EN 206: Power Electronics and Machines

Inverters

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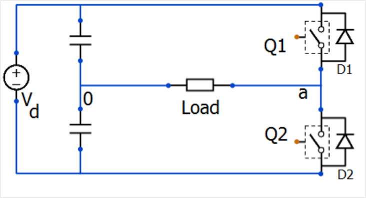
Voltage Source Converters

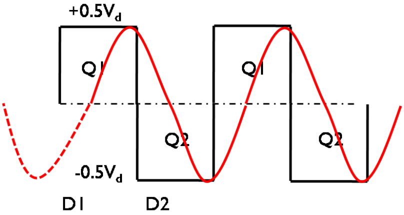
- The fabricated AC voltage is not affected by load
- Applications:
  - AC Motor drives, Un interruptible power supply (UPS)
  - Induction heating, Power conversion from PV array and fuel cell
  - Static Var Compensator, Static Var Generator, Active harmonic fileter
- The power semi conductor devices are always forward biased due to dc supply voltage.
- GTO, BJT, IGCT, Power MOSFET, IGCT are suitable self controlled, forward or assymetric blocking devices
- Feed back diode is always connected across switch for free reverse flow of current.

VSC - General category

- Pulse Width Modulated Inverters
  - Input DC is essentially constant
  - Output voltage magnitude and frequency is controlled
  - Achieved using Pulse Width Modulation Technique
- Square Wave Inverter
  - Input DC is controlled to control output voltage magnitude
  - Inverter can control only frequency of output voltage
  - Output voltage waveform is similar to square wave.
- Single phase inverter with voltage cancellation
  - Input DC is essentially constant
  - Voltage cancellation technique is applicable for single phase inverters only.

Square Wave Inverter - Half bridge



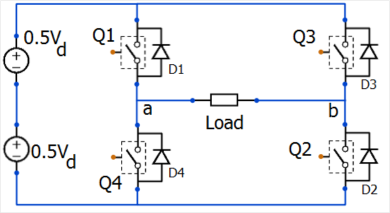


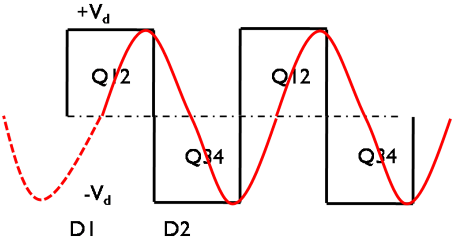
- Inductive load is connected between point 'a' and the centre point '0' of a split capacitor power supply
- Q1 and Q2 are closed alternately for π angle to generate square wave output voltage
- V_{ao} oscillates between $+0.5V_d$ and $-0.5V_d$

Single Phase inverter – Half bridge

- Snubber circuit is not shown for simplicity
- Short gap or lock out time t_d is maintained to prevent any short circuit or shoot-through fault due to turn-off switching delay
- When supply voltage and current are of same polarity power is transferred from dc to ac or else power is fed back to source
- Average power flows from source to the load

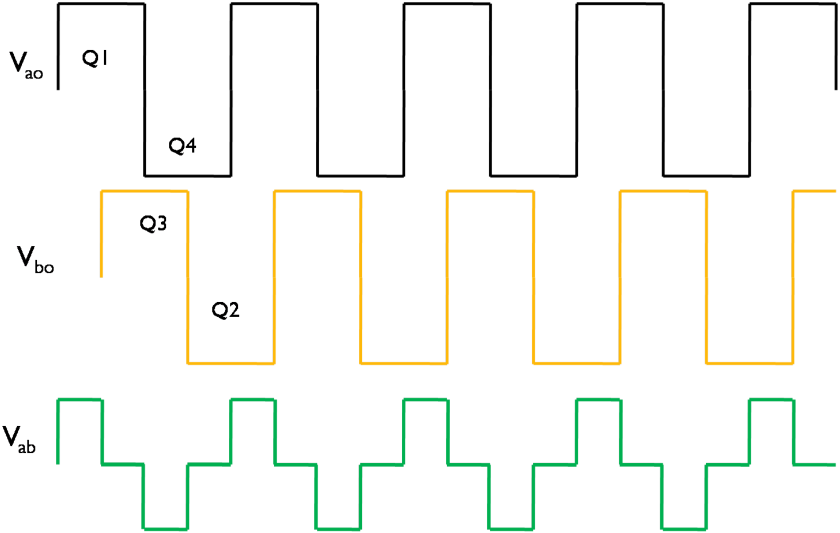
Single Phase Full Bridge Inverter -H Bridge





