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Modelling of a Modified Buck Converter

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Abstract: DC/DC converters are very important system components in electronic devices and are used in consumer electronics, communications, computing, traction, robotics and so on. The studied converter is a modified step-down converter which reduces the input voltage to a lower output voltage. The modification concerns the position of the storage capacitor. It is not connected between the output terminals, but between one input and one output terminal. The model of the converter is calculated and presented, starting from the differential equations which describe the operational modes of the converter in the continuous inductor current mode. After combination to a nonlinear matrix differential equation, a linearization is done. This linearized model is step by step transformed into a signal flow graph. From this graph the transfer functions which describe the converter around an operation point are calculated. As an example one of these transfer functions is drawn. Using signal flow graphs helps to understand the converter, is a second opportunity to calculate the transfer functions and can be applied in a similar way to other DC/DC topologies. The transfer functions are necessary for the controller design, and the graphic representation is useful to understand more sophisticated control concepts, such as two-loop control or state space controllers. The models are compared with the circuit simulation and show a good coincidence.

Keywords: DC/DC converter, Signal flow graph, Transfer function, Large signal model, Small signal model

1. Introduction

To obtain the model of a DC/DC converter only Kirchhoff's voltage law (KVL, the sum of the voltages at a mesh is always zero), Kirchhoff's current law (KCL, the sum of the currents through a node is always zero), and the voltage-current connections of the three basic elements, the resistor, the inductor, and the capacitor in their differential form, are necessary. In this case the converter has in practice three different operational modes. During operational mode M1 the active switch is on and the passive switch is off [1].

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When the active switch is turned off, the diode turns on and mode M2 starts. There are two possibilities to end this mode. When the transistor is turned on again, while the diode is still conducting, the system goes back to mode M1; when the diode turns off before the active switch is turned on again, the third mode M3 (now both the active and the passive switches are off) occurs. Fig. 1, summarizes the three useful modes. When the system changes directly from the second mode M2 into the first mode M1, the converter operates in the continuous inductor current mode CICM, and when the current through the inductor goes to zero and the diode turns off, the converter operates now in the discontinuous inductor current mode DCICM. The CICM is especially used in practical operation. In this study we use the Modified Buck converter (MBuC) as an example to model a DC/DC converter. We start with the ideal converter. That means that the components of the converter are ideal (they have no parasitics, especially parasitic resistors, and the switches turn on and off within zero time).

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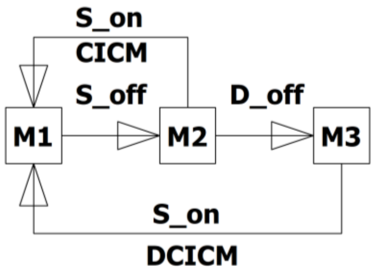


Fig. 1: Operational modes of a DC/DC converter

Fig. 2 shows the circuit diagram of the MBuC. The modification lies in the position of the capacitor. In the original circuit the capacitor is connected between the terminals of the output, and in the modified converter the capacitor is connected between one input and one output terminal [2]. The basic function is the same, but the input current of the converter and the voltage stress of the capacitor differ.

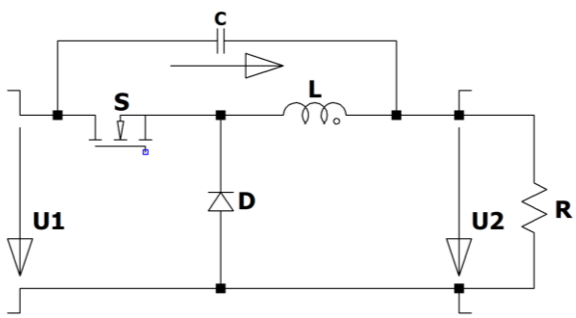


Fig. 2: Circuit diagram of the MBuC

DC/DC converters are very important system components. The basic converters are the Buck, the Boost and the Buck-Boost converters which are described in all text books on Power Electronics. Three examples are [1 - 3]. There are many studies to find other topologies. A very famous study was done by Maksimovic and Cuk [4]. An interesting study which shows more than hundred topologies can be found in [5]. Another simple method to model a Buck converter can be found in [6]. Quadratic converters are studied in [7]. An interesting topological study concerning single switch converters with a high voltage transformation ratio is [8]. 309 references are listed in a comprehensive study about step-up converters [9]. Modified basic converters are presented in [10]. There the modified Buck-Boost converter is described in detail. An investigation concerning modified converters with limited duty cycle range is given in [11].

