1. Objectives - introduction

The converters change the constant voltage of a given value into a constant voltage of another value (or polarity) by means of changing the DC voltage to the pulse train, from which the DC component is then recovered.
A characteristic feature of choke converters is the use of an inductive element (choke !) to store energy in the electromagnetic field, which is then transferred to the load. This process may vary depending on the system parameters, load and way of control - Fig.1.1.

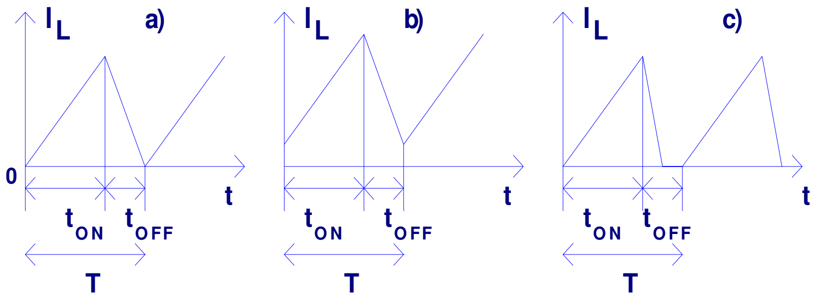


Fig. 1.Current waveforms in the choke: a) critical continuous mode, b) continuous mode, c) discontinuous mode.

In a critical continuous mode, the energy of the electromagnetic field is collected during t_{ON} (key on) and completely transferred to the load during t_{OFF} (key off). At the end of the pulse period T, the choke current that had the peak value I_{Lpk} reaches zero (Fig. 1a).
In the continuous mode - Fig. 1b at the end of the time interval t_{OFF} (key off) the accumulated energy at time t_{ON} is not fully transferred to the load, so the inductor current IL does not reach zero at the end of the period T.
In contrast to the above-mentioned processes in the discontinuous mode - Fig. 1c, the choke energy is transferred faster to the load and the value of the inductor current I_L reaches zero before the end of the pulse period T – hence this is discontinuous mode.
There are 3 basic types of choke converters:
• step down system (buck),
• step up system (boost),
• inverting converter (buck-boost).

1.1. Step down converter (buck converter)

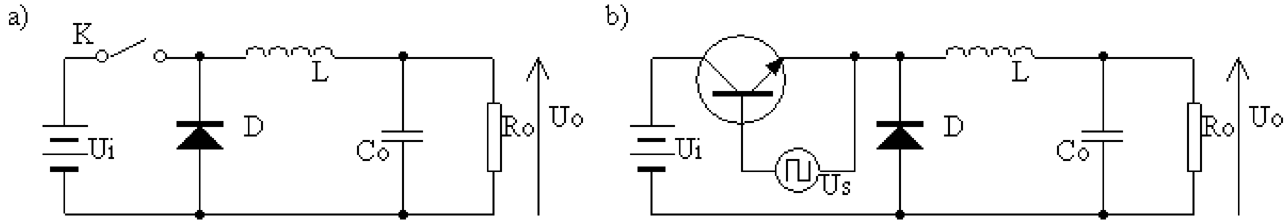


Fig. 2.Step down converter: a) model b) diagram.

Elements of the model - Fig. 2a - have the following properties:

- key at time t_{ON} - short-circuit (R = 0) and t_{OFF} - opening (R = ∞),
- diode D is a perfect rectifier - in the foreword polarization diode series resistance $R_D = 0$ and voltage drop $U_F = 0$, while in the reverse state the diode does not conduct - $R_D = \infty$,
- the choke is in an ideal inductive element, lossless,

Assuming above simplifications, the following relations were obtained, which are valid in the continuous mode - Fig.1.1a.

1.1.1. Operation principle

If the key K - Fig. 2a- is shorted, then the inductor current I_L increases linearly in time t_{ON} to the peak value I_{Lpk} (the diode during this time is polarized reversely). At the moment the K-key is open, the energy stored in choke induces a SEM of the opposite sign, diode D begins to conduct and the accumulated energy goes to the load R_0. Capacitor C_0 acts as a low-pass filter reducing the ripples of output voltage U_{rip}

The relationship of the output voltage U_0 with the input (supply) voltage U_i is:

$$U_0 = \gamma U_i$$

where:

$$\gamma = \frac{t_{ON}}{T}$$

is a duty cycle of the pulse train.

$$T = t_{ON} + t_{OFF}$$

period.

