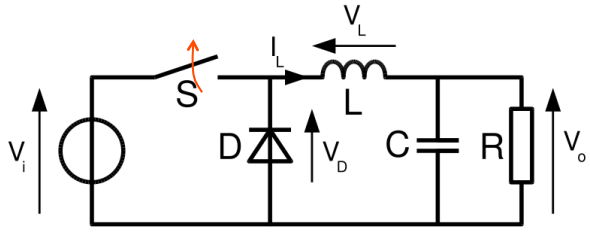
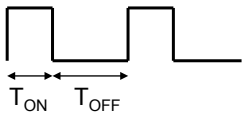
Buck (step-down) converter

The idealized schematic of the Buck converter is reported below. The power device (here indicated as an idealized switch) is driven by a squarewave signal, and the circuit gives an output voltage V_0 of the same polarity of the supply voltage V_i, depending from the duty cycle D of the switching waveform.

The low-pass filter L,C is needed to remove the modulation frequency and to obtain a d.c output voltage on the load, here indicated by the resistance R.
The diode D is needed to allow the current flow in the inductor L when the switch is open (otherwise it would cause an extremely high overvoltage across the switch)

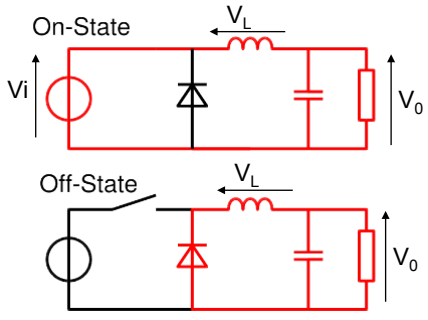




$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \frac{T_{ON}}{T}$$

Analysis of the Buck converter

A simplified analysis of the circuit can be done for the case of ideal switch and diode, and ideal lossless LC filter. For the two cases of switch closed (ON state) and open (OFF state) the circuit can be reduced to the ones indicated in red:



For T_{ON} $V_L = V_i - V_0$
assuming V_0 const. (LC filter cuts off f_M):

$$V_L = L\frac{dI_L}{dt} = const \Rightarrow I_L \text{ is linearly increasing } (V_i > V_0)$$

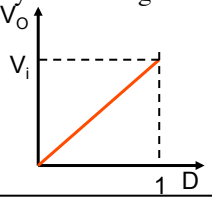
For T_{OFF} $V_L = -V_0$ (assuming $V_D = 0$)

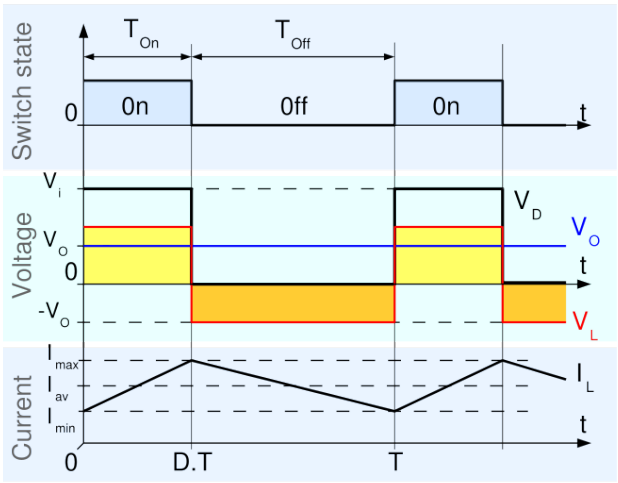
$$V_L = L\frac{dI_L}{dt} = -V_O \Rightarrow I_L \text{ is linearly decreasing}$$

For a lossless L, the total voltage drop in the period T must be zero:

$$\int_{Ton} V_L dt + \int_{Tof\,f} V_L dt = 0 \Rightarrow (V_i - V_0)T_{ON} = V_0 T_{OFF};$$

$$V_O = V_i \frac{T_{ON}}{T_{ON} + T_{OFF}} = V_i D$$

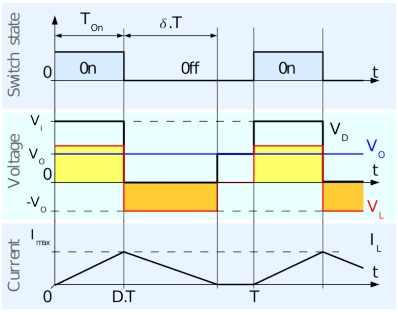


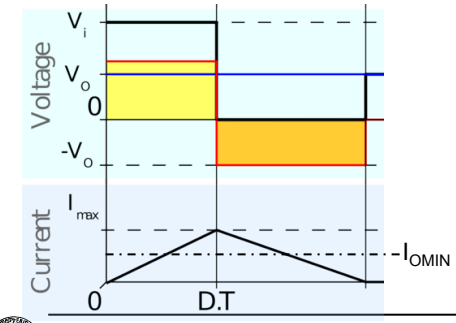


The waveforms for V_L (red plot) and I_L according to the simplified analysis are reported here.