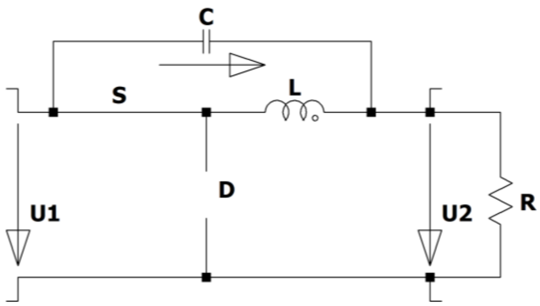
The use of signal flow graphs is treated in the following references. The application of the signal flow graph for the double active bridge converter is dealt in [12]. The signal flow graph of a converter is used to describe the control and dynamics of a converter system in [13]. The modelling of a DC-to-DC multilevel Boost converter is shown in [14]. The signal flow graph model for a high voltage transformation ratio dual input Boost converter using a feed forward control is treated in [15]. A modular multi cell converter can also be described by a signal flow graph as can be seen in [16]. The application of a signal flow graph of the harmonics in a phased-locked loop can be seen in [17]. Graph theory instead of the signal flow graph is used in [18] for a modular multi cell converter. In the paper “Converters to drive two brushed DC machines” [19] the signal flow graph is used to calculate the transfer functions. Switched mode power supplies are treated with the help of the signal flow graph and matrix calculus in [20]. A short condensation of what is really important for using signal flow graphs for DC-to-DC converter descriptions and control can be found in [21].

The main goal of this paper is to show the application and the usefulness of signal flow graphs for analyzing DC-to-DC converters. The design of the signal flow graph is done step by step and is therefore useful for studying and teaching applications. The used MBuC in difference to the normal Buck converter has a punch through of the input voltage on the output voltage. So, it is a more universal system type.

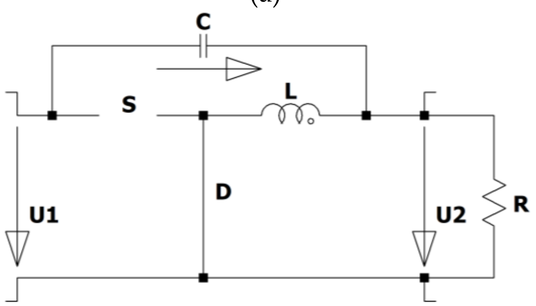
After this introduction the ideal models (the nonlinear large signal model and the small signal model around the operating point) of the converter are calculated in section 2. An intuitive explanation of the linearization is given in the appendix. In the section 3 the signal flow graph is constructed step by step and used to derive the transfer function between the output voltage and the duty ratio. In section 4 models with included parasitic resistors are given. In section 5 simulations are done. Additional aspects are given in section 6. A conclusion ends the paper with section 7.

2. Ideal model

In the continuous mode the circuit is described by two equivalent circuits shown in Fig. 3. The point at the inductor shows where the current flows out of the coil. The arrow for the voltages points from plus to minus. The load is represented by the resistor R.



(a)



(b)

Fig. 3: Equivalent circuits of the idealized modified Buck converter: (a) M1; (b) M2

For mode M1 shown in Fig. 3(a), when the active switch is on, the voltage of the capacitor is across the inductor, and the current through the capacitor is equal to the load current minus the current through the coil. According to KVL and the Ohmic law, the load current is the difference between the input voltage and the voltage across the capacitor divided by the resistor. For the two state variables, the current through the coil and the voltage across the capacitor, one can write as Eq. (1),

$$\frac{di_L}{dt}=\frac{u_C}{L}, \qquad \frac{du_C}{dt}=\frac{(u_1-u_C)/R-i_L}{C} \tag{1}$$

Combination to a state space description leads to the state equation (2),

$$\frac{d}{dt}\begin{pmatrix} i_L \\ u_C \end{pmatrix}=\begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{CR} \end{bmatrix}\cdot\begin{pmatrix} i_L \\ u_C \end{pmatrix}+\begin{bmatrix} 0 \\ \frac{1}{CR} \end{bmatrix}\cdot(u_1) \tag{2}$$

and to the output equation (3),

$$u_2=-u_C+u_1, \tag{3}$$

or written in matrix form as equation (4),

$$u_2=\begin{bmatrix} 0 & -1 \end{bmatrix}\cdot\begin{pmatrix} i_L \\ u_C \end{pmatrix}+[1]\cdot(u_1). \tag{4}$$

In mode M2 the equivalent circuit Fig. 3 (b) is valid. One can immediately see that the voltage across the inductor is equal to the negative input voltage plus the voltage across the capacitor. The current through the capacitor is equal to the one during mode M1. The output equation is also the same one as in the first mode M1 (Eq. (4)). So, one can write equation (5) as,

$$\frac{di_L}{dt}=\frac{-u_1+u_C}{L}, \quad \frac{du_C}{dt}=\frac{(u_1-u_C)/R-i_L}{C} \tag{5}$$