- Split capacitor may not be required
- Q1Q2 and Q3Q4 are operated in pairs and switched alternately to generate square wave output voltage of amplitude V_d
- Feed back current flows through D1D2 and D3D4
- Both diodes are designed to withstand supply voltage V_d.
- H-Bridge inverters are used in four quadrant operation

Voltage Control using Phase Shift

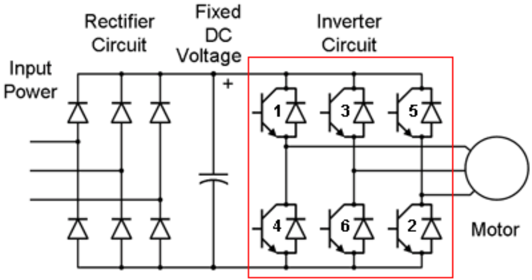


Voltage Control – Phase Shift

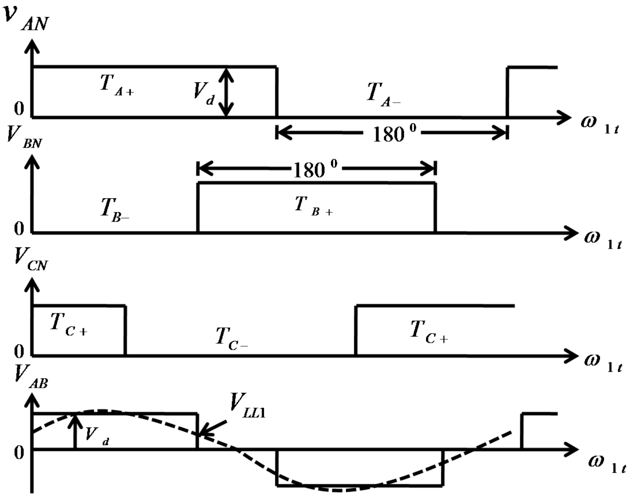
- The output line voltage $V_{ab} = V_{a0} - V_{b0}$ is a quasi-square wave of pulse width "ϕ", which can control the fundamental component of output voltage.
- Assuming a typical lagging load current with perfect filtering:
- Q1, Q2 conducting
  - Active mode with positive voltage and current
- Q1, D3 conducting
  - Free wheeling mode with positive current
- D3, D4 conducting
  - Feedback mode with positive current
- Q3, Q4 conducting
  - Active mode with negative current an negative voltage
- Q4, D2 conducting
  - Free wheeling with negative current
- D1, D2 conducting
  - Feedback mode with negative current

Three Phase Inverter

Induction Motor Fed From AC Drive

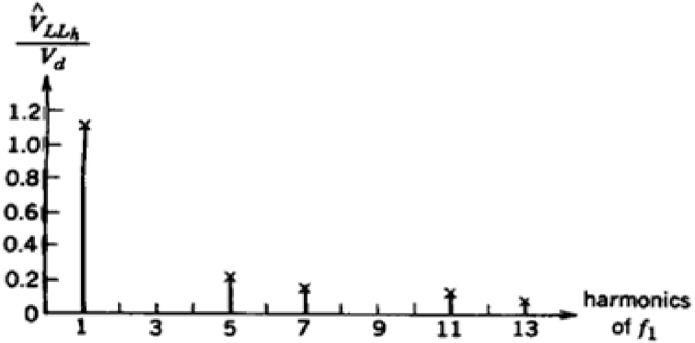


Three Phase Square Wave Inverter - Waveform



(b)