The voltage V_0 is kept constant by the capacitor C that charges during T_{ON} and discharges during T_{OFF}.

Only the average current I_{AV} flows into the load: $I_{AV} = V_0/R$.
Here it is assumed that the current into the inductance I_L do not goes to zero during the entire period T. This assumption is needed for a good operation of the converter, but it can be not always verified: let us determine the condition required for a current $I_L>0$ during all the period T.





If the output current I_{AV} is too low, (due to an increase in the load resistance, or a small value of V_0 for low duty cycle) one can have the case of the top figure. In that case the output voltage is no more constant and depending only by the duty cycle D, but it is also depending from the output current.

Let us define the minimum output current I_{OMIN} that gives a current $I_L>0$ for the whole period, with reference to the bottom figure, by referring to the I_{AVmin} ($I_{AV} = I_O$)

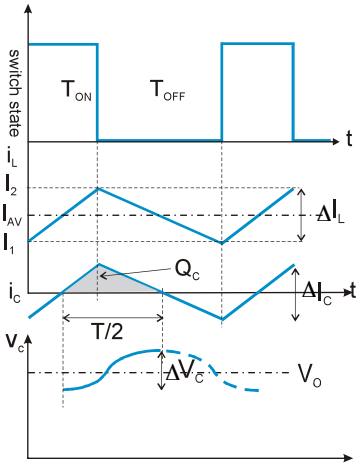
$$V_i - V_O = L\frac{\Delta I_L}{\Delta T} = L\frac{I_{MAX}}{T_{ON}} = L\frac{2I_{OMIN}}{T_{ON}}$$

$$I_{OMIN} = \frac{V_i - V_O}{2L}T_{ON} = \frac{V_i - DV_i}{2L}T_{ON} = V_i T\frac{(1-D)D}{2L}$$

I_{OMIN} depends on the inductance value and on the duty cycle D: for a given V_i the largest value is obtained for D = 50%

Effect of the LC filter

The assumption of constant output voltage V_O implies a perfect filtering of the lowest harmonic frequency f_M of the modulation signal. This in turn implies a filter frequency f_F=0. We will evaluate the oscillation present in V_O for a given f_F, by assuming that the variable current component flows in C, while the constant current value I_{AV} will flow in the load R.



The analysis refers to the waveforms reported here. The max variation of the a.c. current $\Delta I_C = \Delta I_L$ and the total charge Q_C increment in C, as indicated in fig., is:

$$Q_C = \frac{\Delta I_L}{2}\frac{T}{2}\frac{1}{2} \text{ (triangular shape)} \Rightarrow \Delta V_C \equiv \Delta V_O = \frac{\Delta I_L T}{8C}$$

The constant value of output voltage can be related to ΔI_L as:

$$V_O = L\frac{\Delta I_L}{T_{OFF}} \Rightarrow \Delta I_L = \frac{V_O}{L}(1-D)T$$

Substituting this value of ΔI_L in the above expression of ΔV_C, one has:

Effect of the LC filter

$$\Delta V_O = V_O\frac{(1-D)T^2}{8LC} \Rightarrow \frac{\Delta V_O}{V_O} = \frac{(1-D)T^2}{8LC}$$

The ratio $\Delta V_O/V_O$ is indicated as "ripple" of the output voltage. One can express the ripple, by recalling that the lowest harmonic frequency of the modulation signal is f_M = 1/T, and the corner filter frequency is $f_F = \frac{1}{2\pi}\frac{1}{\sqrt{LC}}$

$$\frac{\Delta V_O}{V_O} = \frac{1-D}{2}\pi^2\left(\frac{f_F}{f_M}\right)^2$$

It comes out that the ripple is independent from load, and it decreases as long as $f_F << f_M$

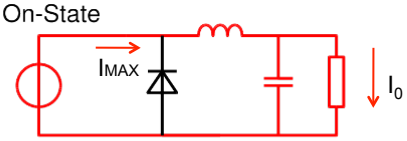
However the minimum value for the filter frequency f_F is determined by the max frequency content of the control signal: obviously f_F must be higher than the max signal frequency f_S ($f_F > f_S$) to leave unaltered the information transferred to the load.
A second point in favor of a larger filter frequency comes out from the need of using lower L and C components: this in turn will reduce the weight, the size (and the cost) of the filter.
All these constraints can be relaxed if one can use fast switching devices, to increase f_M
This will be one of the top requirements for all the power devices that we will study.

