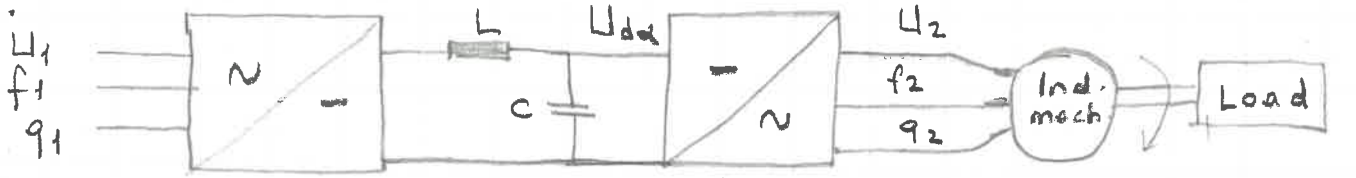
DC-AC CONVERTERS (INVERTERS)

Switch mode dc to ac inverters are used in ac motor drives and uninterruptible ac power supplies where the objective is to produce a sinosoidal ac output whose magnitude and frequency can both be controlled.

This is important for adjustable speed control of ac drives. In order not to decrease torque capability of ac drives, we must keep $\frac{V}{f}$ rate constant. For this reason we must have the ability to change both voltage and frequency simultaneously.

Let me look over different structures for adjustable ac drives with chronological approach

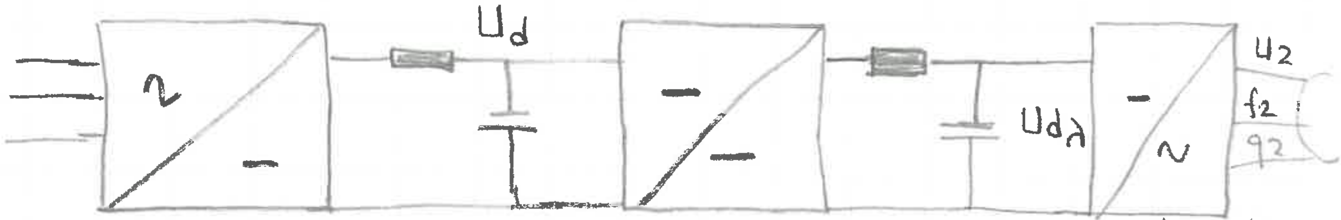
1.



Controlled Rec (α)   Inverter $U_2 / U_{d\alpha}$ = constant

- Higher harmonic distortion
- Higher reactive power consumption
- Voltage is controlled via controlled rectifier
  Frequency is " via inverter

2.



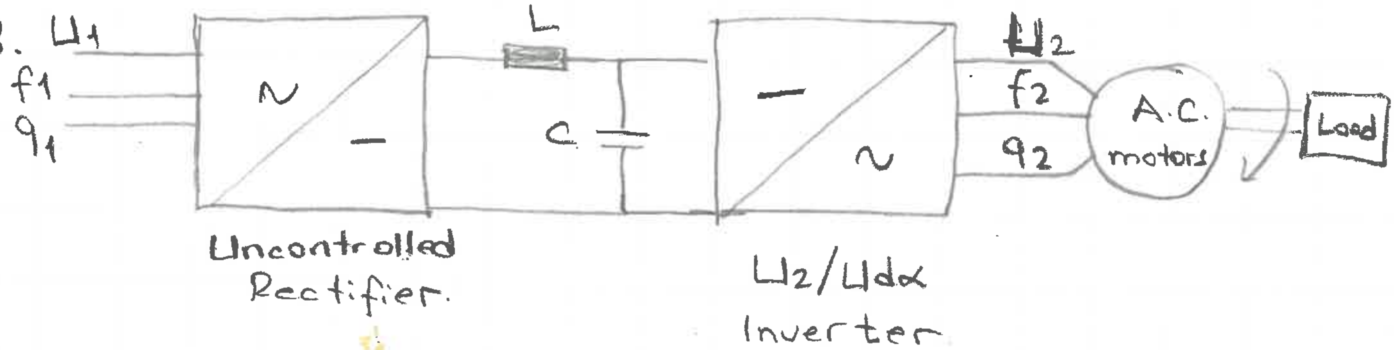
Uncontrolled Rectifier   DC. chopper (λ)   Inverter U_2/U_{d2} = const