Three Phase Inverter - Harmonic Spectrum

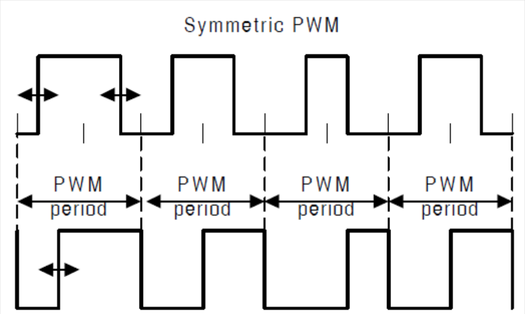


Three Phase Inverter - Analysis

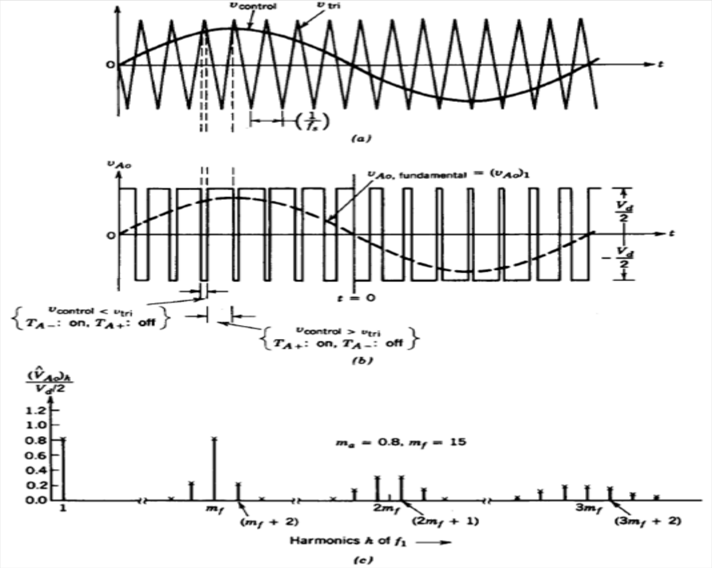
- $V_{LL,1(rms)} = \sqrt{\frac{3}{2}} \times \frac{4}{\pi} \times \frac{V_d}{2} = 0.78V_d$
- V_{LL} does not depend on load condition and contains harmonics due to switching.
- $V_{LL,1(rms)} = 0.78V_d/h$ where, $h = 6n \pm 1$
- It is not possible to control output voltage by using voltage cancellation technique in three phase inverter
- The period of conduction of each switch is determined by the power factor of the load
- Harmonic Spectrum
  - Even and Triplen harmonics are not present
  - PWM switching result in small ripple current

Pulse Width Modulation (PWM)

- Definition:??
- PWM inverters are becoming more popular for control of industrial drives advances in solid-state power devices and microprocessors.
- Frequency and magnitude of voltage and current of the motor can be controlled
- Types: *Hysteresis PWM, Sine triangular PWM and space vector PWM*



Sine Triangular PWM (SPWM)



Sine Triangular PWM (SPWM)

- Peak amplitude of the fundamental frequency component is m_a times $\frac{V_d}{2}$
- The harmonics in the inverter output voltage waveform appear as side bands, centered around the switching frequency
- The harmonics are given by $f_h = (jm_f \pm k)f_1$
- For odd values of j, the harmonics exist only for even values of k.
- For even values of j, the harmonics exist only for odd values of k

Single Phase SPWM - Harmonic Analysis

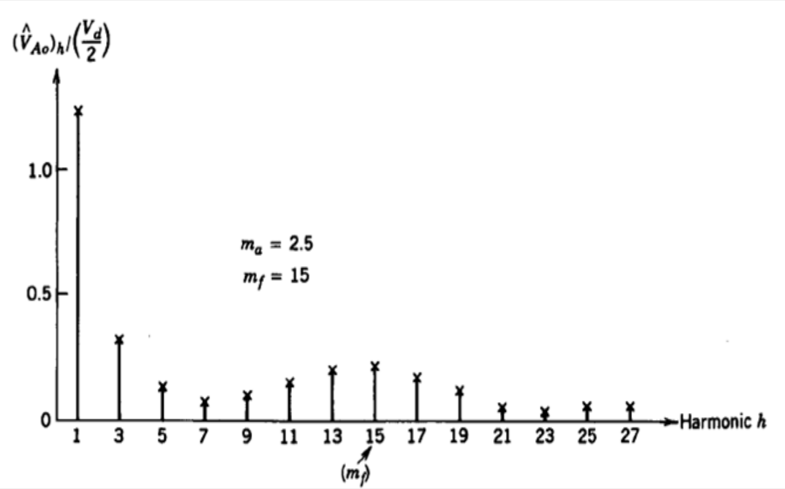
Harmonics of V_{Ao} for a large m_f. $V_{Ao,h}/\frac{V_d}{2} = V_{AN,h}/\frac{V_d}{2}$ is tabulated as a function of m_a.