V_{MAX} and I_{MAX} of the active device

What will be the maximum voltage and current that the active device must carry in the Buck converter?

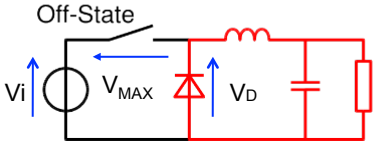
- For the case of switch closed (ON state) the device is carrying the max current I_{MAX}
- For the case of switch open (OFF state) the device is carrying the max voltage V_{MAX}

On-State



during T_{ON} $\quad I_{MAX} = I_L \cong I_0$ (assuming quite constant I_L)

Off-State

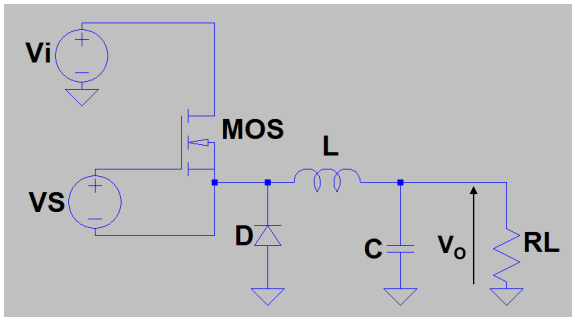


during T_{OFF} $\quad V_{MAX} = V_I - V_D \cong V_I$ (assuming $V_D \cong 0$)

Then the device must be rated for the Input voltage (larger than the output one) and for the output current (larger than the average input one)
- the current rating is also stressed by the reverse recovery of the diode (see the simulation of the circuit)

Circuit analysis of the Buck converter

In this circuit an active device is needed to realize the controlled switch: in the bottom circuit it has been done by using a MOS device. The other power device required is the diode D needed to allow the current flow in the inductance during the T_{OFF} time.
This circuit requires a driving stage (to operate the MOS) that is above ground (the generator V_S has none of the terminals connected to ground). This implies that the driving circuit can be isolated from ground at least by the output voltage V_O (this problem will be discussed in the following)

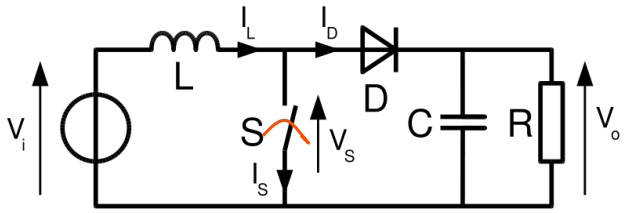


The power conversion efficiency of that circuit is mainly dependent from the steady state and switching losses of both the MOS and the diode (We will discuss these losses in our study of the different power devices).
As an exercise (#1) the transient behavior and the power efficiency for this Buck converter will be evaluated as a function of load current and switching frequency, by using the SwitcherCAD circuit simulator

Boost (step-up) converter

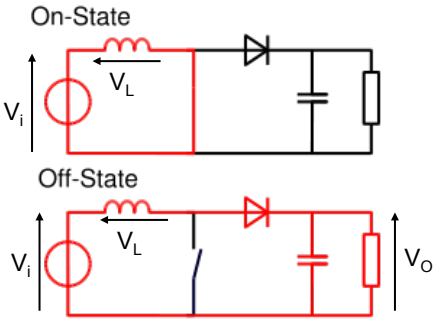
The Boost converter is employed when one needs an output voltage larger than the input one: this is usually the case when a system can be supplied by batteries: to avoid to put many batteries in series one can increase the output voltage using a step-up converter. The applications range from the use in on-chip flash memories for programming and erasing operations, to the one in electric or hybrid cars, to operate the d.c. motor.

The basic idealized circuit for the Boost converter is the one reported here:
the diode is now needed to allow current flow into the load R when the switch is open and to inhibit the discharge of the capacitor C through the switch when it is closed.
The LC filter cuts off the modulation frequency from the output voltage, that is dependent again from the duty cycle D.