As $\gamma = \frac{t_{ON}}{t_{ON}+t_{OFF}} < 1$, so $U_o < U_i$, - step-down converter.

Peak-peak value of inductor current I_{Lpk} (Fig. 1– continuous mode) can be estimated as:

$$I_{Lpk} \cong 2I_0$$

where $I_0 = \frac{U_0}{R_0}$ - load current.

Inductance of the choke can be estimated from equation:

$$.L \geq \frac{U_i}{I_{Lpk}} t_{ON}$$

When designing a real system (Fig. 2.b) one should take into account that across the transistor and diode in the conduction state exists voltage drops, respectively: U_{CEsat} (about 0.5V - 1V) and $U_F \approx 0.4V$ (Schottky diode) and furthermore there are power losses as well as delays during switching (recall the large-signal models and the phenomena in semiconductors during pulse operation).

Typically, the converter works as a voltage controller of a given range of input voltages $U_{imin} \leq Ui \leq U_{imax}$,. - regulation range) is realized by changing the duration of energy storage in the choke $t_{ONmin} \leq t_{ON} \leq t_{ONmax}$. Therefore, the peak current of the choke estimated as;

$$I_{Lpk} \cong 2I_{0max},$$

where $I_{o\,max}$ – maximum average load current
Minimum choke inductance L_{min} can be estimated as

$$L_{min} \cong \frac{U_{imin} - U_{CEsat} - U_0}{I_{Lpk}} t_{ONmax},$$

where:

$$t_{ONmax} = \frac{U_0}{U_{imin}} T$$

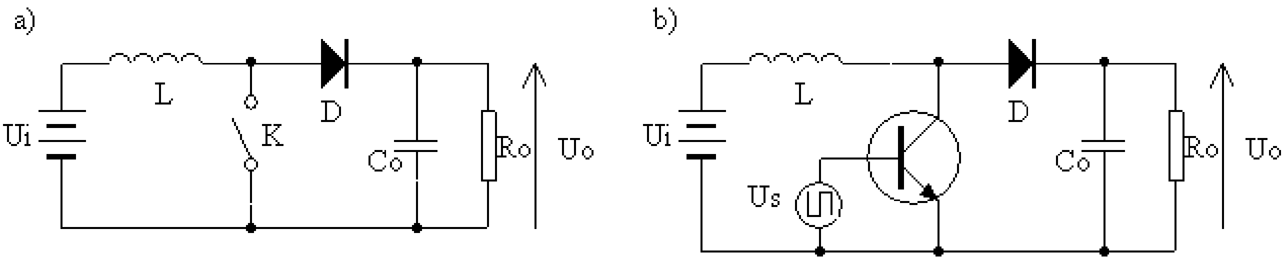
The real choke is the winding (coil) on the ferromagnetic core, so one need to take into account the ohmic losses in the conductor (the phenomenon of skin effect), the capacitance between the turns (neglected when there are only a few turns), the hysteresis loop, losses in the ferromagnetic material and the phenomenon of decreasing the inductor of the choke due to DC magnetization (saturation of the core) – to avoid magnetization a core with air gap is recommended.
The valu of filtering capacitor can be calculated as:

$$C_0 \geq \frac{I_{Lpk} T}{8 U_{tpp}},$$

where U_{rip} – acceptable ripple voltage (peak to peak).

1.2. Up converter (boost converter)

The relevant diagrams are shown in Fig.1.3..



Rys.1.3. Up converter : a) model, b) reat circuit.

1.2.1. Principle of operation

If the key K (Fig.1.3.a) is short, the I_L inductor current increases linearly, and at the end of the time interval t_{ON} reaches the peak value I_{Lpk}. At this moment, the flow of inductor current I_L is interrupted and the energy stored in the magnetic field induces SEM, which is added to the supply voltage Ui. Therefore, the voltage Uo on the capacitor Co and the resistor Ro is the sum of the supply voltages Ui and SEM of the choke (in a perfect model of the phenomenon, the voltage drop across the diode is negligible as well as voltage drop across closed key).
In the idealized model - Fig.1.3a the following relations take place (continuous mode)

$$U_0 = \frac{U_i}{1-\gamma} \ ,\gamma = \frac{t_{ON}}{T}$$

so– $U_o \geq U_i$, - the circuit i san up-convereter.
Peak choke current

$$.I_{Lpk} = 2I_{0max}\left(\frac{t_{ON}}{t_{OFF}} + 1\right) = 2I_{0max}\frac{U_0}{U_i}$$