m_a	0.2	0.4	0.6	0.8	1.0
1	0.2	0.4	0.6	0.8	1.0
m_f	1.242	1.15	1.006	0.818	0.601
$m_f \pm 2$	0.016	0.061	0.131	0.220	0.318
$m_f \pm 4$					0.018
$2m_f \pm 1$	0.19	0.326	0.37	0.314	0.181
$2m_f \pm 3$		0.024	0.071	0.139	0.212
$2m_f \pm 5$				0.013	0.033
$3m_f$	0.335	0.123	0.083	0.171	0.113
$3m_f \pm 2$	0.044	0.139	0.203	0.176	0.062
$3m_f \pm 4$		0.012	0.047	0.104	0.157
$3m_f \pm 6$				0.016	0.044
$4m_f \pm 1$	0.163	0.157	0.008	0.105	0.068
$4m_f \pm 3$	0.012	0.07	0.132	0.115	0.009
$4m_f \pm 5$			0.034	0.084	0.119
$4m_f \pm 7$				0.017	0.050

Sine Triangular PWM (SPWM)

- By choosing m_f as odd integer results in odd symmetry as well as half wave symmetry with time origin.
- Only odd harmonics are present and the even harmonics disappear from the output waveform
- Coefficients of the sine series in the fourier analysis are finite
- Coefficients of the cosine series are zero
- Switching losses are proportional to switching frequency Higher switching frequency $\Rightarrow$ more losses
- Small value of $m_f \leq 21$
  - Synchronous PWM
    - m_f should be an integer otherwise, possibility of sub harmonics
  - m_f should be an odd integer
- Harmonics due to over modulation $(ma > 2.5)$

SPWM - Over modulation

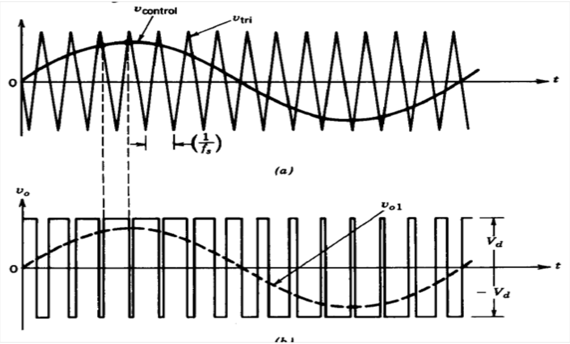


Bi-Polar Voltage Switching

CIRCUIT DIAGRAM

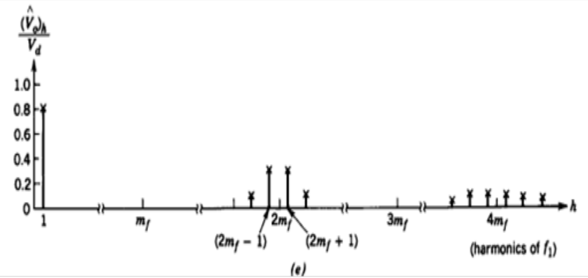
- The diagonally opposite switches (T_{A+} and T_{B-}) and (T_{A-}, T_{B+}) are switches as pairs.
- The output of inverter leg B is negative of the leg A output.
- When T_{A+} is ON, $V_{A0} = +\frac{V_d}{2}$ and when T_{B-} is ON $V_{B0} = -\frac{V_d}{2}$

Bi-Polar Voltage Switching



- The peak of the fundamental frequency component is $V_{0a} = m_a V_d$.
- The voltage switches between V_d and $+V_d$ and hence called as bipolar voltage switching

Bi-Polar Voltage Switching



- The lowest harmonics appear as side band of twice the switching frequency.
- Harmonic component of switching frequency disappear

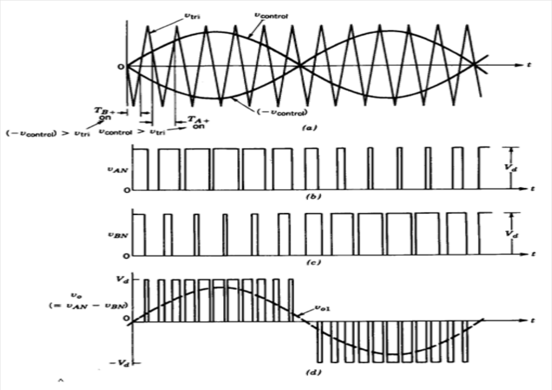
Bi-Polar Voltage Switching

- The output current circulates in a loop through T_{A+} and D_{B+} or D_{A+} and T_{B+} depending on the direction of i_0.
- The output voltage changes between zero and $+V_d$ or zero and V_d and hence names are unipolar voltage switching.
- The voltage jumps in output is limited to V_d compared to $2V_d$ in the case of bipolar scheme.