Analysis of the Boost converter

Simplified analysis for an ideal switch and lossless LC filter:



For T_{ON}: $V_L = V_i$

$$V_L = L\frac{dI_L}{dt} = V_i \Rightarrow I_L \text{ is linearly increasing}$$

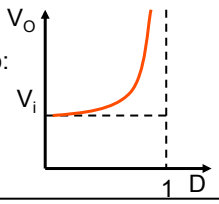
For T_{OFF}: $V_L = V_i - V_0$ (assuming $V_D = 0$)

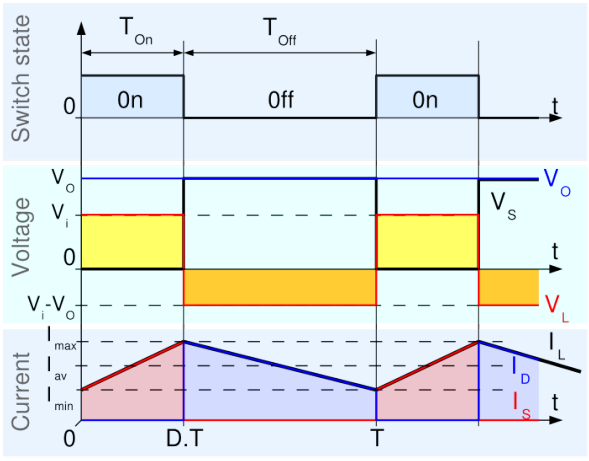
$$V_L = L\frac{dI_L}{dt} = -const \Rightarrow I_L \text{ is linearly decreasing}$$

For a lossless L, the total voltage drop in the period T must be zero, so:

$$\int_{Ton} V_L dt + \int_{Tof\,f} V_L dt = 0 \Rightarrow V_i T_{ON} + (V_i - V_0)T_{OFF} = 0;$$

$$V_O = V_i \frac{(T_{ON} + T_{OFF})}{T_{OFF}} = V_i \frac{1}{1-D}$$





The waveforms for V_L (red plot) and I_L according to the simplified analysis are reported here.
The voltage V_0 is kept constant by the capacitor C that charges through L during T_{OFF} and discharges into the load R during T_{ON}, and $I_O = V_O/R$.

Now the average current I_{AV} into L is the average current absorbed from the input. The output current I_O is linked to I_{AV} through the power balance:

$$P_O = V_O I_O = P_I = V_i I_{AV} \Rightarrow I_O = I_{AV}(1-D)$$

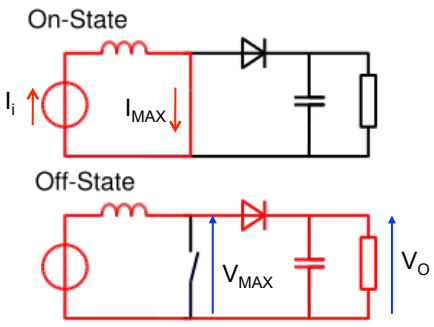
Again it is assumed that the current I_L does not reach zero during the T_{OFF} time. In that case we obtain with an analysis similar to the one done for the Buck a minimum I_{AV} into L, and a min I_O:

$$I_{AV\,\min} = \frac{V_i}{2L} T_{ON} = V_i T \frac{D}{2L}$$

$$I_{O\,\min} = V_i T \frac{(1-D)D}{2L}$$

V_{MAX} and I_{MAX} of the active device

The maximum voltage and current that the active device must carry in the Boost converter :
•For the case of switch closed (ON state) the device is carrying the max current I_{MAX}
•For the case of switch open (OFF state) the device is carrying the max voltage V_{MAX}



During T_{ON} $I_{MAX} = I_I \cong I_{AV}$
(assuming quite constant I_L)

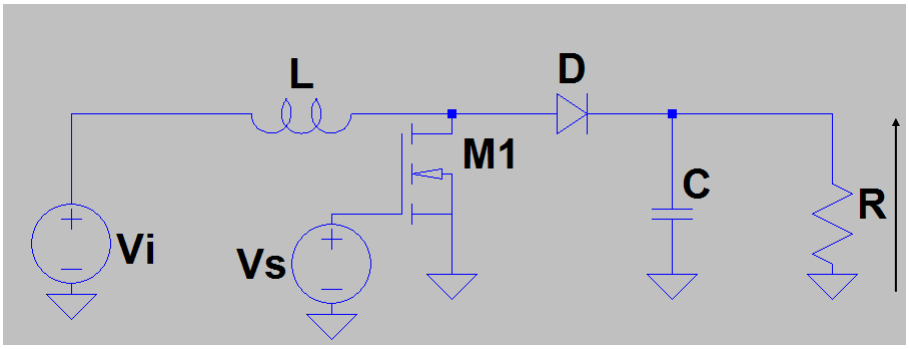
During T_{OFF}: $V_{MAX} = V_0 - V_D \cong V_0$
(assuming $V_D \cong 0$)

