STUDY OF A DC-DC DUAL CHANNEL RESONANT CONVERTER

I. Nagy*/**, J. Hamar*

* Technical University of Budapest, Department of Automation
H-1111 Budapest, Budafoki ut 8. HUNGARY, E-mail: nagy@elektro.get.bme.hu
** Computer and Automation Institute, Hungarian Academy of Sciences

***Abstract* – The paper is concerned with the study of the step-down configuration of a dual channel DC-DC converter family. After a short summary of the basic building blocks, the fundamental principles and operation of the converter family, the theory of the buck configuration is developed and verified by simulation.**
Keywords: Resonant DC-DC converter, asymmetric, symmetric operation, voltage ripple.

I. INTRODUCTION

A special dual channel DC-DC converter family was introduced in [1]. The converter family has step-down, step-up and step up/down configurations. A common feature of the different entities is that they transmit power from input to output through two channels, the so-called positive and negative ones.
Basically two kinds of operation can be distinguished. In the symmetrical case, there is no energy exchange between the positive and the negative channels. In the asymmetrical operation, the time functions of the variables in the two channels are no longer symmetrical ones. From now on our investigations refer to the buck configuration. After a brief summary of the converter family and the operation of one of its members, the step-down or buck converter, the theory for the determination of the output voltages and their ripples will be developed in discontinuous conduction mode (DCM) and continuous conduction mode (CCM) both in asymmetrical and in symmetrical operation. The validity of the theory will be checked by computer simulations in some selected operation points.

II. CONVERTER FAMILY

The resonant converter family has two basic building blocks B_{to} (Fig.1a) and B_{off} (Fig.1b).
Both have controlled switches S_1 and S_2 and one inductance *L*. The controlled switches can conduct current flowing **to** point P in B_{to} and flowing **off** point P in B_{off}.

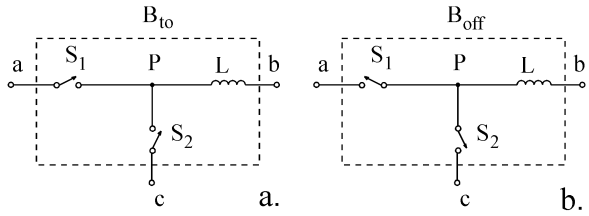

Fig.1. Basic building blocks

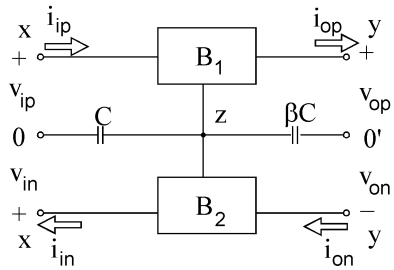

Fig.2. General configuration of the converters

The general configuration of the converters is shown in Fig.2 where two switched capacitances *C* and β*C* are used beside the building blocks. The capacitances across the input and output terminals for short-circuiting the high frequency components of the input and output currents are not shown. Table 1 summarizes the set-up of the three configurations, the buck, the boost and the B&B ones by the two building blocks and their connections to terminals x, y and z. Suffix i and o refer to input and output while suffix p and n refer to positive and negative, respectively (v_{in}<0).
Using Fig.1, Fig.2 and Table 1, the step-down (buck) converter is shown as an example in Fig.3.

Table 1 Set up of the converters

	x	y	z	B_1	B_2
Buck	a	b	c	B_{to}	B_{off}
Boost	b	c	a	B_{off}	B_{to}
B&B	c	a	b	B_{to}	B_{off}

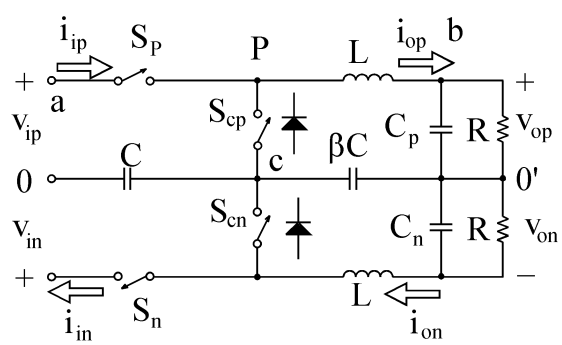

Fig.3. Buck converter

In simpler case the capacitance β*C* can be replaced by short circuit in the buck as in Fig.3, and in the B&B converters and by an interrupt in the boost converter, furthermore terminal 0 and 0' are short-circuited in the latter converter. Further simplification can be accomplished by connecting two clamping diodes in place of the two switches closest to

the output in the positive and in the negative side (Fig.3). The comments made imply the feasibility to build-up altogether 12 configurations.

