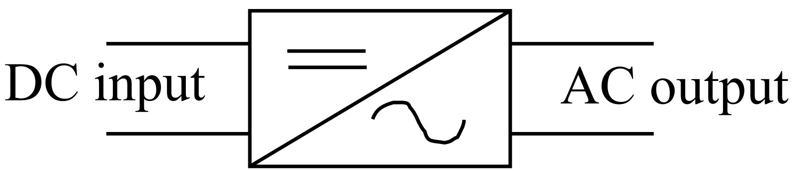
DC to DC: CHOPPER



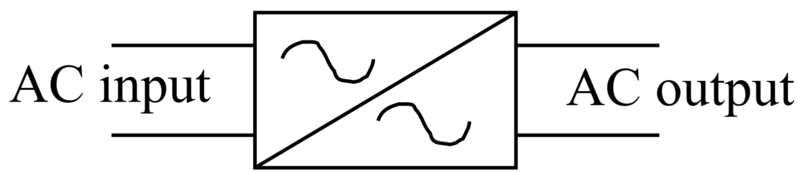
AC to DC: RECTIFIER



DC to AC: INVERTER



AC to AC: CYCLO-CONVERTER



Power Semiconductor Devices

- Power semiconductor devices constitute the heart of modern power electronic apparatus. They are used in power electronic converters in the form of a matrix of on-off switches. and help to convert power from AC-to-DC (rectifier), DC-to-DC (chopper), DC-to-AC (inverter). and AC-to-AC at the same (ac controller) or different frequencies (cycloconverter).

Diode
(Uncontrollable device)
has only two terminals and can not be controlled by control signal.

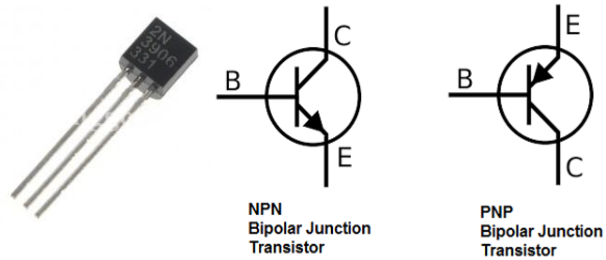
Thyristor or Silicon-Controlled rectifier (SCR)
(Half-controllable device)
is turned-on by a control signal and turned-off by the power circuit.
The on and off states of the device are controlled by control signals

MOSFET, IGBT, BJT, GTO
(Fully-controllable device)
The on and off states of the device are determined by the power circuit.

Fully-controllable devices

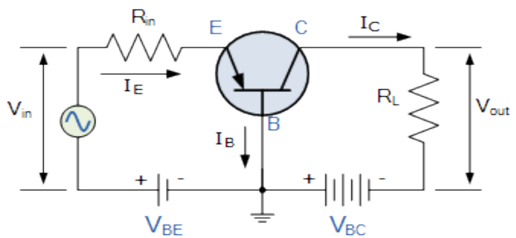
Bipolar Junction Transistors (BJT)

As the **Bipolar Transistor** is a three terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.

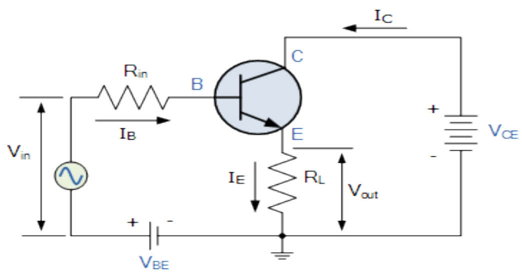


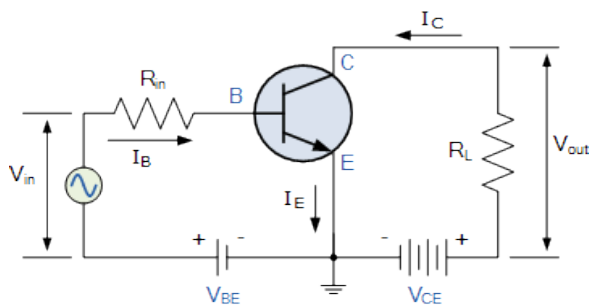
Symbol

Common Base (CB) Transistor Circuit *– has Voltage Gain but no Current Gain.*



Common Collector (CC) Transistor Circuit- *has Current Gain but no Voltage Gain*



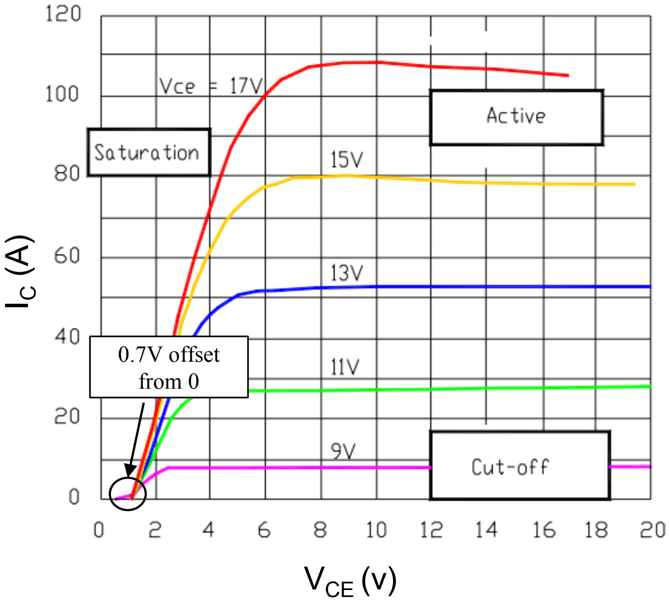


Common Emitter (CE) Amplifier Circuit - *has both Current and Voltage Gain*

Available:
https://www.electronics-tutorials.ws/transistor/tran_1.html

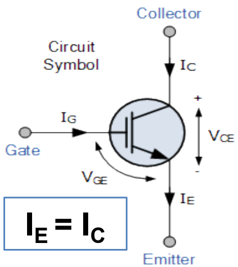
Fully-controllable devices

Insulated Gate Bipolar Transistors (IGBTs)