$\alpha = 0$

- Lower harmonic distortion
- Lower reactive power consumption
- Higher cost

- Voltage is adjusted via dc chopper
  Frequency is adjusted via inverter.

3.



* Lower cost
* Lower harmonic distortion
* " reactive power consumption
* Both voltage and frequency are adjusted via inverter
* thanks to PWM control method, output voltage wave is close to sinusoidal wave.

There are different types dc-ac converters based on some parameters

1. For supply source
   a). voltage source inverters
   b) Current " "

2. According to the number of phases
   a) Single phase
   b) Three phase

3 According to control method
   a) Rectangular wave inverter
   b) Partial rectangular wave inverter
   c) PWM inverter

d) According to circuit structure of single phase inverter

a) Half bridge inverter

b) Full bridge inverter

c) push-pull inverter

SINOSOIDAL PWM

In inverter circuits, the PWM is a bit more complex. why? we would like to the inverter output to be sinusoidal with magnitude and frequency controllable.

In order to produce a sinusoidal output voltage waveform at the desired frequency; a sinusoidal control signal at desired frequency is compared with a triangular waveform.

The frequency of the triangular waveform establishes the inverter switching frequency fs and is kept constant along with it's amplitude Vtri.

fs is also called the carrier frequency.

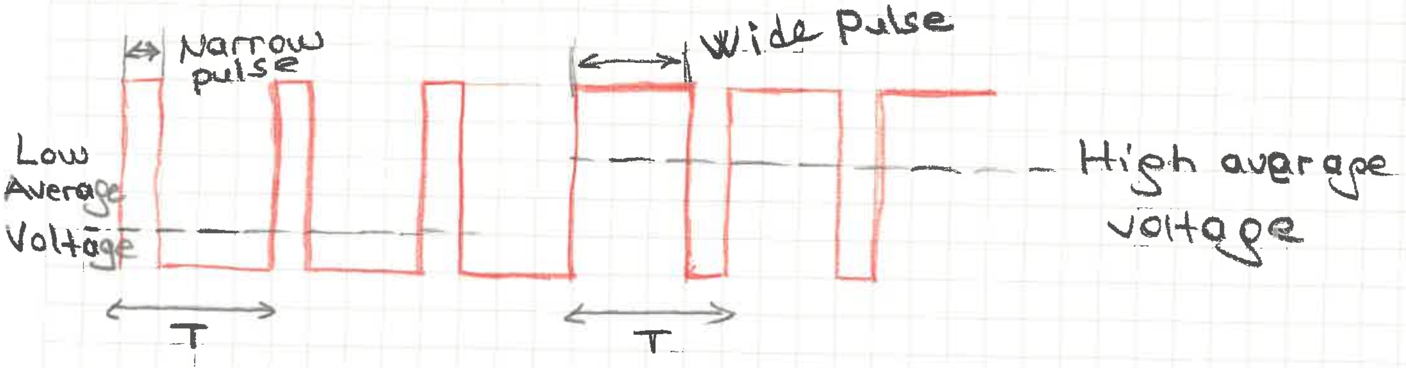
The control signal Vcontrol is used to modulate the switch duty ratio. It has f1 frequency which is the desired fundamental frequency of the inverter voltage output.

It is recognized that the inverter output voltage will not be perfect sinosiodal wave and will contain voltage components at harmonic frequencies of f1.

PULSE-WIDTH MODULATION

Pulse-width modulation is a powerful technique for controlling analog circuits with a controller's digital outputs. In many applications such as from communication to power control PWM is used widely. It is a modulation process with a series on and off pulses and varying duty cycle.