Bi-Polar Voltage Switching

- The switches in the two legs of the full bridge are not switched simultaneously
- Leg A and Leg B are controlled by comparing V_{tri} with $V_{control}$ and $V_{control}$ respectively

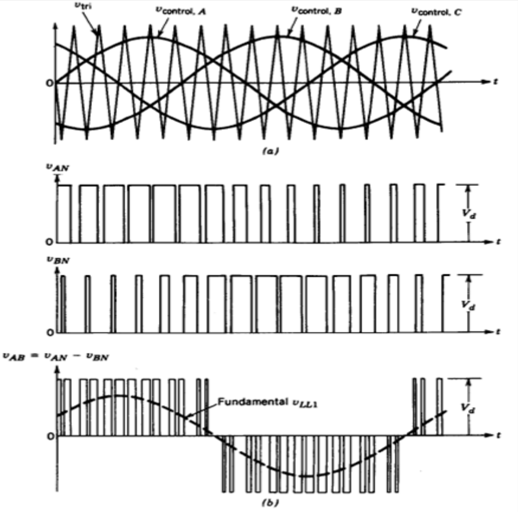
Uni-Polar Voltage Switching



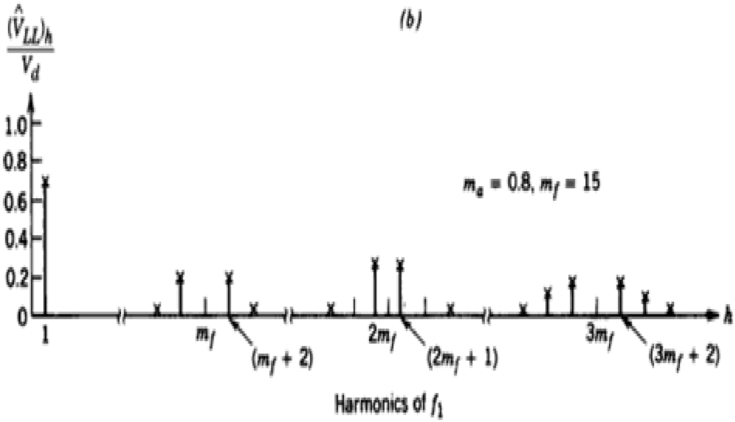
Uni-Polar Voltage Switching Pattern

- Control logic - Switching Pattern
  - $V_{control} > V_{tri}$; T_{A+} on and $V_{AN} = V_d$
  - $V_{control} < V_{tri}$; T_{A-} on and $V_{AN} = 0$
  - $-V_{control} > V_{tri}$; T_{B+} on and $V_{BN} = V_d$
  - $-V_{control} < V_{tri}$; T_{B-} on and $V_{BN} = 0$
- Combination of switch on states and corresponding voltages
  - T_{A+} and T_{B-} on, $V_{AN} = V_d$, $V_{BN} = 0$, $V_0 = V_d$
  - T_{A-} and T_{B+} on, $V_{AN} = 0$, $V_{BN} = V_d$, $V_0 = -V_d$
  - T_{A+} and T_{B+} on, $V_{AN} = V_d$, $V_{BN} = V_d$, $V_0 = 0$
  - T_{A-} and T_{B-} on, $V_{AN} = 0$, $V_{BN} = 0$, $V_0 = 0$
- When all the upper switches are on simultaneously, the output voltage is zero. The same is true for lower switches