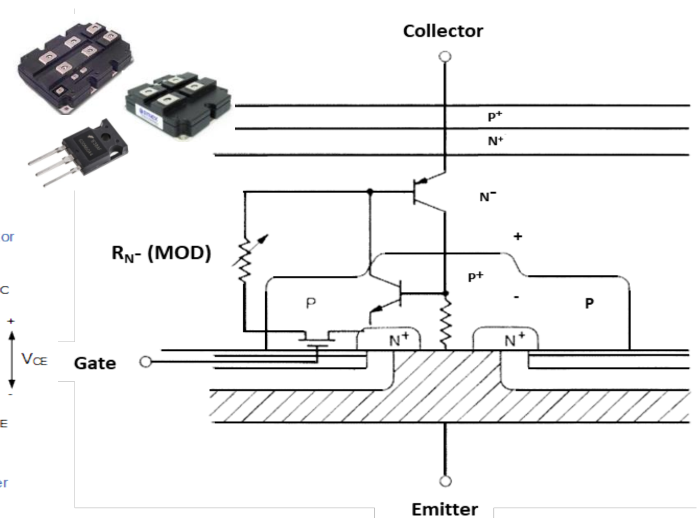


Output I-V characteristics of an NPT-IGBT [IXSH30N60B2D1],

The entire family of curves is translated from the origin by this voltage magnitude. It may be recalled that with a P+ collector, an extra P-N junction has been incorporated in the IGBT structure.



Symbol



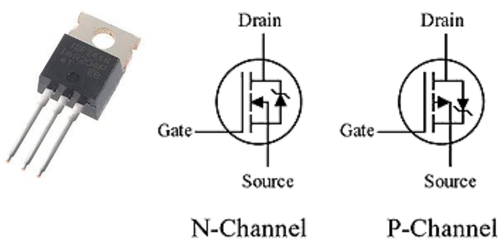
IGBT structure with equivalent circuit

This forward-biases the base-emitter junction of the P-N-P transistor, turning it on and causing conductivity modulation of the N legion. which gives a significant of conduction drop over that of a MOSFET. It is turned-off by reducing the gate voltage to zero or negative, which shuts off the conducting channel in P region.

Fully-controllable devices

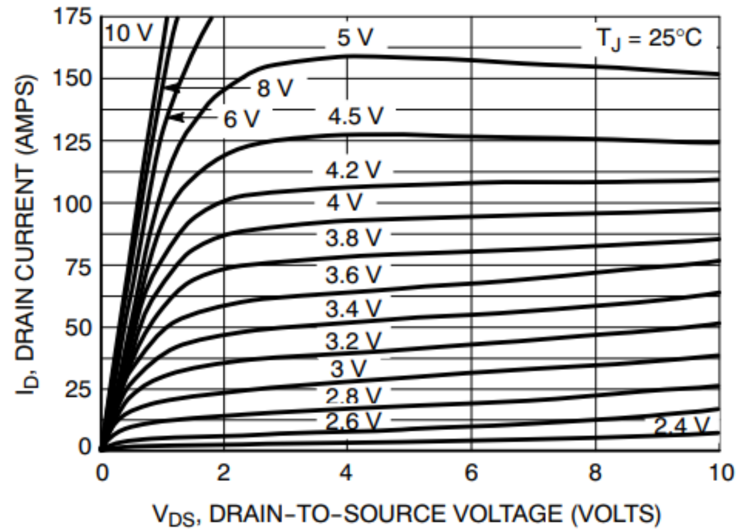
Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

MOSFETs use an electrical field produced by a gate voltage to alter the flow of charge carriers, electrons for n-channel or holes for P-channel, through the semi-conductive drain-source channel. The gate electrode is placed on top of a very thin insulating layer and there are a pair of small n-type regions just under the drain and source electrodes



Symbol

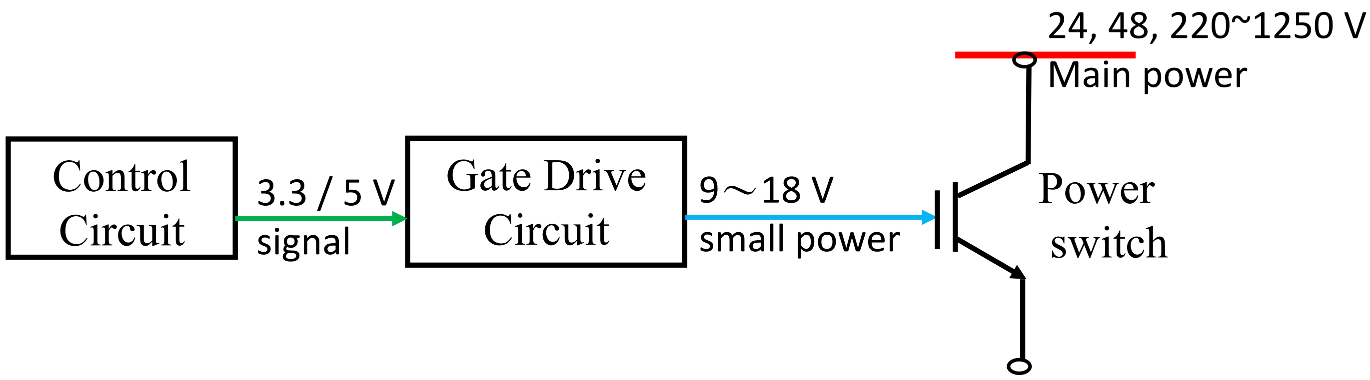
https://www.electronics-tutorials.ws/transistor/tran_6.html



I-V characteristics of an MOSFET [NTD70N033R]