From the point of motor control, the power to be applied to the motor can be controlled by varying voltage at motor terminals. The voltage is controlled by changing the timing of there pulses.



The longer the pulse is on, the faster the motor will rotate. The shorter the pulse is on, the slower the motor will rotate.

In other approach, the wider pulse width, the more average voltage is applied to motor terminals in order to increase magnetic flux level.

Frequency Modulation Ratio (Mf)

$$M_f = \frac{f_s}{f_1}$$

f_s = frequency of carrier signal

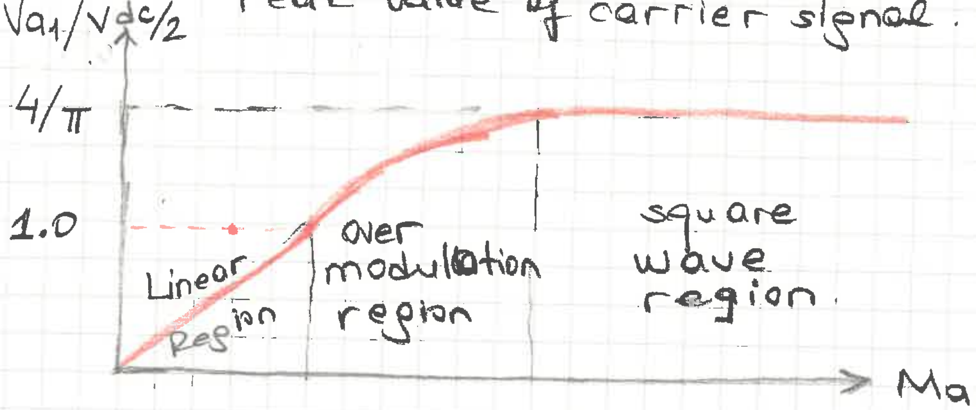
f_1 = frequency of control signal

Important Issues for Mf

* Mf must be integer (otherwise harmonic content will be higher).
* If Mf is equal to three and its triples like 6, 9, ... 3. harmonic will be eleminated in line values (not phase voltage)
* Mf value is increased, harmonic reduces to lower values. But in this case, since switching frequency increases, the switching power losses will be higher. For this reason, an optimisation prosess is needed seriously.

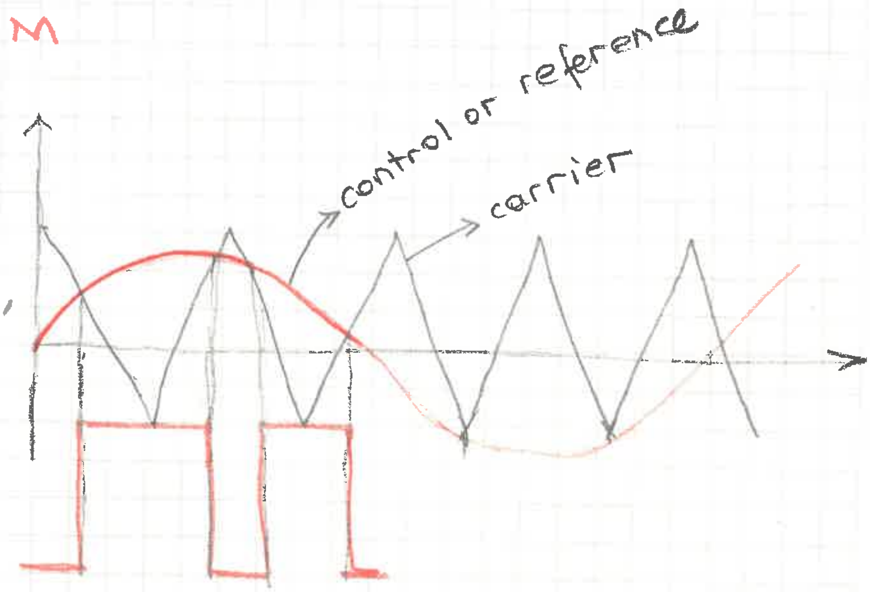
Amplitude Modulation Ratio (Ma)

$$M_a = \frac{\text{Peak value of control signal}}{\text{Peak value of carrier signal}}$$



SINUSOIDAL PWM

In order to control the output voltage and frequency of inverter, Modulation magnitude and frequency are changed:



* The carrier frequency determines the switching frequency of inverter.