III. OPERATION

The steady-state operation is briefly presented in the simplest case when capacitance βC is removed as just described and the two switches on the output side are replaced by diodes in the buck converter. The assumptions used are as follows: idealized and lossless circuit components, constant and smooth input and output voltages, steady-state operation, identical load resistances at the positive and at the negative side (R_p=R_n=R) and the commutation times are neglected.

By turning-on switch S_p, a sinusoidal current pulse $i_{ip} = i_{op} = i_{cp}$ is developed from $wt = 0$ to a_p ($w = 2pf_r = 1/\sqrt{LC}$) in circuit S_p, L, V_{op}, C and V_{ip}. (Fig.4). The capacitor voltage v_c swings from V_{cn} to V_{cp} ($V_{cn} < 0$). The diode D_{cp} is reverse biased from $wt = 0$ on and its voltage becomes zero at $wt = a_p$. Reaching $v_c = V_{cp} = V_{ip}$ value, the clamping diode D_{cp} turns-on and it clamps v_c on the value V_{cp}. The choke current commutates from S_p to D_{cp}.

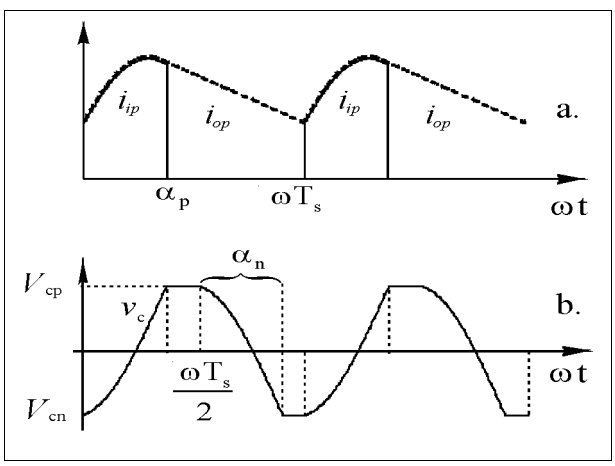

Fig.4. Time functions of input and output (choke) currents (a.) and condenser voltage (b.)

The energy stored in the choke at $wt = a_p$ is partially depleted by the current flowing through the diode in interval $a_p < wt < wT_s$ where $T_s = 1/f_s$ is the switching period. At discontinuous current conduction (DCM) the stored energy is entirely depleted in interval $a_p < wt < a_{ep}$. a_{ep} denotes the extinction angle of the inductor current. The inductor current i_{op} decreases in both cases in a linear fashion. In DCM the current is zero between a_{ep} and wT_s.

The same process takes place at the negative side resulting a negative current pulse and condenser voltage swing after turning-on S_n at the beginning of the next half cycle at $wT_s/2$. An advantage of this converter is the soft switching of S and D. At discontinuous current conduction mode the current is zero at turn-on in S_p and S_n. The voltages between the terminals of S and D are zero at the time of turn-off of S either in CCM or in DCM.

IV. OUTPUT VOLTAGE

The buck converter is studied from now on in symmetrical operation when both the configuration, supply, load and control of the positive and negative channels are identical and four controlled switches are applied. **In CCM** the output voltage relation is given in (a14) (see Appendix A), while **in DCM** it can be found in [2 or 3] and it is repeated here:

$$\frac{v_o}{v_i} = \frac{-1+\sqrt{1+2A/[(f_s/f_r)\cdot RCf_r]}}{A/[(f_s/f_r)\cdot RCf_r]} \qquad (1)$$

where $A = (1+\cos a)/(1-\cos a)$.