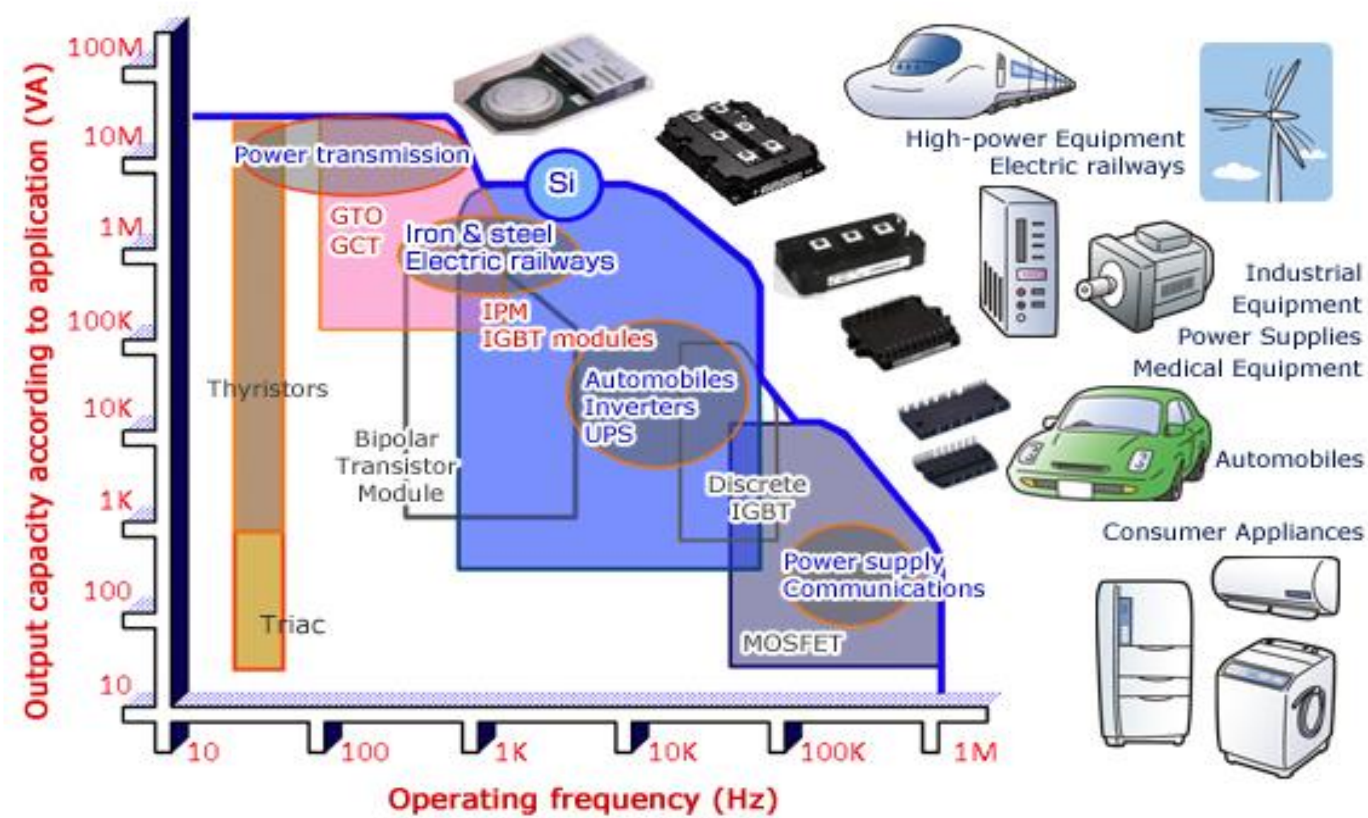
http://www.onsemi.com/pub/Collateral/NTD70N03R-D.PDF

Driver circuit (Base/gate)



- Interface between control (low power electronics) and (high power) switch.
- Functions:
  - **Amplification**: amplifies control signal to a level required to drive power switch
  - **Isolation**: provides electrical isolation between power switch and logic level
- Complexity of driver varies markedly among switches.
  - MOSFET/IGBT drivers are simple
  - BJT drivers are very complicated and expensive.

Comparison and Applications



Currently, the majority of the development in power electronics applied in the area of mid- to high-power conversion is sustained by the evolving IGBT and IPM technologies.

http://www.mitsubishielectric.com/semiconductors/triple_a_plus/technology/01/index.html

Fully-controllable devices

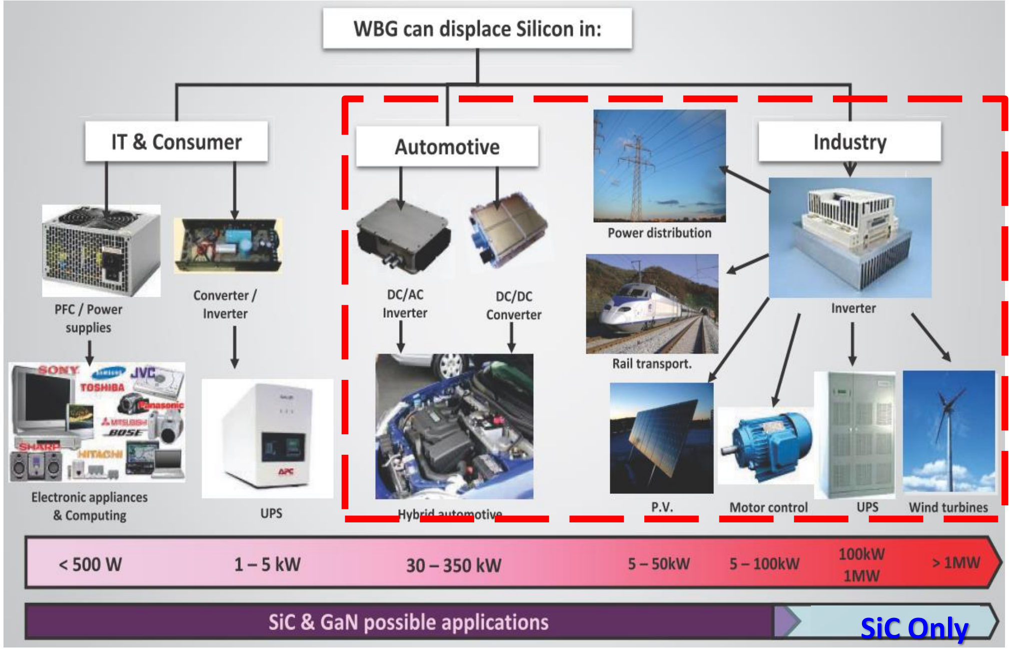
Characteristic	BJT	MOSFET	IGBT	SiC MOSFET
Voltage rating	High <1kV	High <1kV	Very High>1kV	Very High>1kV
Current rating	High	Low	High	Medium
Input Drive	Current h_{FE} 20-200	Voltage V_{GS} 3-10V	Voltage V_{GE} 4-8V	Voltage V_{GS} 15-18V
Input Impedance	Low	High	High	High
Output Impedance	Low	Medium	Low	Low
Switching speed	Slow	Fast	Medium	Very Fast
Cost	Low	Medium	Medium	High

Available: https://www.electronics-tutorials.ws/power/insulated-gate-bipolar-transistor.html

New Power Switch Devices

Wide-band gap (WBG) devices use materials such as silicon carbide (SiC) or gallium nitride (GaN) that are different from silicon-based (Si) compoment and have unique physical paramiter.

