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Charge Pump Buck Converter

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Abstract – The paper proposes a new DC/DC converter topology, based on Buck converter principle. The new converter assures soft turn-on and soft turn-off of the active devices. During of each commutation, the converter pumps a defined charge to the load circuit. Due to this fact, the converter's output current can be easily controlled through the switching frequency. The control through the charge is very efficient for low rates between output voltage and input voltage. The main equations that can be used for the converter's design are also presented in the paper.

Keywords: dc/dc power converter

I. INTRODUCTION

The circuit scheme of the proposed converter is shown in fig.1. The circuit composed by switches $S_1 \div S_4$ and capacitor C is equivalent to a controlled switch that reminds by the Buck's converter configuration. One time the switches S_1 and S_3 are turned on and the switches S_2 and S_4 are turned off and the other time the switches S_2 and S_4 are turned on and the switches S_1 and S_3 are turned off. The devices which are turned on are naturally turned off when the voltage across capacitor C becomes $\pm U_i$ (input circuit voltage –fig .1).

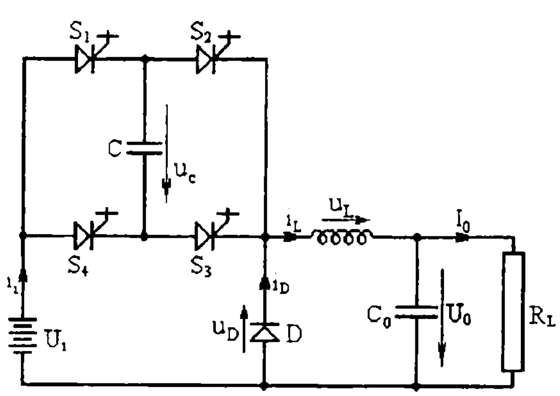

Fig. 1. Proposed circuit topology

With respect to the shape of the inductance current i_L, two conduction modes can be performed:

- Discontinuous operation mode, when the current through the inductor L has zero value intervals.
- Continuous operation mode, when the current through the inductor L has no zero value intervals.

II. DISCONTINUOUS MODE OPERATION

Discontinuous operation mode is described in Fig.2. There are six stages.

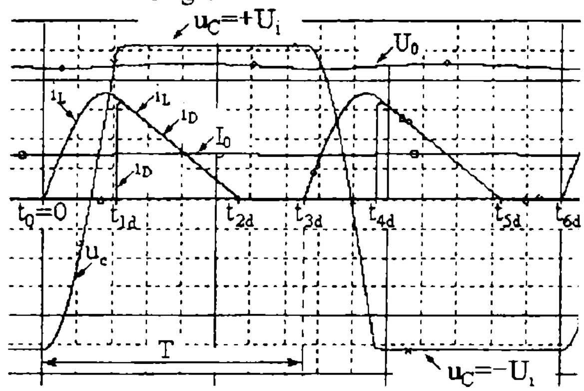

Fig. 2. Discontinuous mode circuit operation

D.1. The First stage

The First stage [$t \in (t_0 ; t_{1d})$] starts in t_0 when S_1 and S_3 are soft (ZCS – zero current switch) turned on. The voltage across capacitor C at point t_0 is ($-U_i$), where U_i is the converter DC input voltage. In this stage, the resonant L-C circuit assures a resonant charge of the capacitor C, from ($-U_i$) to ($+U_i$). For this stage the input current $i_i(t)$ is equal to inductance current $i_L(t)$ (Fig.2). The diode D is off due to the negative value of the voltage across it. The equivalent circuit for this stage is plotted in Fig. 3. The equations which described the behaviour of the circuit are:

$$U_i = u_C(t) + u_L(t) + U_0 \tag{1}$$

We suppose that the input voltage U_i and the output voltage U_0 have constant DC values.
The relations (2) are also available.

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$$u_L(t) = L\frac{di_L(t)}{dt} \qquad u_C(t) = \frac{1}{C}\int i_L(t) \qquad (2)$$

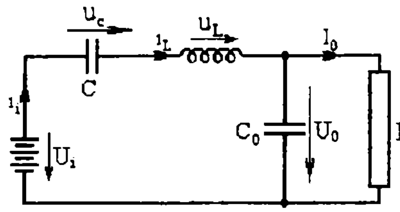

Fig. 3. Equivalent circuit for stage 1

Relations (2) are inserted in equation (1) and equation (3) might find out:

$$\frac{d^2 i_L(t)}{dt} + \omega_0^2 i_L(t) = 0 \quad \text{where} \quad \omega_0^2 = \frac{1}{LC} \qquad (3)$$