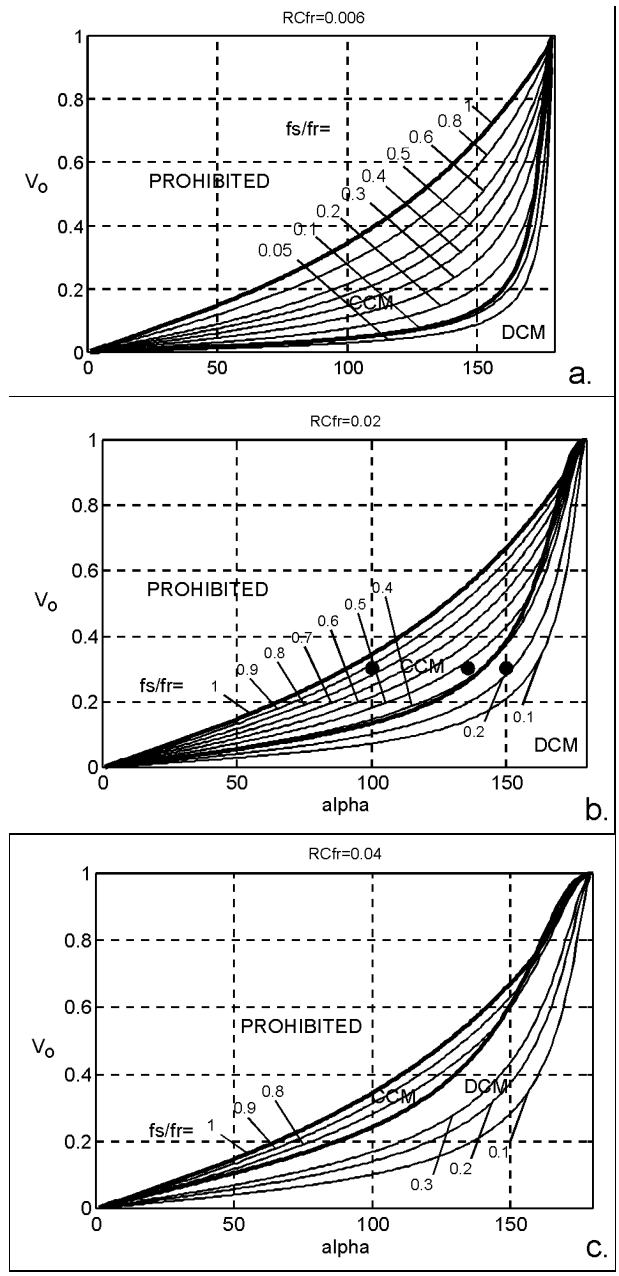

Fig.5. Output voltage versus commutation angle

At the border between CCM and DCM both (a14) and (1) must be satisfied. Its consequence is that there is only one

f_s/f_r value belonging to one commutation angle a at any given RCf_r. These f_s/f_r–a pairs determine the border.

The operation region is bordered by another limit curve $f_s / f_r = 1$. In other words $f_s \le f_r$ must hold and the area $f_s / f_r > 1$ is prohibited. The reason is simple. The change of condenser voltage v_c in one direction must be completed before its change gets started in the opposite direction. Switch S_p and S_n must not be turned on simultaneously, $a \le wT_s / 2$ must hold, the two input currents may flow only in separate intervals.

a and f_s are the control variables for changing v_o/v_i. The output voltage depends on the load R only in DCM.
Fig.5 plotted on the basis of (a14) and (1) shows v_o versus a with parameter f_s/f_r at three different RCf_r values both for CCM and for DCM.
Both the limit curve $f_s / f_r = 1$, and the border between CCM and DCM are drawn by heavy lines in Fig.5 and later in Fig.7.

V. VOLTAGE RIPPLE

Up to now ripple-free output voltage was assumed.