Three Phase SPWM - Switching Pattern



Three Phase SPWM - Harmonic Analysis



Three Phase SPWM - Harmonic Analysis

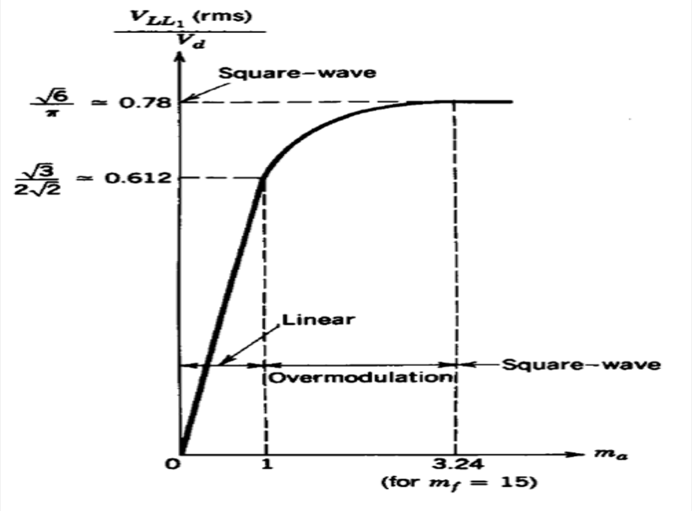
Harmonics of V_{LL} for a large and odd m_f that is multiple of 3.

m_a	0.2	0.4	0.6	0.8	1.0
1	0.122	0.245	0.367	0.49	0.612
$m_f \pm 2$	0.010	0.037	0.080	0.135	0.195
$m_f \pm 4$				0.005	0.011
$2m_f \pm 1$	0.116	0.2	0.227	0.192	0.111
$2m_f \pm 5$				0.008	0.020
$3m_f \pm 2$	0.027	0.085	0.124	0.108	0.038
$3m_f \pm 4$		0.007	0.029	0.064	0.096
$4m_f \pm 1$	0.1	0.096	0.005	0.064	0.042
$4m_f \pm 5$			0.021	0.051	0.073
$4m_f \pm 7$				0.01	0.03

Note: $V_{LL,h}/V_d$ are tabulated as a function of m_a where $V_{LL,h}$ are the rms values of the harmonic voltages.

- Triangular wave form is compared to three sinusoidal waveforms 120^o apart to generate pulses for the bridge circuit
- DC voltage present in the phase voltage gets canceled out in the line voltages
- In the case of three phase inverter, only line voltages are of importance
- The phase difference between m_f^{th} harmonic is zero between two phases and hence cancel out in line voltage, m_f is odd integer and multiple of 3.
- Dominant harmonics present in single phase inverter are eliminated from the line-line voltage of a three phase inverter
- The peak value of fundamental of one of the leg of inverter is $\widehat{V}_{AN,1} = m_a \frac{V_d}{2}$ and the line-line voltage is given by $V_{LL,1(rms)} = \sqrt{\frac{3}{2}}(\widehat{V}_{AN,1}) = 0.612 m_a V_d$

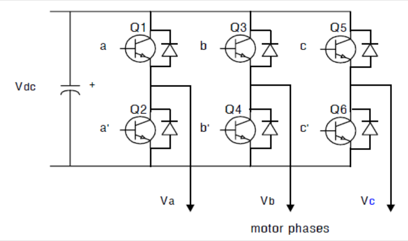
Comparison - PWM techniques



Space Vector PWM

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

$$\begin{bmatrix} V_{a} \\ V_{b} \\ V_{c} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$



- When the upper switch in ON the corresponding lower switch is OFF
- The state of the switch is sufficient to evaluate the output voltage
- There are eight possible combinations for on/off state of the upper switches

SVPWM - On/Off state and Corresponding Output

Switch State			Phase Voltage			Line Voltage		
0	0	0	0	0	0	0	0	0
1	0	0	2/3	-1/3	-1/3	1	0	-1
1	1	0	1/3	1/3	-2/3	0	1	-1
0	1	0	-1/3	2/3	-1/3	-1	1	0
0	1	1	-2/3	1/3	1/3	-1	0	1
0	0	1	-1/3	-1/3	2/3	0	-1	1
1	0	1	1/3	-2/3	1/3	1	-1	0
1	1	1	0	0	0	0	0	0

Sample calculations for Hexagon

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

$$T_{abc-dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\begin{bmatrix} d \\ q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

For vector U_{100}: Substituting a=1, b=0, c=0 gives,

$$\begin{bmatrix} d \\ q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \sqrt{(2/3)} \\ 0 \end{bmatrix}$$

SVPWM - Table for Space Vector

	a	b	c	V_a	V_b	V_c	V_{ab}	V_{bc}	V_{ca}
0_{000}	0	0	0	0	0	0	0	0	0
U_{100}	1	0	0	2/3	-1/3	-1/3	1	0	-1
U_{110}	1	1	0	1/3	1/3	-2/3	0	1	-1
U_{010}	0	1	0	-1/3	2/3	-1/3	-1	1	0
U_{011}	0	1	1	-2/3	1/3	1/3	-1	0	1
U_{001}	0	0	1	-1/3	-1/3	2/3	0	-1	1
U_{101}	1	0	1	1/3	-2/3	1/3	1	-1	0
U_{111}	1	1	1	0	0	0	0	0	0