Then the device must be rated for the max output voltage (larger than the input one) and for the input current (larger than the output one)

Circuit realization of the Boost converter

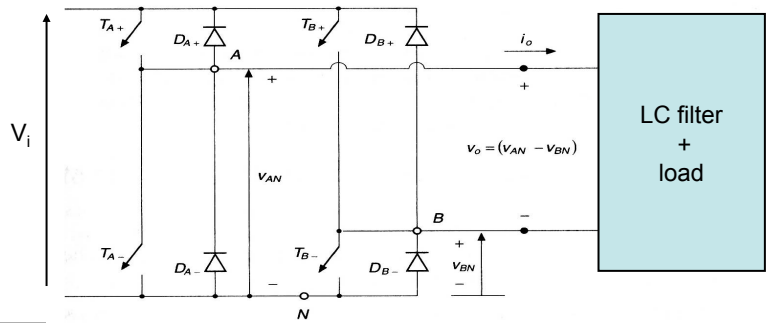
Here it is reported a circuit realized with a power MOS as the active device: in this circuit the driving stage (to operate the MOS) is referred to ground, and this alleviates the driving circuitry.

The previous analysis assumes no losses both in the L,C and in the power devices (MOS and diode). The power conversion efficiency of the circuit is mainly dependent from the steady state and switching losses of both the MOS and the diode.



Bridge converter

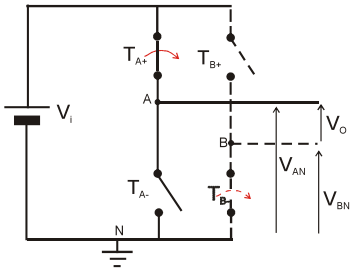
The bridge converter is the most general circuit configuration that allows both the DC/DC conversion (with choice of the polarity of output voltage) and the DC/AC conversion (giving an AC output power from a DC one).
In this circuit, the two switches in the same branch are newer open or closed at the same time, to avoid a short circuit current from power supply (in real cases it is given a finite ΔT between the operation of the two switches of the same branch).
The diodes in parallel to the switches are needed to guarantee the current flow in the ON state if the switches are unipolar (like BJT's). The output is filtered by a lowpass filter



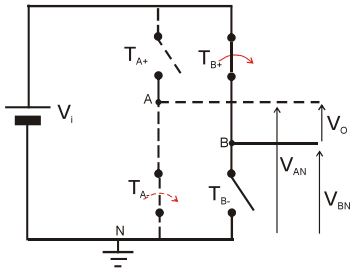
Analysis of the Bridge converter

According to the previous condition, the possible states for each of the branches of the bridge, for a given operation period T, are the following ones:

$T_{A+}on / T_{A-}off$ regardless of T_B



$T_{B+}on / T_{B-}off$ regardless of T_A



One can define two different duty cycles for T_A, and T_B : $D_1 = \frac{T_{TA+on}}{T}$; $D_2 = \frac{T_{TB+on}}{T}$

$V_O = V_{AN} - V_{BN}$; depending on D_1 D_2 : $V_{AN} = \begin{cases} V_i\big|_{T_{A+}on} \\ 0\big|_{T_{A-}on} \end{cases}$; $V_{BN} = \begin{cases} V_i\big|_{T_{B+}on} \\ 0\big|_{T_{B-}on} \end{cases}$

The mean values of V_{AN}, V_{BN} over the T period (assuming the output filtered by a lowpass filter) are:

$$V_{ANav} = \frac{V_I T_{A+on} + 0 T_{A-on}}{T} = V_i D_1 \qquad V_{BNav} = \frac{V_I T_{B+on} + 0 T_{B-on}}{T} = V_i D_2$$

The mean value of the output voltage V_O is then the difference of the average values of V_{AN} and V_{BN}:

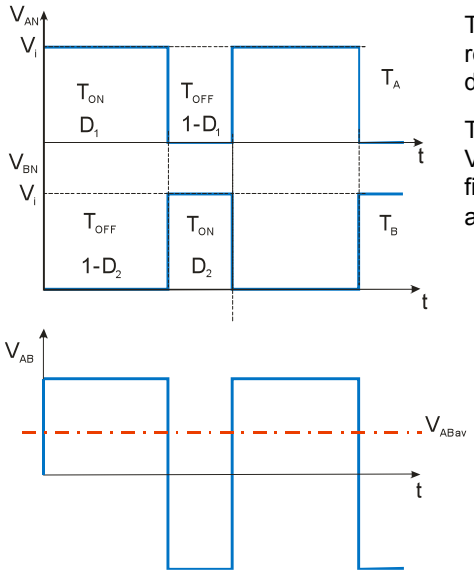
$$V_{Oav} = V_{ANav} - V_{BNav} = V_i D_1 - V_i D_2 \qquad \text{(a)}$$

There are two different modes of operation of the bridge converter, according to the phase relation between the Ton/Toff times of the two branches:

- Bipolar switching
- Unipolar switching

Bipolar switching operation

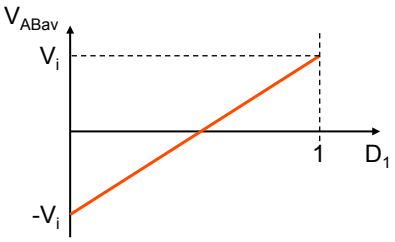
In this case, the switching waveforms for the T_{A+} and T_{B+} (or T_{A-} and T_{B-}) are exactly the opposite each other;



The waveforms of the V_{AN} and V_{BN} voltages are the ones reported here. From these waveforms we have for the duty cycles D_1 and D_2: $D_2 = 1 - D_1$ (b)

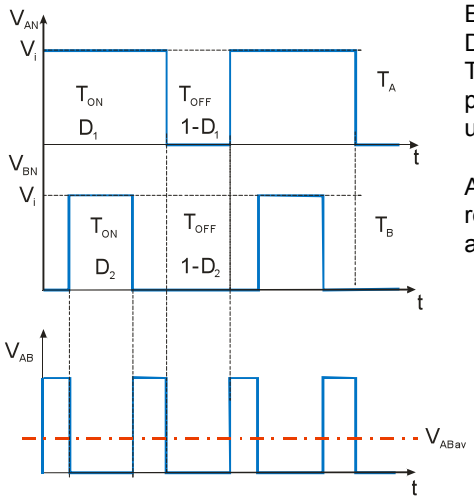
The output voltage V_{AB} is the difference of the V_{AN} and V_{BN} voltages. The average output value V_{ABav} after the filter, recalling relation (a), can be positive or negative according to the value of D_1, ranging from $+V_i$ to $-V_i$:

$$V_{ABav} = \frac{V_i T_{TA+ON} - V_i T_{TB+ON}}{T} = V_i D_1 - V_i D_2 = V_i (2D_1 - 1)$$



Unipolar switching operation

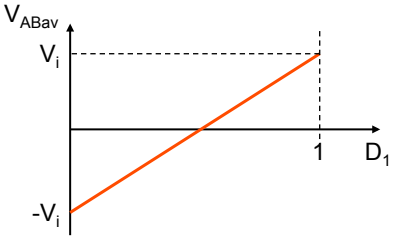
In this case, the switching waveforms for T_{B+} is made of the opposite of the one of T_A+ but time shifted, to have T_{TB+on} centered on the T_{TA+on} time.



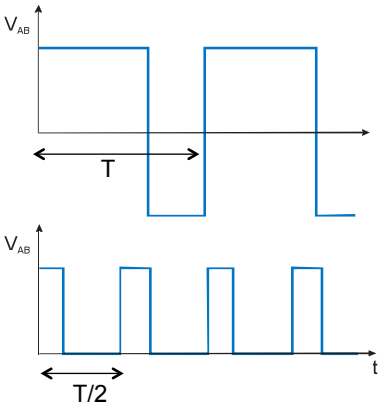
Even in that case the relation (b) holds for the duty cycles D_1 and D_2 : $D_2 = 1 - D_1$
The difference is that now the V_{AB} waveform has a single polarity (either positive or negative) – hence the name unipolar.

Again the average output value V_{ABav} after the filter, recalling relation (a), can be positive or negative according to the value of D_1, ranging from $+V_i$ to $-V_i$.

$$V_{ABav} = V_i D_1 - V_i D_2 = V_i (2D_1 - 1)$$



The difference in the two modes of operation lies in the frequency of the output V_{AB} waveform.