Inductance L of the choke can be estimated as

$$L \cong \frac{U_i}{I_{Lpk}} t_{ON}.$$

When designing a real system (Fig.1.3b), a correction should be made due to changes in the supply voltage.
Teraz

$$L_{min} = \frac{U_{imin} - U_{CRsat}}{I_{Lpk}} t_{ONmax}, \quad (1\text{-}13)$$

where

$$t_{ONmax} = 1 - \frac{U_{imin}}{U_0} T. \quad (1\text{-}14)$$

1.3. Inverter (buck-boost coneter)

The relevant diagrams are shown in Fig. 3

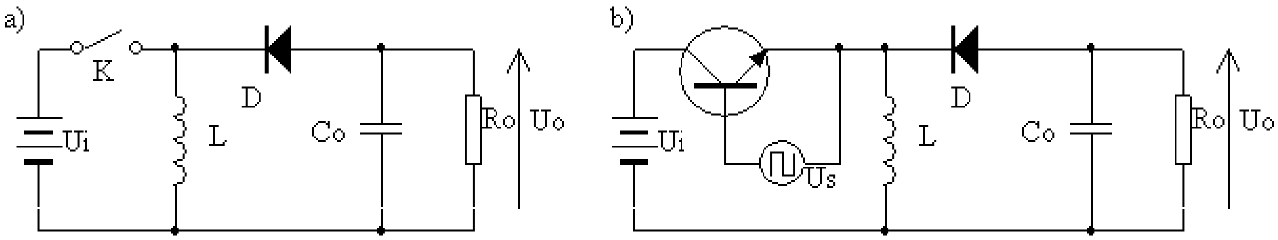


Fig. 3.Inverter : a) model b) real circuit

1.3.1. Principle of operation

If the key K - Fig. 3a is shorted, the inductor current I_L increases linearly, and at the end of the time interval t_{ON} reaches the peak value I_{Lpk} (the diode D is polarized reversely). When the current flow is interrupted, in the choke, SEM with opposite polarity is induced, the diode D goes into conduction mode and the current flow through the load R_0.
Assuming that the choke works in a continuous mode and the elements of the system are perfect - Fig. 3a, the following dependences can be obtained

$$|U_0| = \frac{\gamma}{1-\gamma} \ ,\gamma = \frac{t_{ON}}{T} < 1,$$

or

$$\frac{|U_0|}{U_i} = \frac{t_{ON}}{t_{OFF}}$$

$$I_{Lpk} = 2\,I_{0\max}\left(\frac{t_{ON}}{t_{OFF}} + 1\right),$$

$$L \cong \frac{U_i}{I_{Lpk}} t_{ON}.$$

Taking into account the range of changes in the input voltage U_i, the design dependencies should be corrected:

$$L_{min} \cong \frac{U_{imin} - U_{CEsat}}{I_{Lpk}} t_{ONmax}$$

where

$$t_{ONmax} = \frac{|U_0|T}{U_{imin} + |U_0|}$$

2. Components and instrumentation

The following are schematic diagrams of three inverter circuits drawn on the basis of data sheets of the MC34063 integrated circuit (DC/DC controller) by Motorola, and the related images of printed circuit boards.

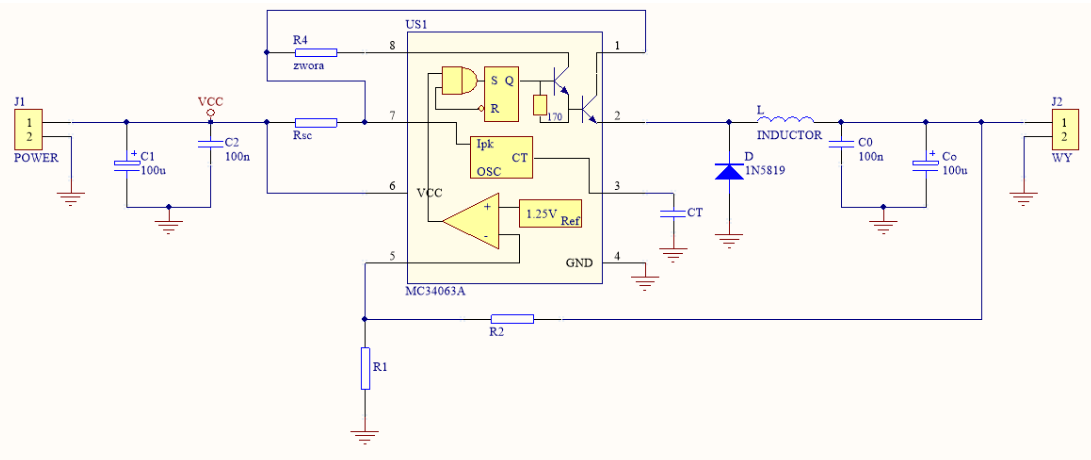


Fig. 4.Application diagram of MC34063 as step-down converter.