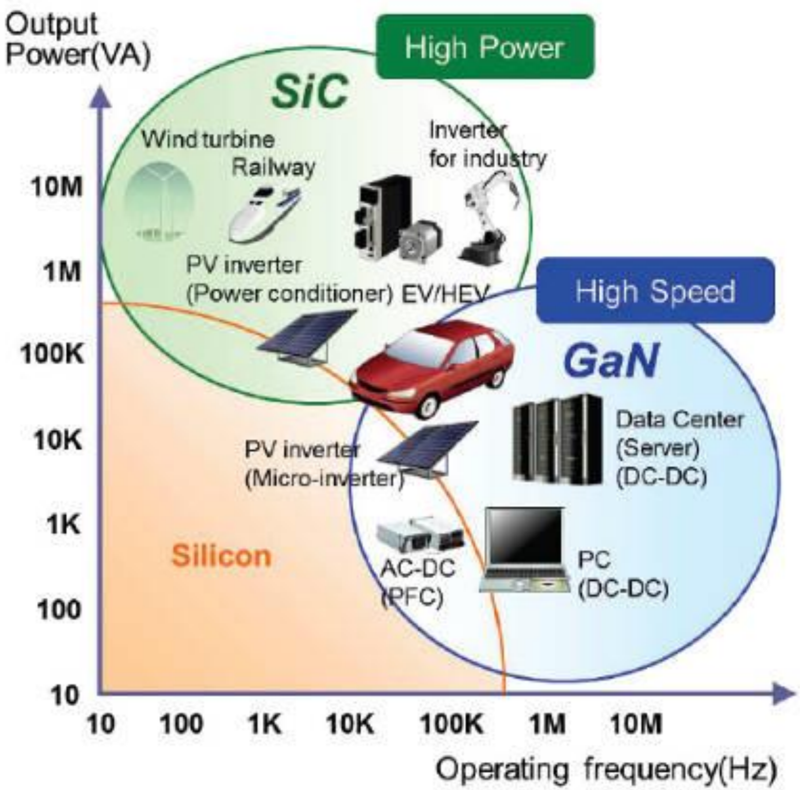
The wide energy gap is characterized by a larger energy difference than Si in the conduction band, enabling them to switch on and off more quickly.



Ref : Yole Développement, Market & Technology trends in Wide BandGap power packaging, 2015

New Power Switch Devices

SiC fits high power demand and higher temperature environment such as motor with built-in drives for electric vehicles and applications.



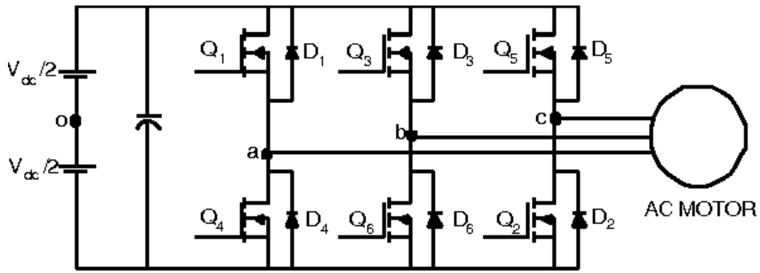
SiC for high power voltages (>1kV) with high current = niche market

GaN on Si for high frequency at midrange voltages (<1kV, up to 100A) = mass market

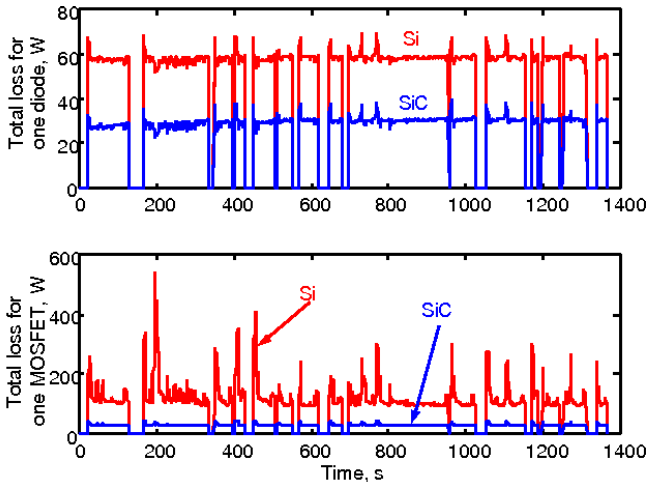
https://uk.tek.com/blog/look-back-apec-thoughts-gan-products

New Power Switch Devices

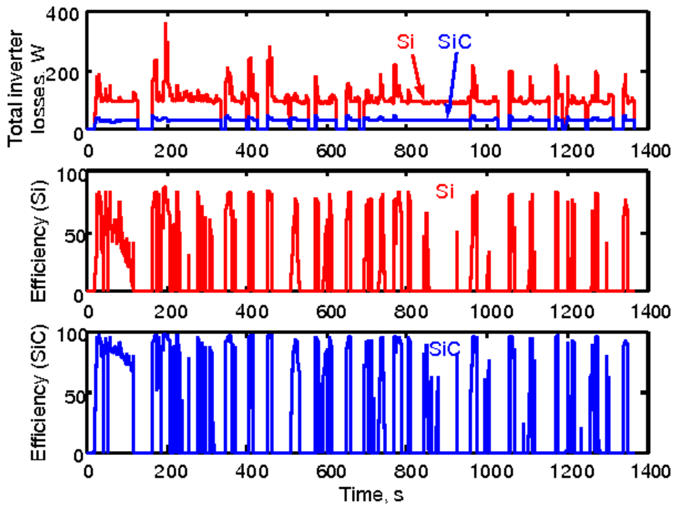
Example: Effect of Silicon Carbide (SiC) Power Devices



*Burak Ozpineci, Leon M. Tolbert, Syed Kamrul Islam, "**Effects of Silicon Carbide (SiC) Power Devices on HEV PWM Inverter Losses",** 27th Annual Conference of the IEEE Industrial Electronics Society , 2001*



Total losses of each MOSFET and diode over the FUDS cycle (Sired, top, and 4H-SiC-blue)