At the point $t_0=0$ the values of the current through the inductance and voltage across capacitor C are:

$$i_L(t_0 = 0) = 0 \quad \text{and} \quad u_C(t_0 = 0) = -U_i \qquad (4)$$

From equation (1) the voltage across inductance, in point t_0 is :

$$u_L(t_0 = 0) = U_i - u_C(t_0) - U_0 = 2U_i - U_0 \qquad (5)$$

Solving equation (3) according with the initial conditions (4) and (5), the main circuit's electric parameters may be find out:

$$\begin{aligned} i_L(t) &= C\omega_0(2U_i - U_0)\sin\omega_0 t \\ u_C(t) &= U_i - U_0 - (2U_i - U_0)\cos\omega_0 t \\ u_L(t) &= (2U_i - U_0)\cos\omega_0 t \end{aligned} \qquad (6)$$

The voltage across diode D (Fig. 1.), is:

$$u_D(t) = -U_0 - (2U_i - U_0)\cos\omega_0 t \qquad (7)$$

At the point $t_0=0$, the voltage across diode D is ($-2U_i$) and represent the maximum reverse voltage of this device. At the point t_{1d}, the voltage across diode D is zero, and diode is soft turn on. The point t_{1d} can be find out from equation (7):

$$t_{1d} = \frac{1}{\omega_0}\arccos\left(-\frac{U_0}{2U_i - U_0}\right) \qquad (8)$$

At the point t_{1d} the voltage across capacitor C has a maximum value of:

$$u_C(t_{1d}) = +U_i \qquad (9)$$

The capacitor C must be a bipolar one with a breakdown voltage larger than the input voltage U_i.

The maximum current I_{LMd} through the inductance is performed when $\omega_0 t=0.5.\pi$ (from equation 6).
At point t_{1d} the current I_{1d} through the inductance may be find out from equations (6) and (8).

$$I_{LMd} = i_L\left(\frac{\pi}{2\omega_0}\right) = C\omega_0(2U_i - U_0) \qquad (10)$$

$$I_{1d} = i_L(t_{1d}) = 2C\omega_0\sqrt{U_i^2 - U_i U_0} \qquad (11)$$

D.2. *The Second stage*

The Second stage [$t\in(t_{1d}\ ;\ t_{2d})$] starts at point t_{1d} when the currents through S_1 and S_3 become zero, the voltage across capacitor C becomes ($+U_i$) and diode D turns on. During this stage the devices S_1 and S_3 may be soft (ZCS) turned off before point t_{2d}. The currents $i_L(t)$ and $i_D(t)$ are equal and they linearly decrease to zero in the time interval $t_{1d} \div t_{2d}$.
The equivalent circuit for this stage is presented in Fig.4.

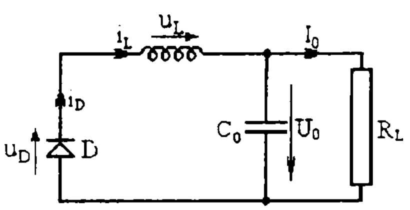

Fig. 4. Equivalent circuit for stage 2 and 4

The equations which describe the behaviour of the circuit are:

$$\begin{aligned} u_L(t) &= L\frac{di_L(t)}{dt} \\ u_L(t) + U_0 &= 0 \end{aligned} \qquad t\in[t_{1d}, t_{2d}] \qquad (12)$$

Solving the equation (12) according to the restriction presented in relation (11), the current variation through inductance L, may be find out:

$$i_L(t) = -\frac{U_0}{L}(t - t_{1d}) + 2C\omega_0\sqrt{U_i^2 - U_i U_0} \qquad (13)$$
$$t \in [t_{1d}, t_{2d}]$$

From the equation (13), the point t_{2d} when the current $i_L(t)$ becomes zero, may be find out:

$$t_{2d} = t_{1d} + \frac{2}{\omega_0 U_0}\sqrt{U_i^2 - U_i U_0} \qquad (14)$$

D.3. *The Third stage*

The third stage [$t\in(t_{2d}\ ;\ t_{3d})$] is characterized by zero current values for all semiconductor devices. In this stage the load is fed only by the energy stored in the output capacitor C_0 . The voltage across the capacitor C is preserved and its value is $+U_i$.