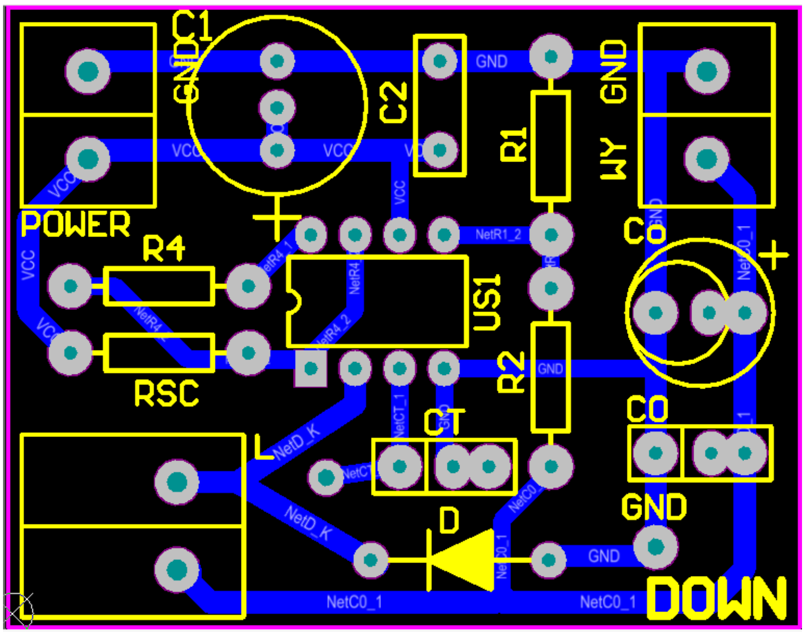


Fig. 5.PCB od down-conveter

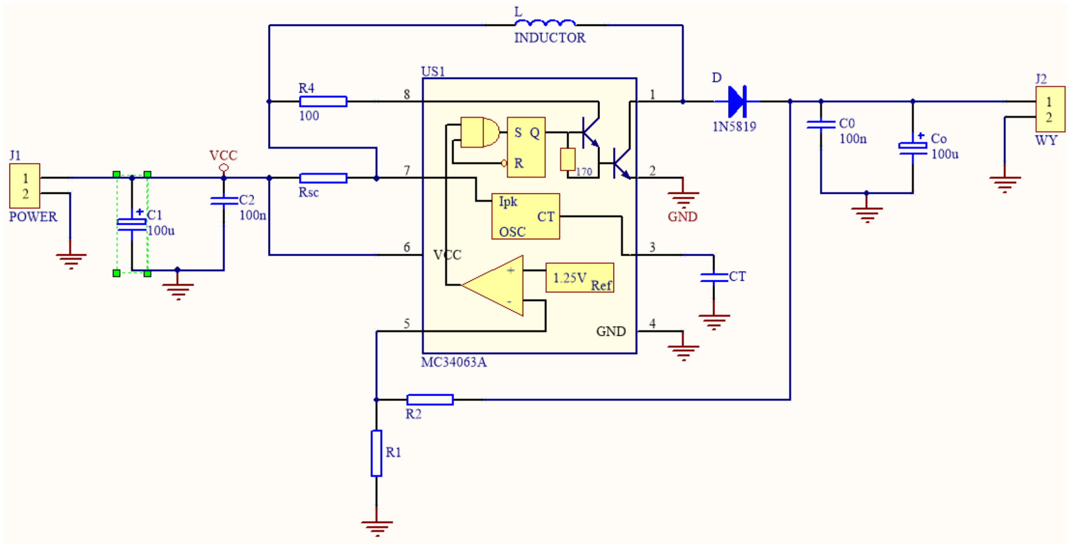


Fig. 6.Application diagram MC34063 as up-converter

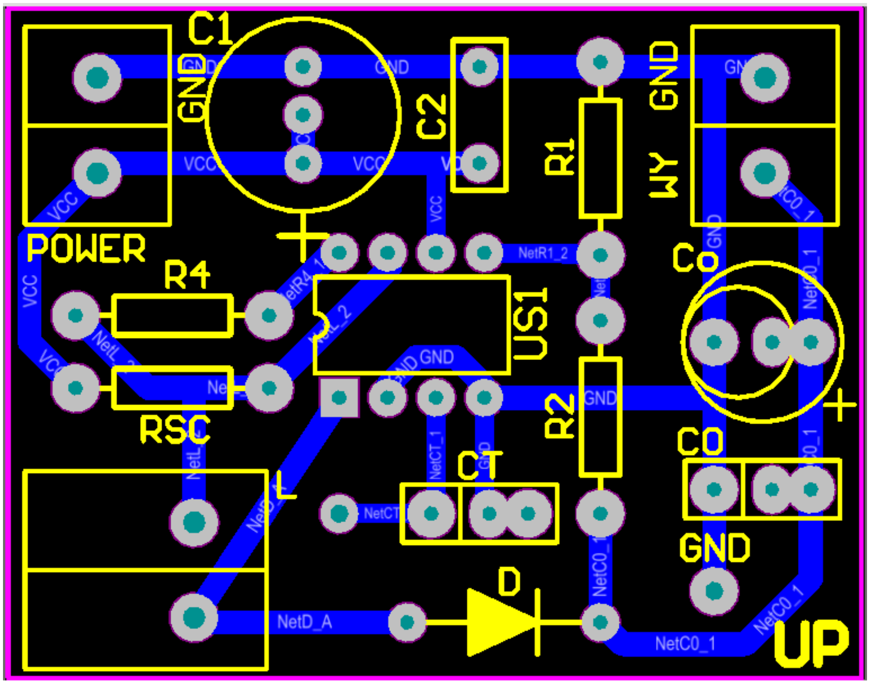


Fig. 7.PCB of up-converter

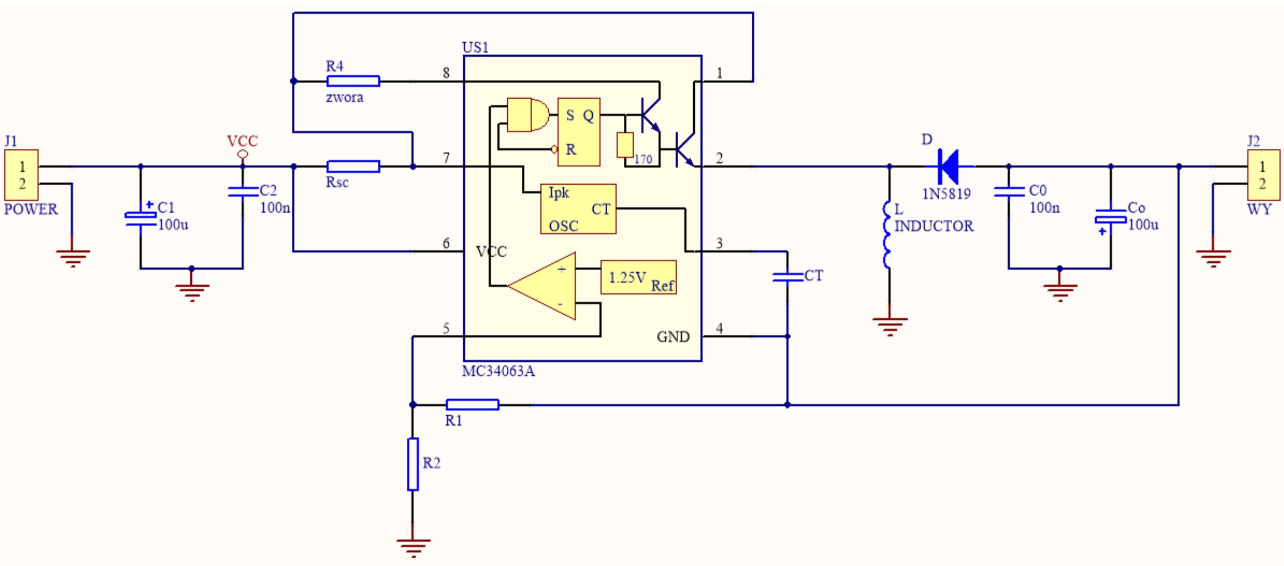


Fig. 8.Application diagram of MC34063 as inverter

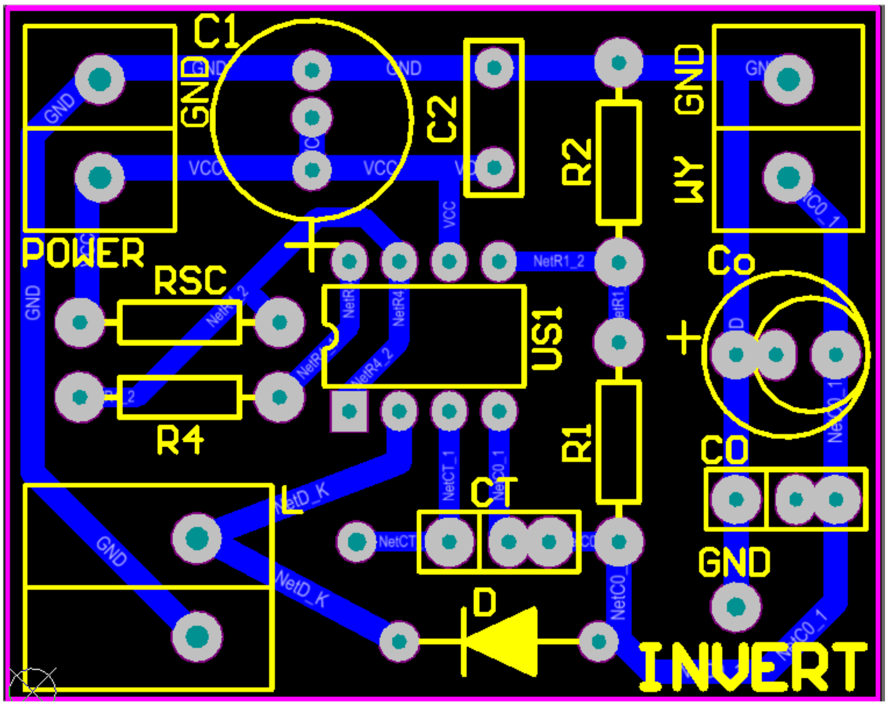


Fig. 9.PCB of an inverter

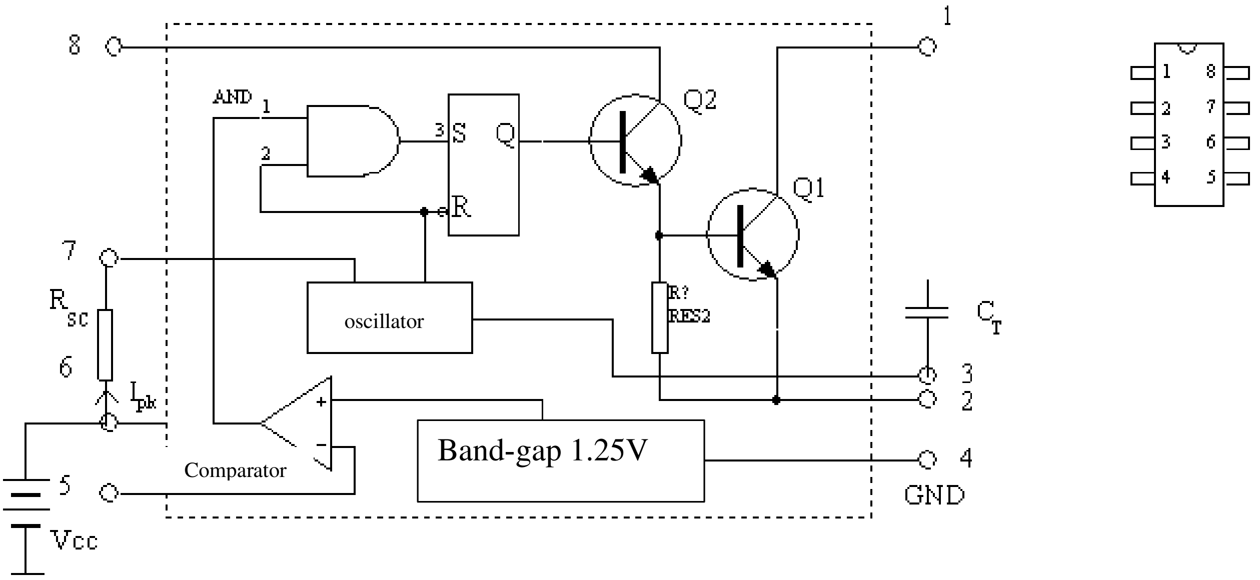


Fig. 10.Block diagram of MC34063

MC34063 controller consists of 1.25V reference voltage source, comparator, oscillator with adjustable duty factor γ, protection system against exceeding the permissible peak value key current (I_{pk} current is sampling via shunt resistor R_{SC}) and electronic key (switch) composed of transistors Q1 and Q2 in the Darlington configuration.
The pulse period T is determined by means of an external C_T capacitor of a suitable value. Manufacturers of the MC34063 IC adapted the system to the structure of three basic types of choke converters - Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9.

3. Preparation

3.1. Readings