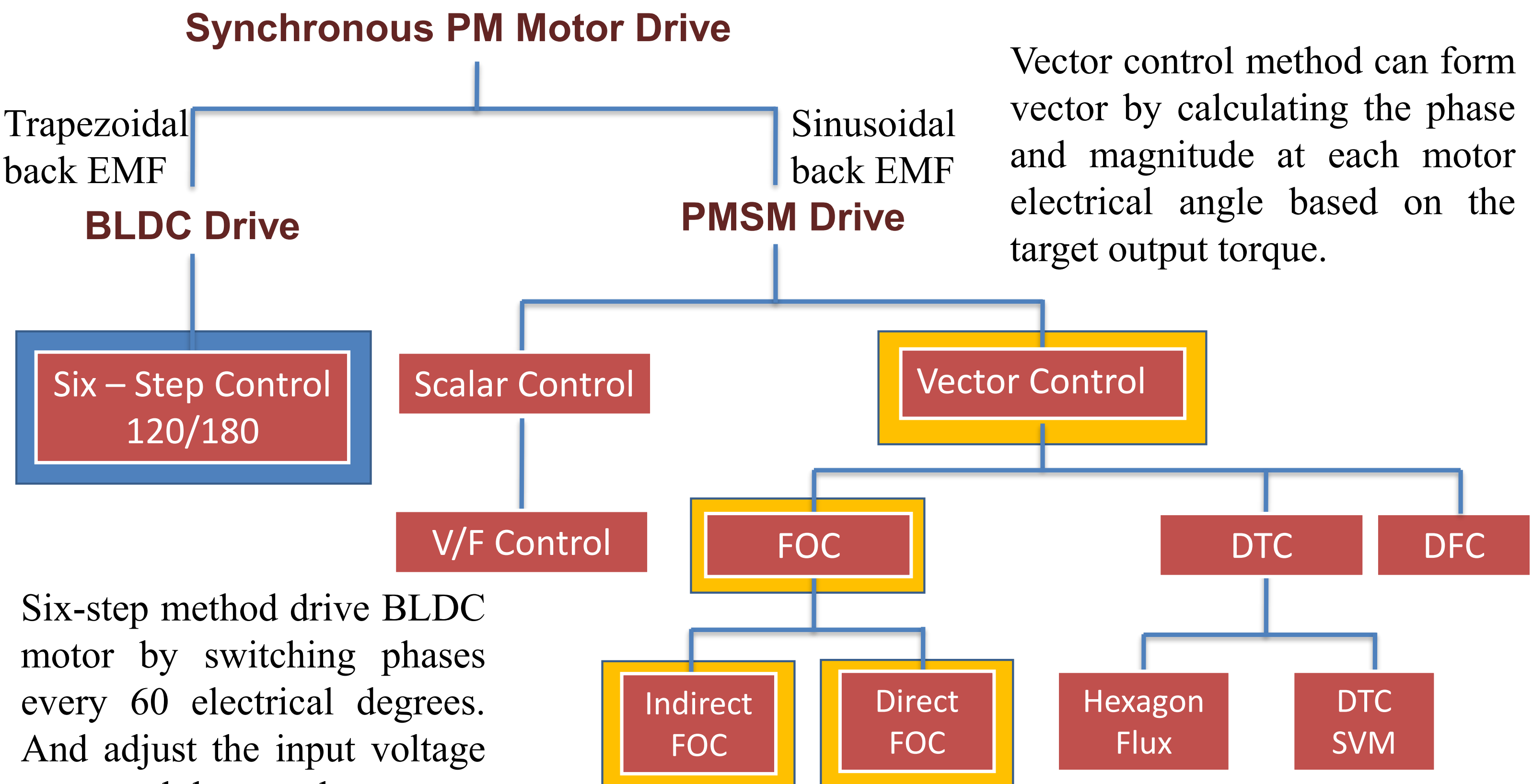


Total losses and the efficiency of the inverter over the FUDS cycle (Si-red, top, and 4H-SiC-blue)

Motor control method and drive circuit

Motor control method

Brushless motor controls the steering, speed, and torque by adjusting the voltage combination of each phase in the drive circuit.

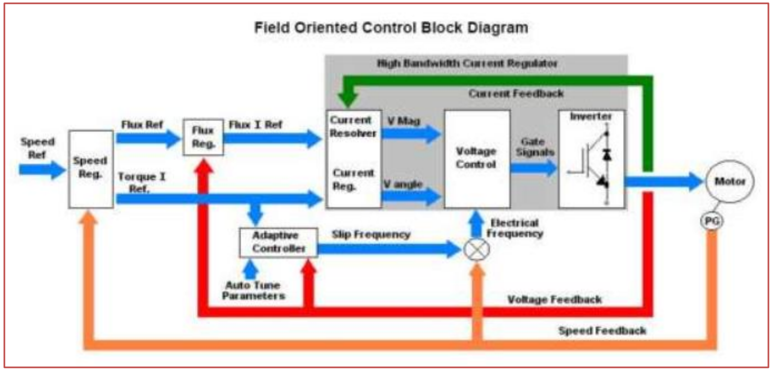


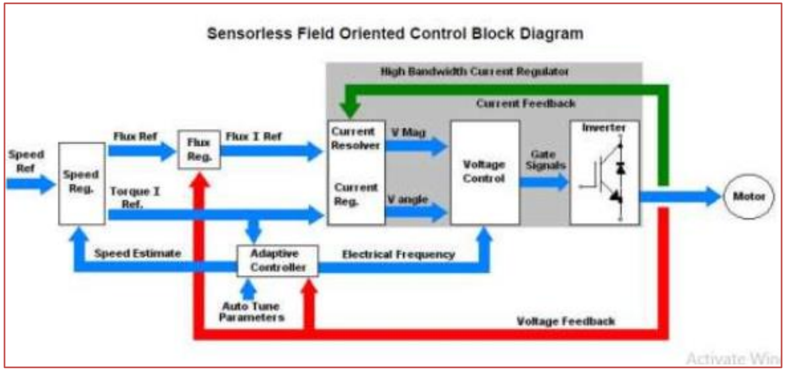
Vector control method can form vector by calculating the phase and magnitude at each motor electrical angle based on the target output torque.

Six-step method drive BLDC motor by switching phases every 60 electrical degrees. And adjust the input voltage to control the speed.

Field Oriented Control (FOC)

- More Accurate than V/f Control.
- There are 2 types
  - Sensored FOC
  - Sensorless FOC