In the bipolar mode the fundamental frequency of the output voltage is 1/T

in the unipolar mode the fundamental requency of the output voltage is 2/T.

The latter case allows a better filtering with the same LC filter (same filter frequency), and then the output ripple is reduced for the same L,C values, or the same ripple is obtained with lower L,C values (filter less costly)

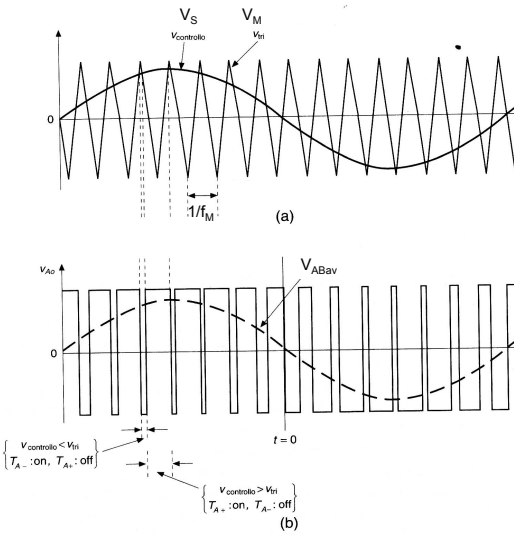
DC/AC converter (Inverter)

The inverter is a DC/AC converter. It converts a DC power supply in input in a sine (AC) power output.
The inverters are widely used for uniterruptible power supply (UPS) and AC motors. By using as input block a rectifier bridge they can also convert the constant amplitude and frequency AC power of the main grid, in a variable AC power of given amplitude and frequency, to control the speed and power of AC motors (AC/AC converters).

The basic scheme is based on the bridge converter configuration, operating in the bipolar switching mode. To obtain a sine output voltage V_{ABav} we need to vary the duty cycle D_1 in time according to the sine waveform. The frequency f_S of the sinusoidal output must be obviously much less than the switching frequency $f_M = 1/T$, to allow a good filtering of f_M with LC filter, while leaving unaltered the f_s of the sine output.

To obtain the above a PWM modulation is used, as described before, by comparing a sawtooth signal at a frequency f_M (that corresponds to the frequency 1/T that opens and closes the switches) with a sine f_S that corresponds to the control signal.
Again one must note that if an AC output of a relatively high frequency f_S is needed (say above some KHz) the switching frequency for a good filtering must be in the range of some hundreds of KHz, and that poses a challenge for the power devices needed.

Here it is schematically indicated the PWM scheme needed to obtain a sine output from a bridge converter.



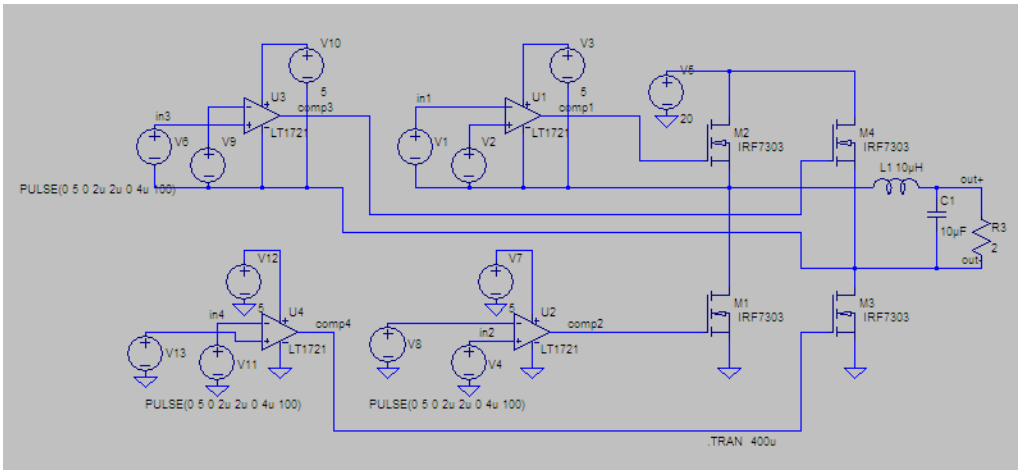
The T_{A+} and T_{B+} switches are driven by the comparator output (while the T_{A-} and T_{B-} by the inverted one). The comparator makes a comparison between the V_S and V_M waveforms

For $V_S > V_M$ T_{A+}(and T_{B-}) is closed and $V_{AB} = V_i$

For $V_S < V_M$ T_{B+} (and T_{A-}) is closed and $V_{AB} = -Vi$

The modulation frequency f_M (and his harmonics) is filtered from the output leaving the sine waveform V_{ABav}.