* The control frequency determines the frequency of output signal.

In inverter logic, the switches of A phase, S_{A+} and S_{A-} are controlled based on the comparison of $V_{control}$ and $V_{carrier}$ as independent of the direction of current:

* If $V_{control} > V_{carrier}$ S_{A+} is ON → means $V_{output} = \frac{1}{2} V_{dc}$ or $V_{output} = V_{dc}$ dependent on half-bridge or full-bridge.

* If $V_{control} < V_{carrier}$ S_{A-} is ON → means $V_{output} = -\frac{1}{2} V_{dc}$ or $-V_{dc}$ dependent on half-bridge or full-bridge connection.

* if $0 \leq Ma \leq 1$, fundamental component peak value $V_{A1} = Ma \cdot \frac{V_{dc}}{2}$

* if $Ma = 1$, $V_{A1} = \frac{V_{dc}}{2}$ as a max value. It means that max. output voltage value of inverter is obtained.

* if $ma > 1$, this region is called as over-modulation region

The operation in the over-modulation region contains more harmonics as compared to linear region.

Major drawback of sinusoidal pwm is that max Ma value is 0.785. It means 78.5 % of inverter capacity can be used only. In order to increase this value different PWM methods had been developed like the third harmonic injection PWM or space vector PWM (SVPWM).

Third harmonic injection method increases this value to 90.7 %. But it requires much more calculation in the memory of microcontroller.

Space Vector PWM obtains the same score with 90.7 %. In addition, since only one power switch is switched in any time, the switching losses are diminished by making inverter more efficient.

FOR HALF BRIDGE INVERTER

The analysis of the DC-AC inverters is done taking into accounts the following assumptions

1- The current entering terminal voltage is considered positive

2- The switches are unidirectional

3- The current i_a is the same for the power switches.

S_1 is on $\quad 0 < t \leq T_1 \quad V_o = \frac{V_{in}}{2} = \frac{V_{dc}}{2}$

S_4 is on $\quad T_1 \leq t < T_2 \quad V_o = -\frac{V_{in}}{2} = -\frac{V_{dc}}{2}$

$$V_a = \sqrt{\frac{1}{\pi} \int_0^{\pi} \left(\frac{V_{dc}}{2}\right)^2 \cdot d(\omega t)}$$

$V_a = \frac{V_{dc}}{2}$ rms voltage value

$$V_{a_1} = 2 \cdot \frac{1}{\pi} \int_0^{\pi} \frac{V_{dc}}{2} \cdot \sin(\omega t) \cdot d(\omega t)$$

$V_{a_1} = \frac{2\sqrt{2}}{\pi} \cdot \frac{V_{dc}}{2}$ Fundamental component voltage value

FOR FULL BRIDGE INVERTER

When the switches S_1 and S_2 are turned on simultaneously for a duration $0 < t \leq T_1$ (S_4 and S_3 are off) $V_{ab} = V_{dc}$.