D.4. The Fourth stage

The fourth stage [$t \in (t_{3d} ; t_{4d})$] starts in t_{3d} when S_2 and S_4 (Fig.1) are soft (ZCS – zero current switch) turned on. Due to this fact, the equivalent circuit from Fig.3 is valid, but the capacitor C is connected in a reverse position. All the equations presented till now are valid with the correction (15).

$$u_C(t) \rightarrow -u_C(t) \quad t \in [t_{3d}, t_{6d}] \tag{15}$$

In this stage, the resonant L-C circuit assures a resonant charge of the capacitor C, from $+U_i$ to $-U_i$. The currents behaviour is similar to those described in the first stage. In the point t_{4d} the voltage across capacitor C is ($-U_i$) (see Fig. 1 and Fig,2). The devices S_2 and S_4 naturally turn off because the current flow is soft commutated through diode D.

D.5. The Fifth stage

In this stage [$t \in (t_{4d} ; t_{5d})$] the current through the inductance L (Fig.1, 2 and 3) linearly decrease to zero. The equations (12), (13), (14) and the equivalent circuit plotted in Fig. 4 are also valid. The turn of command for the devices S_2 and S_4 (Fig.1) may be performed in this stage too. The charge of the capacitor C is preserved till to the point t_{6d} (Fig.2).

D.6. The Sixth stage

This stage [$t \in (t_{5d} ; t_{6d})$] is similar to the third stage (Fig.2). The currents through the inductance L and through the diode D are zero, and the load is fed only by the energy stored in the output capacitor C_0 . The voltage across the capacitor C is preserved and its value is $-U_i$.

Energetic evaluation

During the first and the fourth stage, the input source U_i , deliver to the circuit a charge quantity equal with:

$$\Delta Q = \int_{t_0}^{t_{1d}} i_L(t)dt = C[u_C(t_{1d}) - u_C(t_0)] = 2CU_i \tag{16}$$

That means that for each turn on operation, the input source U_i , delivers to the circuit a quantity of energy ΔW, equal with:

$$\Delta W = \int_{t_0}^{t_{1d}} U_i \cdot i_L(t)dt = U_i \cdot \Delta Q = 2CU_i^2 \tag{17}$$

The power absorbed from the input source is:

$$P_i = \Delta W f = 2CU_i^2 f \tag{18}$$

where f is the frequency of switch on signals, equal to the frequency of current pulses which flow through the inductance L.. This frequency is two times greater than the circuit operation cycle's frequency (Fig.2).

$$f = \frac{1}{T} = \frac{1}{t_{3d} - t_0} = \frac{2}{t_{6d} - t_0} \tag{19}$$

If we consider no loses in the circuit, the output power P_0 is equal to the input power P_i .

$$P_0 = P_i \Leftrightarrow U_0 I_0 = 2CU_i^2 f \tag{20}$$

If it's imposed a fix dc output voltage, the switch on frequency f is linear dependent by output current I_0.

$$f = \frac{U_0 I_0}{2CU_i^2} \tag{21}$$

The converter controls the output current by means of the switch frequency of the devices $S_1 \div S_4$. The boundary between discontinuous and continuous operation mode is performed by the following equation:

$$t_{2d} - t_0 = T = \frac{1}{f} \tag{22}$$

According to the equations (8) and (14), the maximum switch frequency for the discontinuous operation mode, f_{MD} is:

$$f_{MD} = \frac{1}{T_{mD}} = \tag{23}$$

$$= \left[\frac{1}{\omega_0} arccos\left(-\frac{U_0}{2U_i - U_0} \right) + \frac{2}{\omega_0 U_0} \sqrt{U_i^2 - U_i U_0} \right]^{-1}$$

III. CONTINUOUS MODE OPERATION

For continuous mode operation, the switch frequency must be larger than f_{DM} , defined in the equation (23). In this case, the current through the inductance L, will never has a zero value. The stages three and six from Fig.2, are not any more. The behaviour of the circuit can be described by four stages, only two of them being different (Fig.5).

C.1. The First stage

The first stage [$t \in (t_0 ; t_{1c})$] may be defined almost identically like in the discontinuous mode operation.

The equivalent circuit is also the same (Fig. 3) and the equation which described the circuit behaviour are similar to equations (1), (2) and (3).