Schematic of a Bridge DC/AC Converter with Power MOS



Drive circuits for High side devices

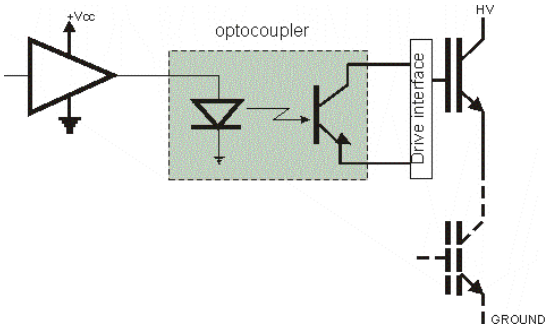
There are many ways to drive MOSFET/IGBT with discrete components; however IC Drivers offer convenience and features that attract designers.
The foremost advantage is compactness. IC Drivers intrinsically offer lower propagation delay. As all important parameters are specified in an IC Driver, designers need not go through time consuming process of defining, designing and testing circuits to drive MOSFET/IGBTs.

For driving the upper MOSFET/IGBT in a bridge topology, or in a buck converter, low side drivers or integrated IC drivers cannot be used directly. This is because the source/emitter of upper MOSFET/ IGBT is not connected at ground potential.

Galvanic isolation between drive and power device can be obtained by using transformers. This is a very old technique, and depending on the range of frequencies being handled and power rating, transformers can be designed to be quite efficient. The gate drive transformer carries very small average power but delivers high peak currents at turn-on and turn-off of MOSFET/IGBT.
The main problem is the bandwidth of the transformer that must give at the output pulses and not sine waves (pulse transformers)

Drive circuits: optoisolator

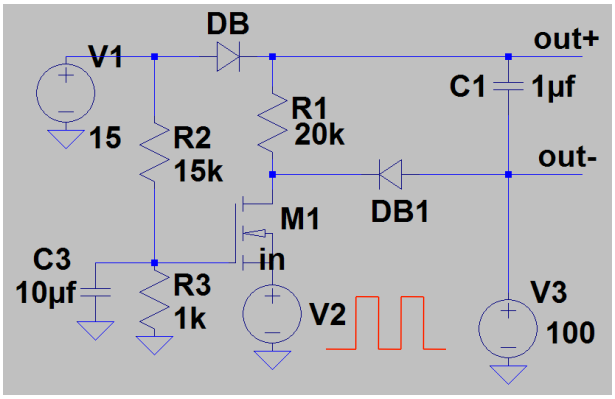
A galvanic isolation can be also obtained by using opto-couplers to drive high side devices. They are made by optical coupling between a light emitting diode at the input, and a phototransistor at the output, that gives an amplified collector current when light strikes on its base.



The drive coupling through opto-couplers have the following advantages:
1.They can be used to give a very high isolation voltage; 2500 to 5000 Volts of isolation is achievable by use of proper opto-couplers.
2. Signals from DC to several MHz can be handled.
3. They can be easily interfaced to Microcomputers or other controller ICs or any PWM IC.
One disadvantage is that the opto-coupler adds its own propagation delay.

Drive circuits: bootstrapping technique

Another possibility is to use the Bootstrap Technique as shown in this schematic .



The basic bootstrap building elements are the level shift circuit, made by bootstrap diode DB, level shift transistor M1, bootstrap capacitor C1 and diode DB1.
The bootstrap capacitor is the floating, source-referenced component of the bootstrap arrangement, generating a d.c. voltage across it that can be used to bias the drive IC of the high side IGBT. Here a voltage of 100V has been assumed as the output (common point) of a bridge arm.

The previous circuit shows how a charge pump creates a higher Vcc to be used for the driver IC for the Upper MOSFET/IGBT.
Here the pair of N-Channel and P-Channel MOSFETs acts as switches, alternately connecting incoming supply voltage to output through capacitors and Schottky diodes, isolating it and almost doubling it.
Switching frequency in several hundred Kilohertz is used and, therefore, low ripple isolated output voltage is available as DC Supply for the Driver of Upper MOSFET/IGBT.
The disadvantages of this technique are longer turn-on and turn-off delays and 100% duty cycle is not possible