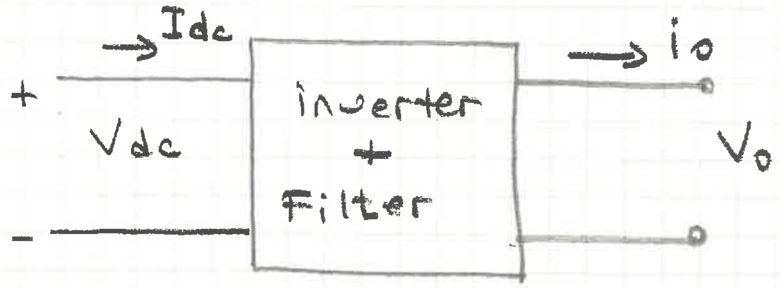
When the switches S_3 and S_4 are turned on simultaneously for a duration $T_1 \leq t \leq T_2$

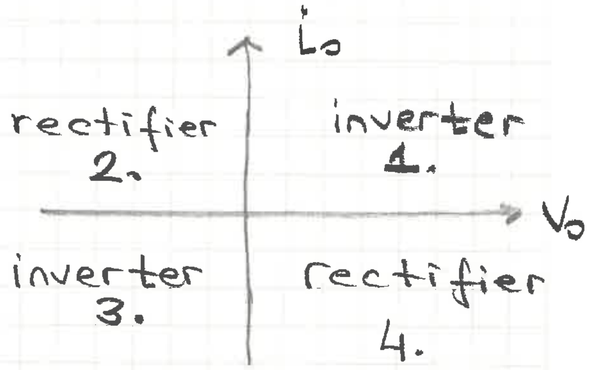
$V_{ab} = -V_{dc}$

$V_{ab} = V_{dc}$ rms voltage value.

$V_{ab_1} = \frac{2\sqrt{2}}{\pi} \cdot U_d$ Fundamental component voltage value

Power Flow for inverters





Any inverter operates as rectifier when the power flow is from the load to the electricity network.

Example

A half bridge inverter with 300V and 50Hz supplies to a 15Ω resistor. By omitting the circuit losses:

a) Find out Vrms, Irms and power of the load

b) Find out input current and rms and avarage current value passing from each transistor.

$V_a = \frac{V_{dc}}{2}$ for half bridge $\quad I_a = \frac{V_a}{R} = \frac{150}{15} = 10\,A$.

$= \frac{300}{2} = 150\,V$.

$P = \frac{V_a^2}{R} = 1500\,W$.

b) $I_i = \frac{V_{dc}/2}{R} = 10\,A \qquad I_{TAV} = \frac{I_i}{2} = 5\,A$

$I_{Trms} = \frac{I_i}{\sqrt{2}} = 7.07\,A$.

Example

An induction motor is controlled via SPWM inverter. The parameters of motor are given as following:

$P = 2.2\ kW$ $n = 1400\ rpm$ $U = 380\ V$ $I = 5A$ $f = 50\ Hz$

$\cos\Phi = 0.78$ $p = 2$ $R_1 = 2.39\ \Omega$, $R_2' = 2.13\ \Omega$

$X_1 = 15.4\ \Omega$ $X_2' = 12.13\ \Omega$ Y connected. 3~

a) For nominal operation Find out synchronous speed, slip, torque and efficiency.

b) For nominal current loading, when the output of inverter is 190V, 25 Hz, find out slip and speed of motor.

a) $$n_s = \frac{60 \cdot f_1}{P} = \frac{60 \cdot 50}{2} = 1500\ rpm \qquad s = \frac{n_s - n}{n_s}$$

$$s = \frac{1500 - 1400}{1500} = 0.066 \qquad P_i = P_{elec} = \sqrt{3} \cdot U \cdot I \cdot \cos\Phi$$

$$P_i = \sqrt{3} \cdot 380 \cdot 5 \cdot 0{,}78 = 2566\ W$$

$$T = \frac{P_{mech}}{\omega} = \frac{P_{mech}}{\frac{2\pi \cdot n}{60}} = \frac{2200}{\frac{2\pi \cdot 1400}{60}} = 15\ Nm$$

$$\eta = \frac{P_d}{P_{in}} = \frac{P_{mech}}{P_{elec}} = \frac{2200}{2566} = 85\ \%$$