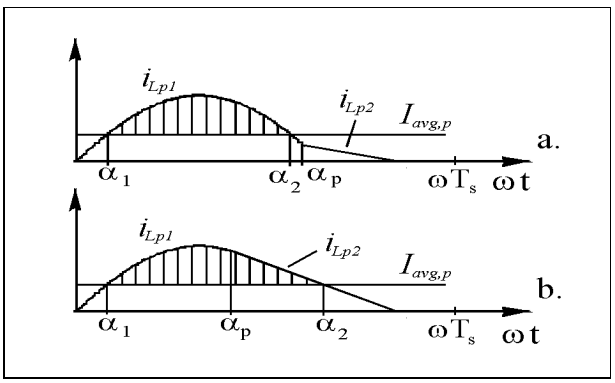

Fig.6. Choke current time functions

Let us investigate the effect of the change in a and f_s at RCf_r=const. on the output voltage ripple Δv_o with finite output filter capacitance C_o (Fig.3). The assumptions used are as follows: All approximations applied earlier hold in the calculation of the choke current. It implies ripple-free output voltages. The total AC components of the choke currents are flown through capacitance C_o and their average or DC values I_{avg} are flown through the load.
Fig.6 shows the instantaneous i_{Lp} and average value $I_{avg,p}$ of the choke current flowing in the positive channel. $a_2 < a_p$ in Fig. a and $a_2 > a_p$ in Fig. b. The calculation of the peak to peak voltage ripple Δv_o in one switching period is described in Appendix B. The way of calculation is simple. First the change in charge ΔQ of the output capacitance C_o is determined in period T_s, and then $\Delta v_o = \Delta Q / C_o$ is computed. ΔQ is proportional to the hatched area in Fig.6.

In **DCM** the voltage ripple is derived in Appendix B and is given by (b12) when $a_2 \le a$ and by (b13) when $a_2 > a$.

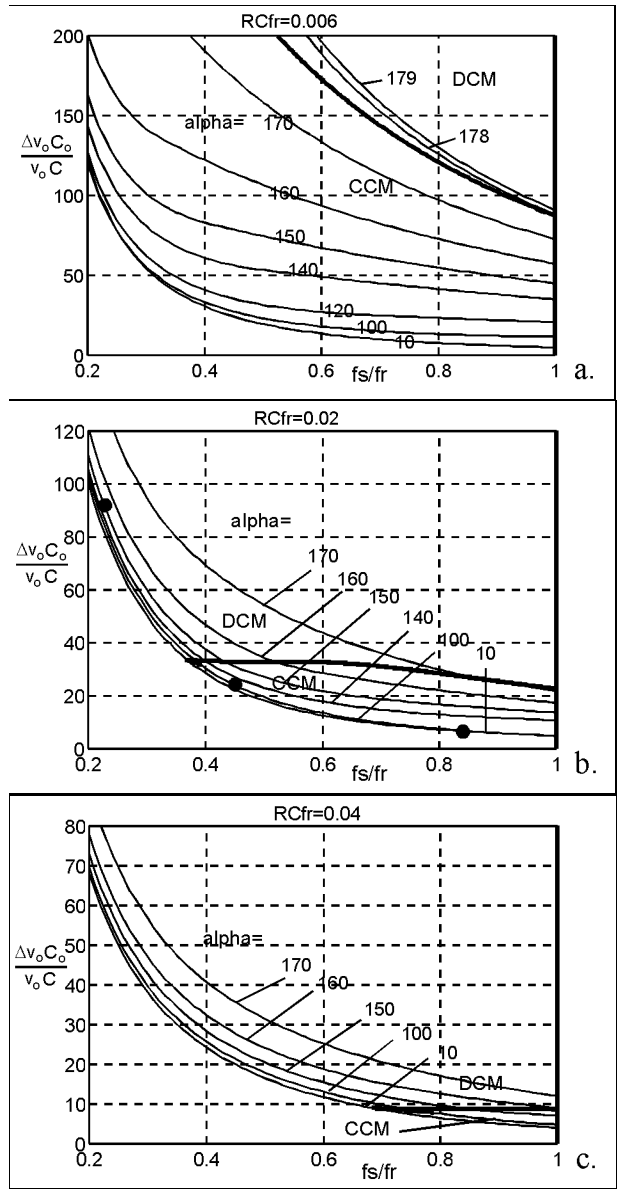

Fig.7. Output voltage ripple versus switching frequency

In **CCM** (b12) and (b13) hold, provided that, the substitutions $a \to a'$; $a_1 \to a_1'$; $a_2 \to a_2'$ and $v_r \to v_r'$ are carried out. As explained in Appendix B the basic equations and therefore the final relations are the same both in DCM and in CCM if a reference frame transformation (rotation) is introduced in CCM. The three new angles a', a_1' and a_2' differ from the old ones only by the angle of rotation j [(b19)].

The quantity $\frac{\Delta v_o}{v_o}\frac{C_o}{C}$ being proportional to the voltage ripple is plotted as a function of control variable f_s/f_r with parameter a for three different RCf_r on the basis of (b12) and (b13) in Fig.7.

VI. SIMULATION RESULTS

In order to verify the theory computer simulations have been performed. In all cases MATLAB/SIMULINK program package was used.