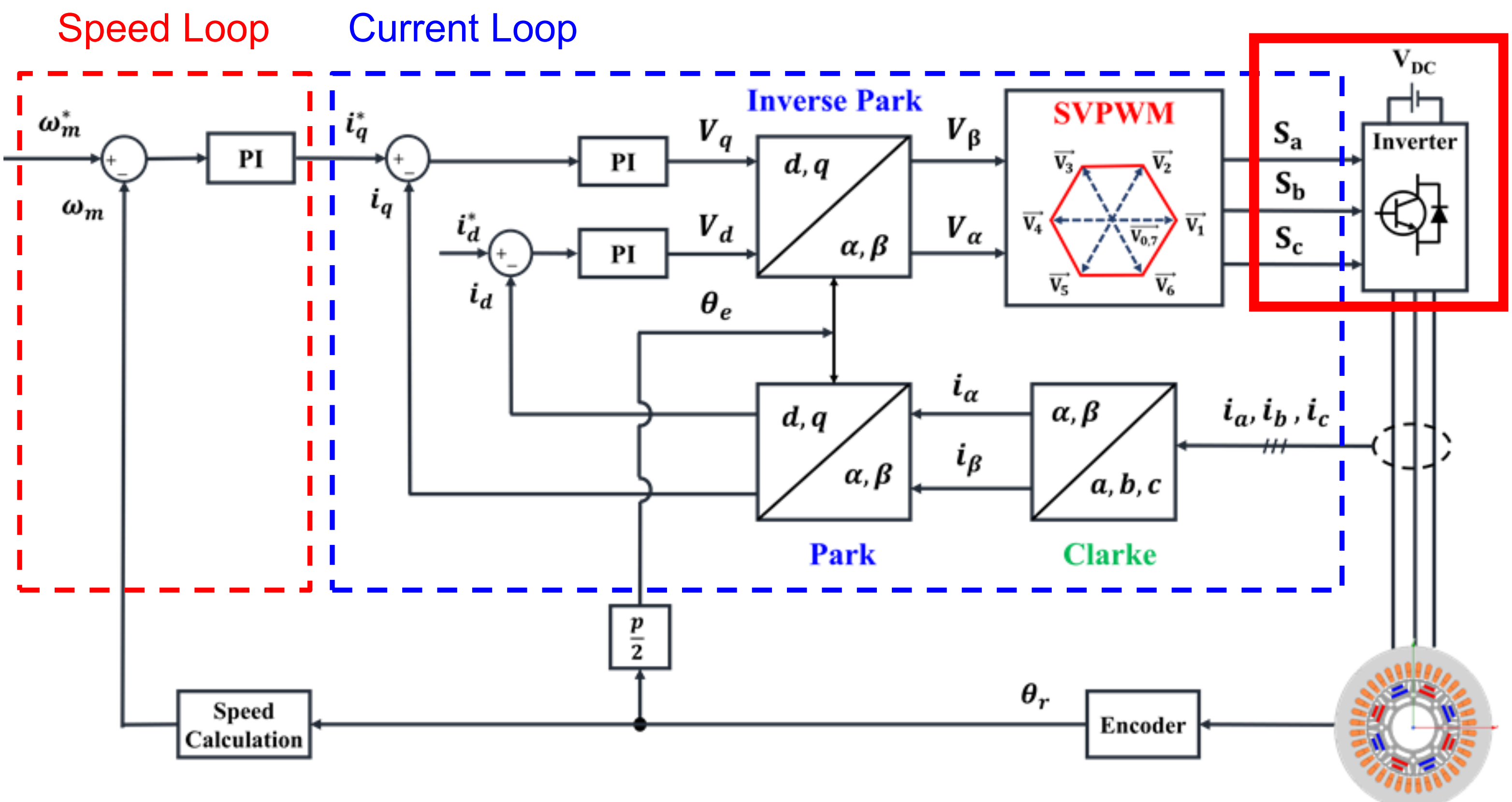


- Feedback through position sensor
- Better speed regulations up to 0.01%
- Faster response to load variations

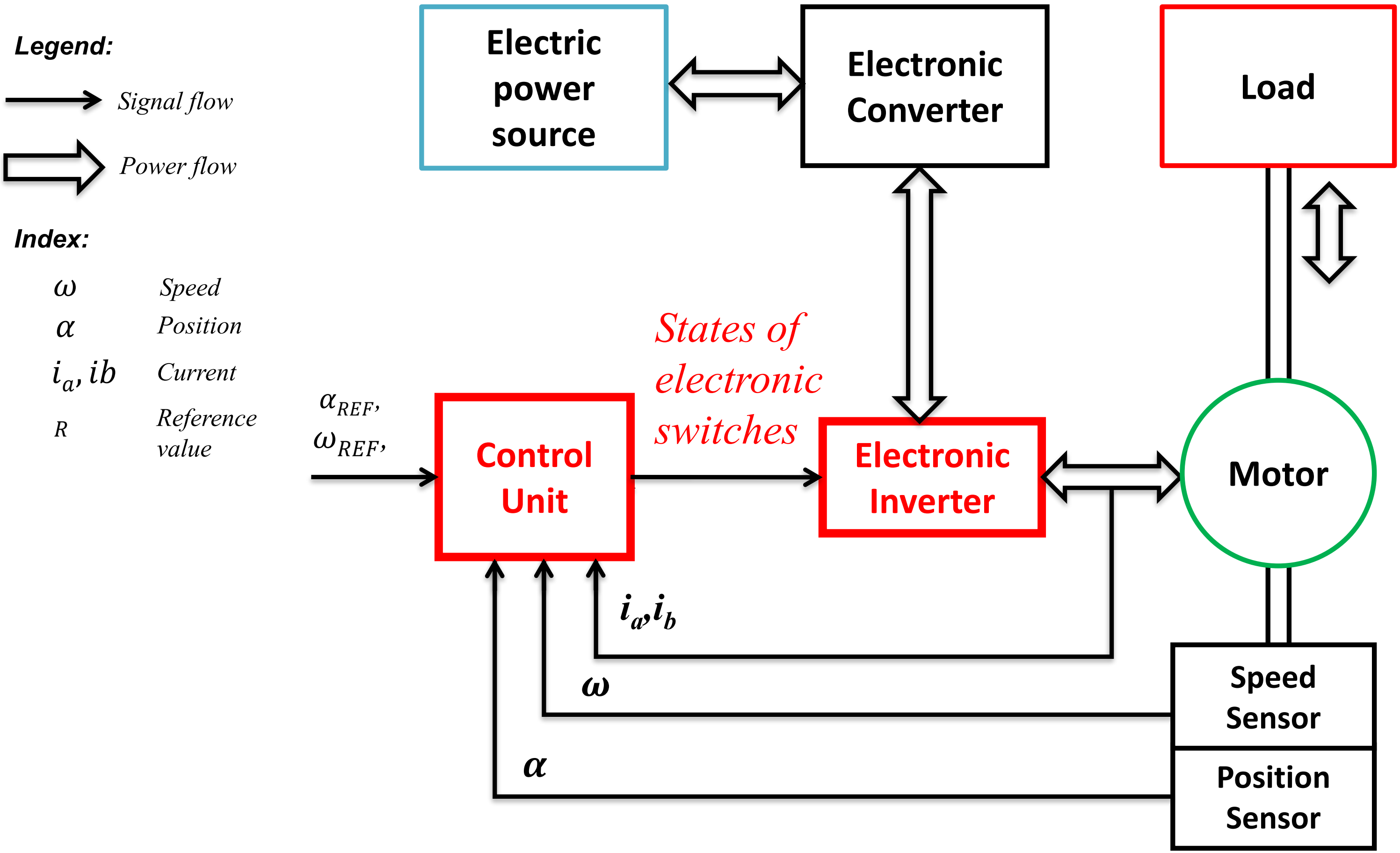
- No feedback through position sensor
- Feedback is derived through motor terminals
- Drive need to go through “Auto tuning”

Control Architecture of FOC for PMSM

The motor drive circuit is the INVERTER part on the right side of the control block figure below. Which receives switch commands and transmits energy to the motor.