[1] Lab materials and lectures of the course.
[2] U. Tietze, Ch. Schenk, Electronic circuits. Handbook for Designers and Applications, Springer, 2008, p. 907-926, .
[3] P. Horowitz, W. Hill, The Art of Electronics, Cambridge Univ. Press, London, 2015, p. 636-674

3.2. Problems

1. What is the operation principle of the step down converter – derive the simplified formula for the output voltage; sketch waveforms of currents and voltages?
2. What is the operation principle of the step up converter – derive the simplified formula for the output voltage; sketch waveforms of currents and voltages?
3. What is the operation principle of the inverter – derive the simplified formula for the output voltage; sketch waveforms of currents and voltages?
4. What are the criteria for the selection of system components: choke, transistor, diode and output capacitor C_0

5. Why is the R_{SC} resistor needed to sample the choke current in the system?

3.3. Detailed preparation

Based on data provided by the tutor:

- Type of the converter (up, down, invert)
- Output voltage U_0;
- Input voltage U_i (or range of input voltage U_{imin} U_{imax})
- Maximum output current I_{omax},
- Allowed ripple voltage U_{rip} ,

student should estimate:

- inductance L of the choke,
- resistance of shunt resistor R_{sc} for limiting the maximum key and choke current,
- resistors R_1 i R_2 in the feedback loop,
- capacitor C_T
- output capacitor C_0.

NOTICE: In the lab available are chokes of the inductances 100μH, 150μH, 220μH, 330μH (I_{Lmax}<=1A). It is recommended to choose a little higher value than calculated to limit the peak current I_{Lpkmax}; Capacitor C_T can be chosen from the set {560p, 1n, 1.6n}; It is recommended to choos R_1 = 1.2 kΩ and calculate R_2 and choose the closest value from E24 series.

From data sheet of the IC MC34064 capacitor C_T can be chose assuming operating frequency. From the graph in data sheet times t_{ON} i t_{OFF} can be read out. The t_{ON} can be also calculated from the empirical equation:

$$C_T[pF] \approx 40 t_{ON}[\mu s]$$

Maximum choke current can be estimated as (assuming continuous mode – Fig. 1):