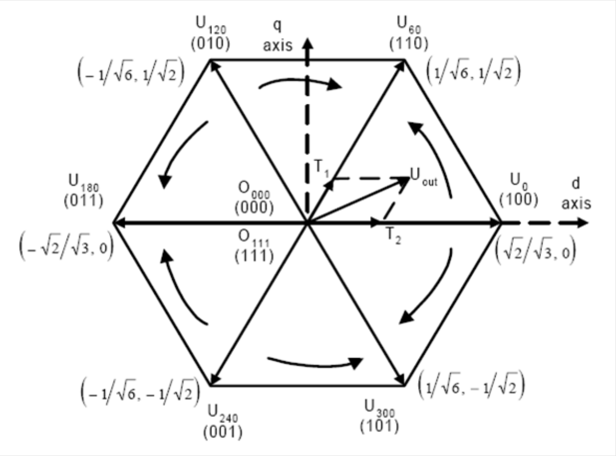
The generated or reference voltage shall lie in the hexagon formed by the above vectors.

SVPWM- Hexagon of Vectors

- There are total of 6 sectors in which the reference voltage U_{out} shall belong to.
- If the reference output voltage magnitude and angle is given, then $|U_{out}|$ and α can be computed. Where α is angle between U_{out} and U_x.
- From $|Uout|$ and α, the sector of reference voltage U_{out} can be easily computed.
- Time period for which the vectors shall operate is given by:

$$T_1 + T_2 + T_0 = T_{pwm}$$
$$T_1 = \sqrt(2) T_{pwm} |U_{out}| cos(\alpha + 30^0)$$
$$T_2 = \sqrt(2) T_{pwm} |U_{out}| sin(\alpha)$$
$$T_{pwm} U_{out} = T_1 U_x + T_2 U_{(x \pm 60)} + T_0 (0_{000} or 0_{111})$$

SVPWM - Switching Direction



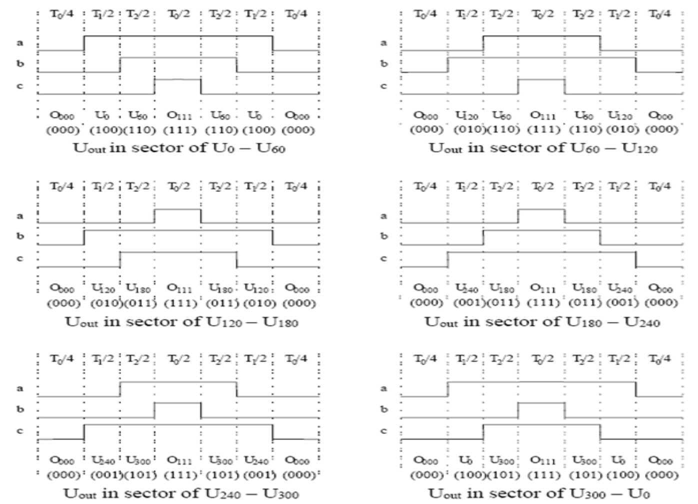
SVPWM - Switching Pattern

- The maximum value of U_{out} is the shortest radius of the envelope
- The maximum rms value of line-line voltage is $\frac{V_d}{\sqrt{2}}$ and the maximum rms value of phase voltage is $\frac{V_d}{\sqrt{6}}$ which is $\frac{2}{\sqrt{3}}$ times higher than that of sine triangular PWM technique
- If the motor is rated for V_{rms} (three phase L-L) then the dc bus requires shall be $V_d = \sqrt{2} \times V_{rms}$
- U_x can be basic closest space vector on either side of U_{out}. $U_{x+60}(orU_{x-60})$ is basic space vector on the opposite side

SVPWM - Switching

- T_1 represents component on U_x and T_2 represent component on the other vector Each PWM channel switches twice per every PWM period except when the duty cycle is 0% or 100%.
- There is a fixed switching order among the three PWM channels for each sector
- Every PWM period starts and ends with O_{000}; The amount of O_{000} inserted is the same as that of O_{111} in each PWM period
- The above is applicable for symmetric PWM

Three Phase SPWM - Switching Pattern



Three Phase SPWM - Inverter Output