b) $$I = \frac{U/\sqrt{3}}{Z} = \frac{190/\sqrt{3}}{\sqrt{\left(2.39 + \frac{2.13}{s}\right)^2 + \left[(15.4) + 12.3)\cdot\frac{25}{50}\right]}}$$

$$Z = \frac{190/\sqrt{3}}{5A} = 21.99\ \Omega \Rightarrow s = 0.144$$

$$n_s = \frac{60 \cdot f_1}{P} = \frac{60 \cdot 25}{2} = 750\ rpm$$

$$n = (1 - s) \cdot n_s \Rightarrow n = 642\ rpm$$

RL yüklü üç fazlı tam köprü bağlantılı eviricide $R = 10\Omega$ $L = 20\,mH$ $m_a = 0.8$, $f_{sin} = 60\,Hz$, $f_{tri} = 1260\,Hz$ ve $V_{dc} = 100\,V$'tur.

a) Çıkış geriliminin ve akımının temel bileşenini bulunuz

b) En tehlikeli 3 harmonik için THD değerini akım için bulunuz. ($I_{5,rms} = 0{,}36$, $I_{7rms} = 0{,}11$, $I_{11,rms} = 0{,}09\,A$)

a) $m_a = \dfrac{V_1}{V_{dc}} \Rightarrow V_1 = 0.8 \cdot 100 = 80\,V.$

$$I_n = \frac{V_n}{Z_n} = \frac{V_n}{\sqrt{R^2 + (n 2\pi f \cdot L)^2}} = \frac{80}{\sqrt{10^2 + (1 \cdot 2\pi 60 \cdot 0{,}02)^2}}$$

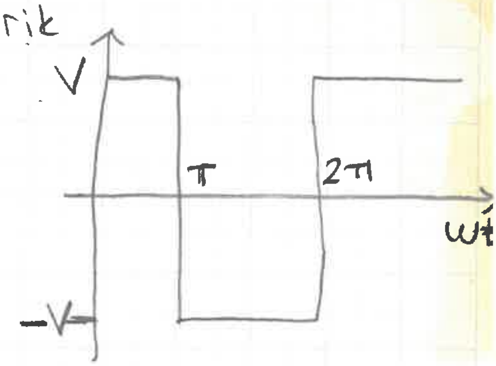
$I_n = 6.39\,A = I_1$

$I_{1,rms} = 6.39/\sqrt{2} = 4.52\,A.$

b) $$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n,rms}^2}}{I_{1,rms}} = \frac{\sqrt{0{,}11^2 + 0{,}36^2 + 0{,}09^2}}{4.52}$$

$THD = \%\,8.7$

Şekildeki kare dalganın trigonometrik fourier serisini bularak çizgisel spekturumunu çiziniz?



Bu fonksiyon simetriktir.

Bu nedenle $a_{av} = 0$'dır
(single function)

$f(t) = -f(t)$ cos (and a_n) terimler seride bulunmaz. Fonksiyon tek fonksiyondur. Dolayısıyla sadece b_n katsayıları bulunur.

$$b_n = \frac{1}{\pi}\left[\int_0^{\pi} V \cdot \sin n\omega t \cdot d(\omega t) + \int_{\pi}^{2\pi} (-V) \cdot \sin \cdot n \cdot \omega t \cdot d(\omega t)\right]$$

$$= \frac{V}{\pi}\left\{\left[-\frac{1}{n} \cdot \cos n\omega t\right]_0^{\pi} + \left[\frac{1}{n} \cos n\omega t\right]_{\pi}^{2\pi}\right.$$

$$b_n = \frac{V}{n \cdot \pi}\left(-\cos n\pi + \cos 0 + \cos n2\pi - \cos n\pi\right) = \frac{2V}{\pi n} \cdot (1 - \cos n\pi)$$

$$f(t) = \frac{4V}{\pi} \cdot \sin \omega t + \frac{4 \cdot V}{3\pi} \cdot \sin 3\omega t + \frac{4 \cdot V}{5\pi} \cdot \sin 5\omega t$$