$$I_{Lpk} \approx \begin{cases} 2I_{0max} & ;(down\ converter) \\ 2I_{0max}\dfrac{U_0 + U_F - U_{CEsat}}{U_{imin} - U_{sat}} & ;(up\ converter) \\ 2I_{0max}\left(1 + \dfrac{|U_0| + U_F - U_{CEsat}}{U_{imin} - U_{CEsat}}\right) & ;(inverter) \end{cases}$$

where U_{CEsat} (saturation voltage across the transistor) should be taken from data sheet (c.a. 0.6V) and U_F (foreword diode voltage) can be taken as 0.5V (Schottky diode).
Minimum inductance for which continuous mode is guaranteed can be calculate as:

$$L_{min} \approx \begin{cases} \left(\dfrac{U_{imin} - U_{CEsat} - U_o}{I_{Lpk}}\right) t_{ON} & ;(down\ converter) \\ \left(\dfrac{U_{imin} - U_{CEsat}}{I_{Lpk}}\right) t_{ON} & ;(up\ converter) \\ \left(\dfrac{U_{imin} - U_{CEsat}}{I_{Lpk}}\right) t_{ON} & ;(inverter) \end{cases}$$

where t_{ONmax} can be taken as = t_{ON}, and U_{CEsat} should be read from the catalog notice for I_{Lpk}
The value of shunt resistor can be estimated from:

$$R_{SC} = \frac{0.3V}{I_{Lpk}}$$

Resistors R_1 and R_2 in feedback loop are related to dependence:

$$|U_0| = U_{ref}\left(1 + \frac{R_2}{R_1}\right),$$

where U_{ref} = 1.25V – reference voltage of internal Bandgap circuit.