Modern Electric Drive



Pulse Width Modulation

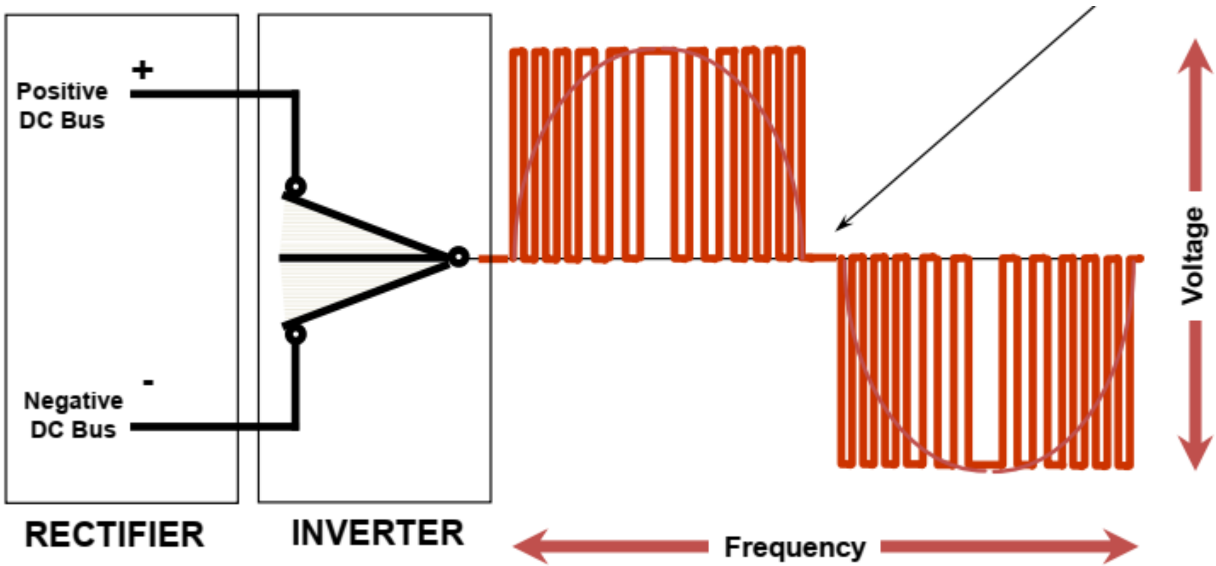
Pulse-Width Modulation (PWM)

- The electrical converter and inverter blocks on the previous page are used to control the high voltage output with digital signals.
- When they work, DC voltage for power is continuously switched by the transistor with control signal, and the voltage transfer to a series of square wave pulses.
- By controlling the proportion of the turn-on-time of the pulse, called the duty ratio, its output can be adjusted as the equivalent voltage during long-term operation.
- This method is called **pulse width modulation (PWM)**, where the pulse has switching frequency, and width is the length of time that square wave is on refer to duty.

Pulse-Width Modulation (PWM)

Pulse Width Modulation

How often you switch from positive pulses to negative pulses determines the frequency of the waveform



Pulse-Width Modulation (PWM)

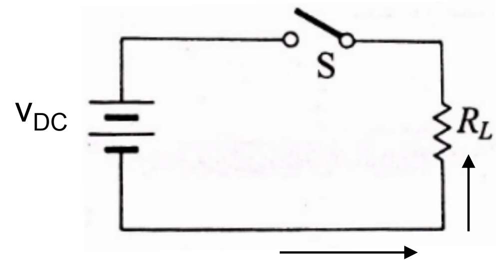
- The basic principle of PWM can be stated that under constant supply voltage V_{DC}, when voltage is applied to the resistance load in pulses. The instantaneous output voltage v_0 is determined:

$$V_0 = \frac{T_{ON}}{T_{ON} + T_{OFF}} V_{DC}$$

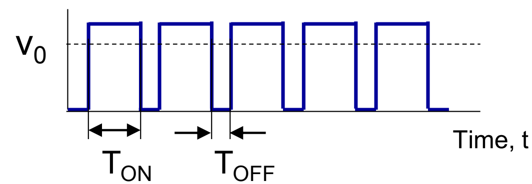
- The voltage applied to the load can thus be changed using the time duty-cycle ratio

$$w = \frac{T_{ON}}{T_{ON} + T_{OFF}}$$

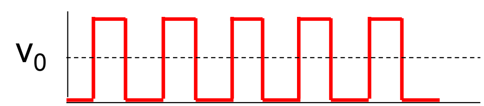
Pulses with fixed frequency and magnitude but variable width



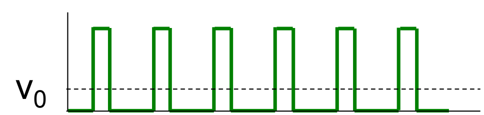
V_0 (Instantaneous voltage)