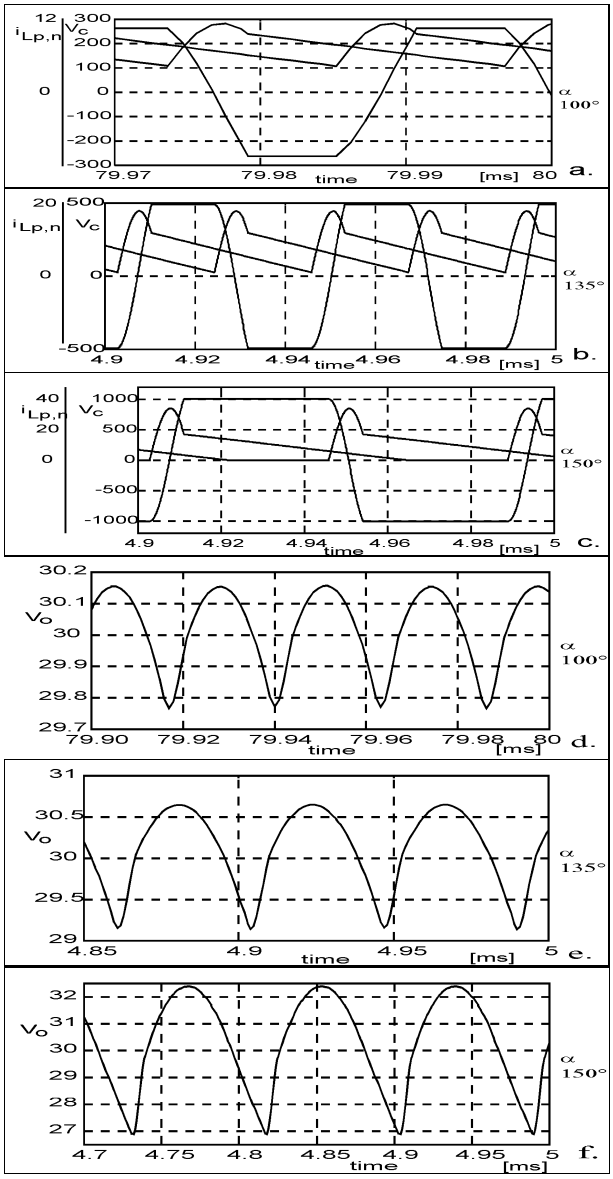

Fig.8. Simulation results

The circuit parameters selected are as follows: The inductances on both side L = 100μH, the resonating capacitance C = 100nF, the resonant frequency $f_r = 1/(2p\sqrt{LC}) = 50.3\,\text{kHz}$. The input voltages v_{ip}=-v_{in}=100V, the output capacitances $C_p = C_n = C_o = 50\,m\text{F}$.

Three points have been marked in Fig.5b and Fig.7b where the simulation results were developed. The time functions of the inductor currents and v_c are plotted in Fig.8a, b and c. The output voltage ripple is shown for the same three operation points in Fig.8d, e and f. The calculation and simulation results are practically identical. They are presented for the voltage ripple in Table 1. The simulation results confirm the theory.

Table 1. Calculation and simulation results

v_o [V]	f_s/f_r	a [°]	RCf_r	Δv_o [V]	$\Delta v_o/v_o$ [%]
30	0.86	100	0.02	0.384	1.28
30	0.462	135	0.02	1.494	4.98
30	0.231	150	0.02	5.382	17.94

VII. CONCLUSIONS

After introducing the DC-DC resonant converter family having 12 members, only the buck configuration was studied. Both the output voltage v_o and its ripple Δv_o were determined as a function of the two control variables; the commutation angle a and the switching frequency f_s.

First the conclusions for continuous conduction mode (CCM) are summarized.

- CCM can be realized only in region $RCf_r \le 0.06$ or $R/\sqrt{L/C} < 0.06\cdot(2p)$ (Fig.5 and 7). The load resistance R must be much smaller than the characteristic impedance $\sqrt{L/C}$.
- The output voltage v_o is independent of the load and of RCf_r [(a14)]. The curves v_o versus a with parameter f_s/f_r are the same in Fig.5 a, b and c [(a14)].
- Keeping f_s/f_r constant, v_o can be changed in wide range with a (Fig.5).
- Keeping a constant, v_o is modified only moderately with f_s/f_r (Fig.5).
- The voltage ripple Δv_o is smaller than in DCM (Fig.7). The filter requirement is lighter. Better dynamic performance can be achieved.
- The zero current switching of switches S_p and S_n are lost and the condenser voltage peak v_{cpeak} is high.