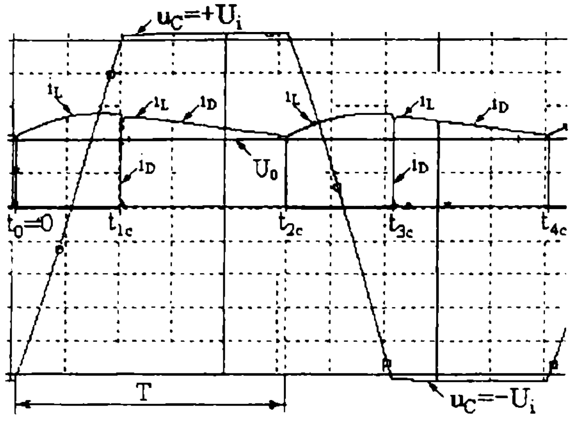

Fig. 5. Continuous mode circuit operation

The initial conditions are different. These are:

$$i_L(t_0=0)=I_{L0} \text{ and } u_C(t_0=0)=-U_i \qquad (24)$$

According with these initial values, the relations of the main circuit's electric parameters may be find out:

$$\begin{aligned} i_L(t) &= C\omega_0(2U_i-U_0)\sin\omega_0 t + I_{L0}\cos\omega_0 t \\ u_C(t) &= U_i-U_0-(2U_i-U_0)\cos\omega_0 t + \\ &\quad +\omega_0 L I_{L0}\sin\omega_0 t \qquad (25) \\ u_L(t) &= (2U_i-U_0)\cos\omega_0 t - \omega_0 L I_{L0}\sin\omega_0 t \end{aligned}$$

where I_{L0} represent the initial (or minimal) value of the current through the inductance L (equation 24).
At the point t_{1c} the voltage across diode D becomes zero and the voltage across the capacitor C becomes equal to $+U_i$. According to equations (25), the equation (26) might be written:

$$\omega_0 L I_{L0}\sin\omega_0 t_{1c} - (2U_i-U_0)\cos\omega_0 t_{1c} = U_0 \qquad (26)$$

Also, at the point t_{1c}, the current through the inductance L, will be :

$$I_{1c} = C\omega_0(2U_i-U_0)\sin\omega_0 t_{1c} + I_{L0}\cos\omega_0 t_{1c} \qquad (27)$$

C.1. The Second stage

The second stage [$t\in(t_{1c};t_{2c})$] starts at the point t_{1c}, when the current through the devices S_1 and S_3 is soft transferred through the diode D. In the point t_{2c} a new turn on commutation of the devices S_2 and S_4 is performed. The point t_{2c} is in accord with the equation:

$$t_{2c} = t_0 + T = 0 + T = T \qquad (28)$$

where $(T)^{-1}$ is the circuit switch frequency. The current through the inductance L, has a similar equation as in the discontinuous mode operation:

$$i_L(t) = -\frac{U_0}{L}(t-t_{1c}) + I_{1c} \qquad t\in[t_{1c},t_{2c}] \qquad (29)$$

At the point t_{2c} the current through inductance L will have again the value I_{L0}. Combining (28)with (29), results:

$$I_{L0} = I_{1c} - \frac{U_0}{L}(T-t_{1c}) \qquad (30)$$

From equations (26), (27) and (30), the values of t_{1c} and I_{L0} may be find out.
The stages tree and four are similar to the stages one ... .
In the continuous operation mode, the relations (20) and (21) are preserved, so for a known output voltage the needed output current may be delivered using a circuit switch frequency given by the relation (21). Theoretically the switch frequency, f, might be as large as the current I_0 fix it, according to equation (21). Practically the maximum switch frequency is dependent by the switching performances of the diode D which support a pulsed current with the frequency f (21), and by the switching performances of the devices $S_1\div S_4$ which have to support a pulsed current with a frequency of 0.5f.
The maximum value I_{LMc}, of the current through the inductance L is:

$$I_{LMc} = \sqrt{I_{L0}^2 + \omega_0^2 C^2 (2U_i - U_0)^2} \qquad (31)$$

IV. CONCLUSIONS

The circuit presented in this paper has the following advantages than the conventional buck circuit:

- It is able to control the output current by means of the circuit switch frequency and the value of capacitor C. This assures very small ratio between output voltage U_0 and input voltage U_i. These small rates are difficult to be assured by the standard Buck converter at a high frequency.
- The circuit can be easily controlled by switching frequency.
- The circuit assure soft commutations both for the switching devices $S_1\div S_4$ and for the diode D.
- It is important that the turn off of the devices $S_1\div S_4$ are performed at zero current and at zero voltage too (it is a natural turn off). The zero current state and then reverse voltage across these devices are sustained for a long period of time, so this devices have no power loses at turn off. Due to this fact, the single restrictions for the devices $S_1\div S_4$ selection is to have good turn on capabilities. For high power operation, fast thyristors may be used.

- The possibility to design and to select the inductance L in relation with capacitor C, gives to designer the possibility to select a less value for the inductance than for the standard Buck converter for the same performances.

The circuit can be used for high power and for small power too.

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