Large time ratio



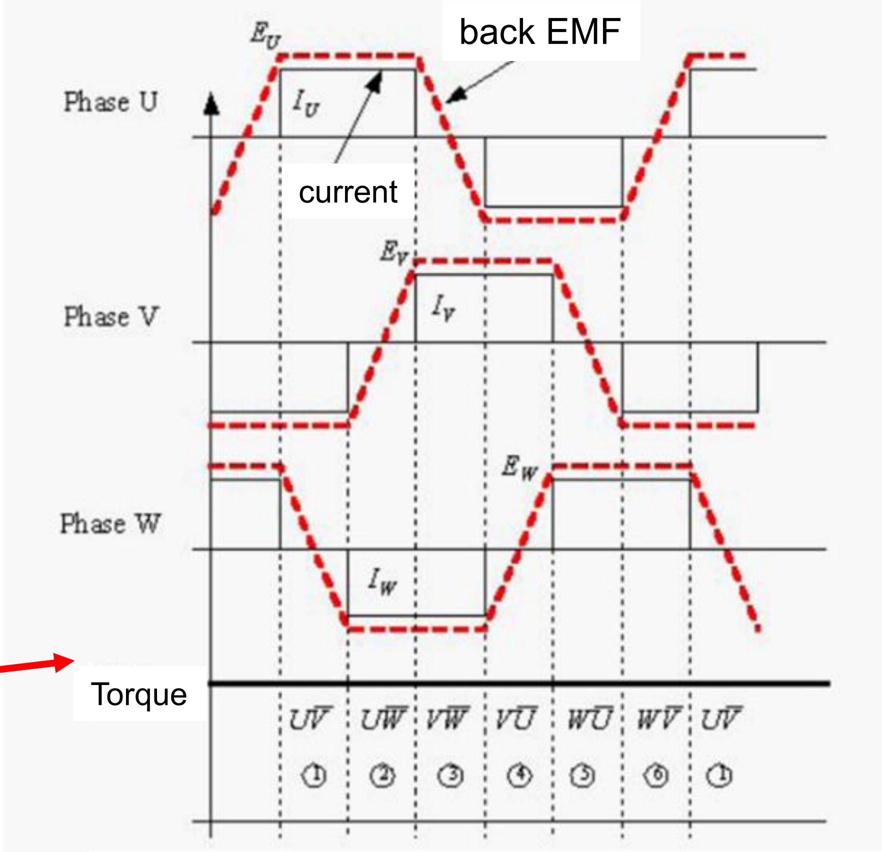
Medium time ratio



Small time ratio

Brushless DC (BLDC) Drive

Trapezoidal back EMF

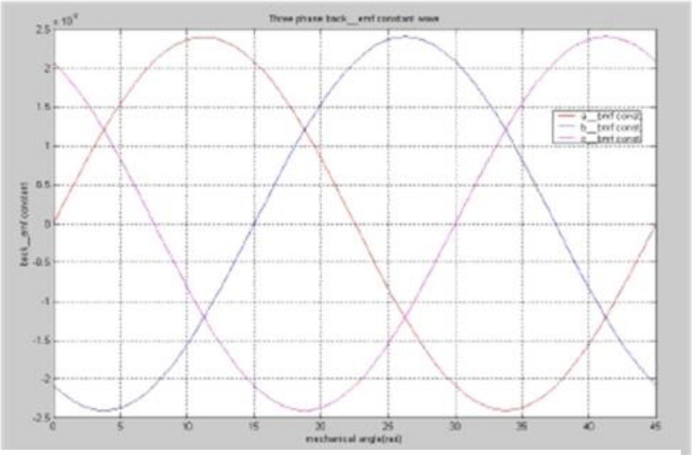


Ideal condition

$$T = k_{E_U}.i_U + k_{E_V}.i_V + k_{E_W}.i_W$$
$$= 2K_E I$$

Sinusoidal drive for PMSM (Sinusoidal)

Sinusoidal back EMF



$$T = k_{eA}.i_A + k_{eB}.i_B + k_{eC}.i_C$$

$$= K_e.\sin\theta.I\sin\theta +$$

$$K_e.\sin(\theta - 120^0).I\sin(\theta - 120^0) +$$

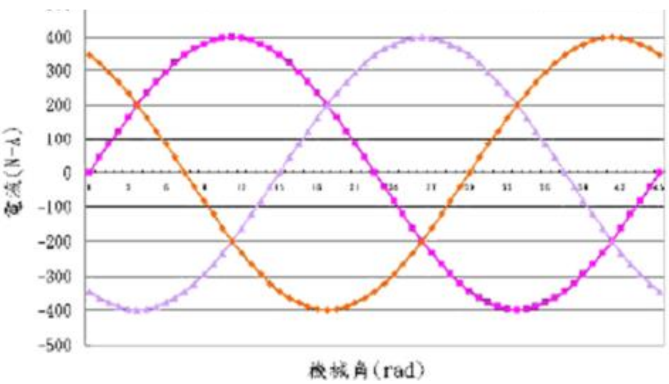
$$K_e.\sin(\theta + 120^0).I\sin(\theta + 120^0)$$

$$= K_e.\mathrm{I}.\{sin\theta^2 + sin^2(\theta - 120^0)$$

$$+sin^2(\theta + 120^0)\}$$

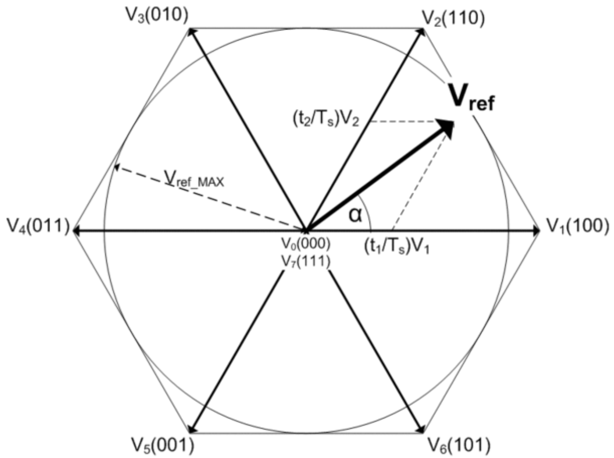
$$=\frac{3}{2}K_e\mathrm{I}$$

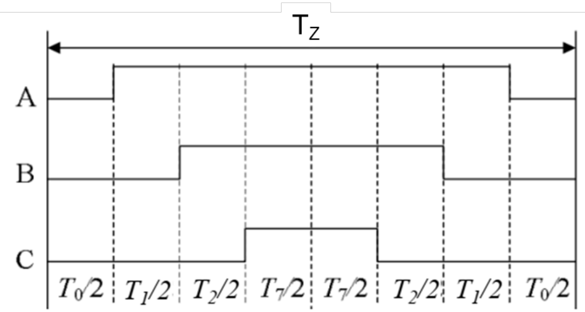
Three-phase sinusoidal wave current

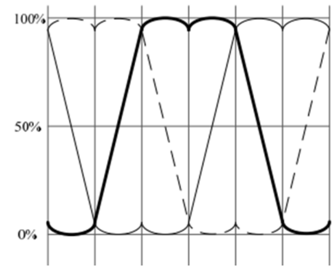


Space Vector PWM (SVPWM)

- Space vector modulation (SVM) is an algorithm for the control of pulse width modulation (PWM). It is used for the creation of alternating current (AC) waveforms; most commonly to drive 3 phase AC powered motors at varying speeds from DC using multiple class-D amplifiers. There are variations of SVM that result in different quality and computational requirements. One active area of development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to these algorithms.







- https://en.wikipedia.org/wiki/Space_vector_modulati