The conclusions for discontinuous conduction mode (DCM) are as follows:

- DCM can be set at any RCf_r or at any load conditions (Fig.5 and 7).
- v_o depends on the load or on RCf_r [(1)].
- DCM region is getting wider by increasing R in the plane v_o versus a (Fig.5).
- The filter capacitance C_o must be increased to reduce Δv_o to CCM level (Fig.7).
- Keeping f_s/f_r constant, Δv_o does not change significantly with a in region $a < (120° \sim 140°)$.
- Zero current switching of S_p and S_n is inherent advantage.

The simulation results verify the theory presented.

APPENDIX A DERIVATION OF v_{op}, v_{on} IN CCM

The time functions of the choke current i_{Lp} are as follows:

$$i_{Lp1}(wt) = I_{op} \cdot \cos wt + I_{kp} \sin wt \qquad \text{(a1)}$$

in the interval $0 \le wt \le a_p$,and

$$i_{Lp2}(wt) = I_{op} \cos a_p + I_{kp} \sin a_p - \frac{1}{L} v_{op}\left(t - \frac{a_p}{w}\right) \qquad \text{(a2)}$$

in the interval $a_p \le wt \le wT_s$. Here $I_{op} = i_{Lp}(0)$

and $$I_{kp} = \frac{v_{ip} - v_{cn} - v_{op}}{\sqrt{L/C}} \; ; (v_{cn} < 0) \qquad \text{(a3)}$$

i_{Lp} is the projection of I_{op} and I_{kp} on the axis x'' rotating with angular speed w (Fig.a1). Its peak value

$$\hat{I}_{Lp} = \sqrt{I_{op}^2 + I_{kp}^2} \qquad \text{(a4)}$$

i_{Lp} takes its peak value at angle $a_{pm} = \mathrm{tg}^{-1}(I_{kp} / I_{op})$ (Fig.a1), provided that, $a_p \ge a_{pm}$ (Fig.4).

The choke current must be the same at $wt = 0$ and at $wt = wT_s$ in steady state:

$$i_{Lp}(wt = 0) = i_{Lp}(wt = wT_s) = I_{op} \qquad \text{(a5)}$$

The condenser voltage change is the result of current $i_c = i_{Lp}$ in interval $0 \le wt \le a_p$

$$\frac{1}{wC}\int_0^{a_p} i_{Lp1}\, \mathrm{d}(wt) = v_{cp} - v_{cn} = 2v_{c1} \qquad \text{(a6)}$$

where v_{c1} is the positive sequence component of the peak condenser voltages (Fig.4). Substituting (a1) into (a6)

$$\frac{1}{wC}\left[I_{op} \sin a_p + I_{kp}(1 - \cos a_p)\right] = 2v_{c1} \qquad \text{(a7)}$$

and (a2) into (a5).

$$I_{op} \cos a_p + I_{kp} \sin a_p - \frac{1}{L} v_{op}\left(T_s - \frac{a_p}{w}\right) = I_{op} \qquad \text{(a8)}$$

Expressing I_{op} from (a8) and substituting it into (a7)

$$-I_{kp} + v_{c1} wC + \frac{1}{2L} v_{op}\left(T_s - \frac{a_p}{w}\right)\frac{\sin a_p}{1 - \cos a_p} = 0 \qquad \text{(a9)}$$

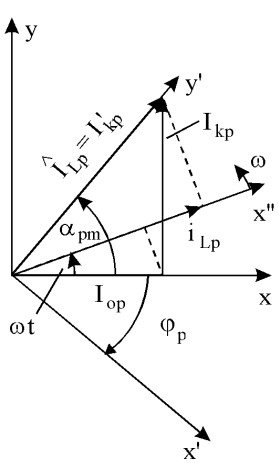

Fig.a1 Composition of choke current i_{Lp}

The expression obtained in a similar way for the negative channel is

$$-I_{kn} + v_{c1} wC + \frac{1}{2L} v_{on}\left(T_s - \frac{a_n}{w}\right)\frac{\sin a_n}{1 - \cos a_n} = 0 \qquad \text{(a10)}$$

where $$I_{kn} = \frac{-v_{in} + v_{cp} - v_{on}}{\sqrt{L/C}} \qquad \text{(a11)}$$