Capacitor C_0 should be chosen to achieve small enough output ripple voltage:

$$C_0 \geq \begin{cases} \frac{I_{Lpk}}{8U_{rip}}T & ;(down\ converter) \\ \frac{9I_0}{U_{rip}}t_{ON} & ;(up\ converter) \\ \frac{9I_0}{U_{rip}}t_{ON} & ;(inverter) \end{cases}$$

3.4. Simulations

Simulations should be carried out using simplified converter circuits as in– Fig.1.2- 1.4 using transistor 2N2369 or equivalent, and Schottky diode e.g.1N5819.
During simulation one should:

- observe waveforms of voltages and currents and compare them with that calculated, in particular, pay attention to the shape of the inductor current I_L (t).
- try to calculate the energy efficiency,
- chose t_{ON} for different U_{imin} and U_{imax} so, to achieve the same output voltage U_o - notice changes in inductor current

4. Contest of the report

1. Assemble the circuit according to schematic diagram and PCB (one of Fig. 5, Fig. 7, Fig. 9).
2. Assemble the measurement setup as in Fig. 11. Pay attention for polarization of input voltage and check if the circuit is working properly for nominal input voltage and highest possible R0.

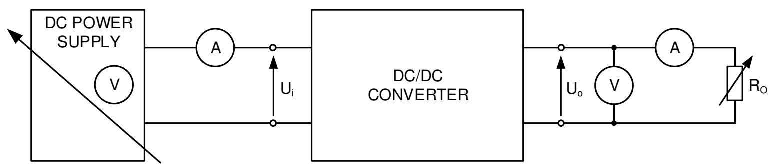


Fig. 11. Measurement setup.

4.1. Measurement of Converter Working Frequency

3. Adjust input voltage and R_L for nominal values $U_i = U_{inom}$. Using scope with probe "x10" observe the voltage on C_T and/or choke. To stabilize the waveform on the scope can be necessary to adjust R_L. Save most representative waveform and print it in report – compare with that achieved in simulations.

4.2. Relationship $U_O = f(U_i)$ measurement, for R_O as parameter

4. Connect the DC power supply to the regulator input and adjust the load in series with the ampermeter. Connect voltmeters to the input (can be used the internal one in power supply) and output (Fig. 11).
5. Measure and plot the relationship $U_O = f(U_I)$ for at least one load resistance R_L.
6. Estimate the ΔU_0 (in the range of satisfactory value of $\underline{U_0}$) for the given load resistance and calculate the stabilization coefficients S_U,

$$S_U = \frac{\Delta U_0}{\Delta U_i}$$

7. Specify the minimum input voltage U_{imin} for which nominal output voltage is achieved for given R_L value.

4.3. Relationship $U_0 = f(I_0)$ measurement with, U_I as parameter

8. Measure and plot the relationship $U_0 = f(I_0)$, for at least one input voltage U_i. Measurements should be performed by changing the load resistance value from the unloaded state ($R_L = \propto$) to the shorted state ($R_L = 0$).
9. Determine the output voltage stabilization range ΔU_0 (in the range of satisfactory value of U_0) and the value of the output resistivity of the converter.

$$r_{out} = \frac{\Delta U_0}{\Delta I_0}$$

4.4. Power efficiency measurement

10. For nominal input voltage and for different load R_L calculate the power efficiency:

$$\eta = \frac{P_0}{P_i} = \frac{U_O I_0}{U_{inom} I_i}$$

where $P_0 = U_0 I_0$ power dissipated in the load. Plot the function $\boldsymbol{\eta = \eta(I_0)}$

4.5. Reference voltage measurement

11. Using a voltmeter, measure the reference voltage of the regulator (U_{REF} - voltage drop on R_1). Take the measurement with unloaded converter ($R_O = \propto$).

5. Appendices – proposed result tables.

N0.	**Relationship $U_o = f(U_i)$**	
	R_L = ……Ω, ($I_{o\ nom}$ = ...A)	
	S_U = ………..V/V	
	U_i [V]	U_o [V]
1.		
2.		

N0.	**Relationship $U_O = f(I_O)$**					
	U_{in} = …….V					
	r_{out} = …….Ω					
	U_o [V]	I_i [mA]	I_o [mA]	P_{in} [W]	P_{out} [W]	η [%]
1.						
2.						