The output voltages from (a9) and (a10) are

$$v_{op} = (v_{ip} - v_{c2}) \cdot \frac{2(1 - \cos a_p)}{(wT_s - a_p)\sin a_p + 2(1 - \cos a_p)} \qquad \text{(a12)}$$

$$v_{on} = (v_{in} + v_{c2}) \cdot \frac{2(1 - \cos a_n)}{(wT_s - a_n)\sin a_n + 2(1 - \cos a_n)} \qquad \text{(a13)}$$

where $v_{c2} = (v_{cp} + v_{cn})/2$ is the negative sequence component of the peak condenser voltages. In symmetrical operation the commutation angles (a_p and a_n), the input voltages (v_{ip}, $|v_{in}|$), the output voltages (v_{op}, v_{on}), the peak condenser voltages (v_{cp} and $|v_{cn}|$) and the output currents are identical and v_{c2}=0. The output voltage $v_o = v_{op} = v_{on}$ is

$$v_o = \frac{2(1 - \cos a)}{\left[\dfrac{2p}{(f_s / f_r)} - a\right]\sin a + 2(1 - \cos a)} v_i \qquad \text{(a14)}$$

APPENDIX B OUTPUT VOLTAGE RIPPLES IN DCM AND CCM

DCM. *First, assuming* $a_2 \le a_p$

The change of the charge of the output capacitance C_p within one period in the positive channel

$$\Delta Q_p = \frac{1}{w}\int_{a_1}^{a_2} i_{Lp1}\mathrm{d}(wt) - I_{avg,p}\frac{a_2 - a_1}{w} \qquad \text{(b1)}$$

where i_{Lp1} is given by (a1) and (a3). The initial value of current i_{Lp1} is I_{op}=0. Furthermore, $I_{avg,p} = v_{op} / R$ and from Fig.6a: $\sin a_1 = I_{avg,p} / I_{kp}$; $a_2 = p - a_1$, and from (a1), (b1)

$$\Delta Q_p = \frac{I_{kp}}{w} 2\cos a_1 - I_{avg,p}\frac{p - 2a_1}{w} \qquad \text{(b2)}$$

The ripple of the output voltage

$$\frac{\Delta v_{op}}{v_{op}} = \frac{1}{v_{op}}\frac{\Delta Q_p}{C_p} = \frac{1}{wC_p}\left[\frac{I_{kp}}{v_{op}} 2\cos a_1 - \frac{p - 2a_1}{R}\right] \qquad \text{(b3)}$$

Second, assuming $a_2 > a_p$

Now the change of the charge is as follows

$$\Delta Q_p = \frac{1}{w}\int_{a_1}^{a_2} i_{Lp1}\mathrm{d}(wt) + \frac{1}{w}\int_{a_p}^{a_2} i_{Lp2}\mathrm{d}(wt) - \frac{a_2 - a_1}{w} I_{avg,p} \qquad \text{(b4)}$$

where $$i_{Lp2} = I_{kp} \sin a_p - \frac{1}{wL} v_{op}(wt - a_p) \qquad \text{(b5)}$$

Based on (b5) and Fig.6b the angle

$$a_2 = a_p + \frac{wL(I_{kp} \sin a_p - I_{avg,p})}{v_{op}} \qquad \text{(b6)}$$

Substituting (a1) and (b5) into (b4)

$$\Delta Q_p = \frac{I_{kp}}{w} m_p - \frac{C}{2} v_{op} (a_p - a_2)^2 - I_{avg,p} \frac{a_2 - a_1}{w} \qquad \text{(b7)}$$

where $m_p = \cos a_1 - \cos a_p + (a_2 - a_p)\sin a_p$.

From $\Delta v_{op} = \Delta Q_p / C_p$ the output voltage ripple

$$\frac{\Delta v_{op}}{v_{op}} = \frac{1}{wC_p}\left[\frac{I_{kp}}{v_{op}} m_p - \frac{wC}{2}(a_p - a_2)^2 - \frac{1}{R}(a_2 - a_1)\right] \qquad \text{(b8)}$$

After similar considerations in the negative side the voltage ripple when $a_4 = p - a_3 \le a_n$

$$\frac{\Delta v_{on}}{v_{on}} = \frac{1}{wC_n}\left[\frac{I_{kn}}{v_{on}} 2\cos a_3 - \frac{p - 2a_3}{R}\right] \qquad \text{(b9)}$$

where $a_3 = \sin^{-1}\frac{I_{avg,n}}{I_{kn}}$ and when $a_4 > a_n$

$$\frac{\Delta v_{on}}{v_{on}} = \frac{1}{wC_n}\left[\frac{I_{kn}}{v_{on}} m_n - \frac{wC}{2}(a_n - a_4)^2 - \frac{1}{R}(a_4 - a_3)\right] \qquad \text{(b10)}$$

$$\text{where } a_4 = a_n + \frac{wL(I_{kn}\sin a_n - I_{avg,n})}{v_{on}} \qquad \text{(b11)}$$

and $m_n = \cos a_3 - \cos a_n + (a_4 - a_n)\sin a_n$.

The time scale starts from $wT_s/2$ in the formulae related with the negative channel.

In symmetrical configuration and operation the output voltage ripple in both channels from (b3)

$$\frac{\Delta v_o}{v_o} = \frac{C}{C_o}\left[2v_r \cos a_1 + \frac{2a_1 - p}{2pRCf_r}\right] \qquad \text{(b12)}$$

when $a_2 \le a$, and on the basis of (b8)

$$\frac{\Delta v_o}{v_o} = \frac{C}{C_o}\left[v_r \cdot m - \frac{(a - a_2)^2}{2} - \frac{(a_2 - a_1)}{2pRCf_r}\right] \qquad \text{(b13)}$$

when $a_2 > a$, with $v_{c,peak}=V_{cp}=V_{cn}$

$$v_r = \frac{v_i + v_{cpeak} - v_o}{v_o} \qquad \text{(b14)}$$

$a_1 = \sin^{-1}[1/(v_r \cdot 2pRCf_r)]$; $a_2 = a + v_r \sin a - 1/(2pRCf_r)$

and $m = \cos a_1 - \cos a + (a_2 - a)\sin a$.

The capacitance of the output filter is $C_o = C_p = C_n$.

CCM. Now the initial value of current i_{Lp1} is not zero in (a1): $I_{op} \ne 0$. The derivation of the relations for the voltage ripple can be straightforward by introducing a reference frame transformation. The new reference frame x'-y' is turned by

$$j_p = \frac{p}{2} - \mathrm{tg}^{-1}\frac{I_{kp}}{I_{op}} \qquad \text{(b15)}$$

from the old one x-y (Fig.a1).

By introducing $wt' = wt + j$ as new time scale, the time functions i_{Lp1} and i_{Lp2} of (a1) and (a2) are simplified to

$$i_{Lp1}(wt') = I_{kp}' \cdot \sin(wt') \qquad \text{(b16)}$$

$$i_{Lp2}(wt') = I_{kp}' \sin a_p' - \frac{1}{wL} v_{op}(wt' - a_p') \qquad \text{(b17)}$$

$$\text{where } I_{kp}' = \sqrt{I_{kp}^2 + I_{op}^2} \qquad \text{(b18)}$$

Eq.(b16) and (b17) has the same form in the new reference frame as that of (a1) and (b5) in the original one.

All equations derived for the positive channel in DCM hold in CCM as well, provided that, I_{kp}, a_p and wt are replaced by I_{kp}', a_p' and wt'. Similar statement holds for the negative channel.

In symmetrical configuration and operation

$$j = \frac{p}{2} - \mathrm{tg}^{-1}\frac{v_r \cdot (1 - \cos a)}{v_r \cdot \sin a - b} \qquad \text{(b19)}$$

$$\text{where } b = 2p(f_r / f_s) - a \qquad \text{(b20)}$$

The output voltage ripple can be calculated from the same relations as in DCM with the substitutions $a \to a'$; $a_1 \to a_1'$; $a_2 \to a_2'$ and $v_r \to v_r'$ where

$$a_*' = a_* + j \qquad \text{(b21)}$$

$$v_r' = \sqrt{\frac{2v_r^2(1 - \cos a) - 2v_r b \sin a + b^2}{(1 - \cos a)^2}} \qquad \text{(b22)}$$

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