Combination leads to the state space equation (6),

$$\frac{d}{dt}\begin{pmatrix} i_L \\ u_C \end{pmatrix}=\begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{CR} \end{bmatrix}\begin{pmatrix} i_L \\ u_C \end{pmatrix}+\begin{bmatrix} -\frac{1}{L} \\ \frac{1}{CR} \end{bmatrix}(u_1) \tag{6}$$

The converter operates with a fixed switching frequency and is controlled by the duty cycle d, that is the on-time of the active switch referenced to the switching period as mentioned in equation (7),

$$d=\frac{T_{ON}}{T} \tag{7}$$

When the switching period is short compared to the time constants of the converter (in practice the time constants are up to one hundred higher), one can combine the two modes by weighting them with the duty cycle d in mode M1 and by one minus the duty cycle (1-d) in mode M2, leading to the state space model of the idealized converter consisting of the state Eq. (8) and the output equation, which is the same as in Eq. (4), according to

$$\frac{d}{dt}\begin{pmatrix} i_L \\ u_C \end{pmatrix}=\begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{CR} \end{bmatrix}\begin{pmatrix} i_L \\ u_C \end{pmatrix}+\begin{bmatrix} -\frac{1-d}{L} \\ \frac{1}{CR} \end{bmatrix}(u_1) \tag{8}$$

It is easy to see that the description is nonlinear, because there is a multiplication between the duty cycle d and the input variable u_1 in the first line. A simple way to linearize the system is to use the disturbance (perturbation) method. This leads to a linearization around an operating point. For all variables of the system one uses a combination of the operating point value (written with capital letters and a zero in the index) and a perturbation variable which changes the operating point value (written by a hatted small letter). So, one gets for the state variables as (9),

$$i_L = I_{L0} + \hat{i}_L, \qquad u_C = U_{C0} + \hat{u}_C \tag{9}$$

and for the input variables (10),

$$u_1 = U_{10} + \hat{u}_1, \qquad d = D_0 + \hat{d}. \tag{10}$$

These transformations must be inserted into (8). For the first equation one gets equation (11),

$$\frac{d}{dt}\left(I_{L0} + \hat{i}_L\right) = \frac{d}{dt}\hat{i}_L = \\ = \frac{1}{L}\left\{\begin{matrix} U_{C0} + \hat{u}_C - \\ \left(U_{10} + \hat{u}_1\right) + D_0\hat{u}_1 + U_{10}\hat{d} + U_{10}D_0 + \hat{d}\hat{u}_1 \end{matrix}\right\} \tag{11}$$

Omitting the product of two perturbations (in our case $\hat{d}\hat{u}_1$) leads to the small signal model of the modified Buck converter as in (12) and (13),

$$\frac{d}{dt}\begin{pmatrix}\hat{i}_L \\ \hat{u}_C\end{pmatrix} = \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{CR}\end{bmatrix}\begin{pmatrix}\hat{i}_L \\ \hat{u}_C\end{pmatrix} + \begin{bmatrix} -\frac{1-D_0}{L} & \frac{U_{10}}{L} \\ \frac{1}{CR} & 0\end{bmatrix}\begin{pmatrix}\hat{u}_1 \\ \hat{d}\end{pmatrix} \tag{12}$$

$$\hat{u}_2 = \begin{bmatrix}0 & -1\end{bmatrix}\cdot\begin{pmatrix}\hat{i}_L \\ \hat{u}_C\end{pmatrix} + \begin{bmatrix}1 & 0\end{bmatrix}\cdot\begin{pmatrix}\hat{u}_1 \\ \hat{d}\end{pmatrix} \tag{13}$$

The operating point values on the right side of Eq. (11) must be zero. So, one gets for the operating point connections as (14), (15) and (16),

$$U_{C0} - (1-D_0)U_{10} = 0 \text{ leading to } U_{C0} = (1-D_0)U_{10} \tag{14}$$

$$U_{20} = U_{10} - (1-D_0)U_{10} = D_0 U_{10} \tag{15}$$

$$-I_{L0} - \frac{U_{C0}}{R} + \frac{U_{10}}{R} = 0 \quad I_{L0} = \frac{U_{10} - U_{C0}}{R} = \frac{U_2}{R} = I_{LOAD} \tag{16}$$

In the stationary case the output voltage of the MBuC is equal to that of the original Buck converter. The mean current through the inductor is equal to the load current. With the linearized small signal model one can calculate the ideal transfer functions around the operating point. The state equation Eq. (12) must be Laplace transformed. One gets (17),

$$\begin{bmatrix} s & -\frac{1}{L} \\ \frac{1}{C} & s + \frac{1}{CR}\end{bmatrix}\begin{pmatrix} I_L(s) \\ U_C(s)\end{pmatrix} = \begin{bmatrix} -\frac{1-D_0}{L} & \frac{U_{10}}{L} \\ \frac{1}{CR} & 0\end{bmatrix}\begin{pmatrix} U_1(s) \\ D(s)\end{pmatrix} \tag{17}$$

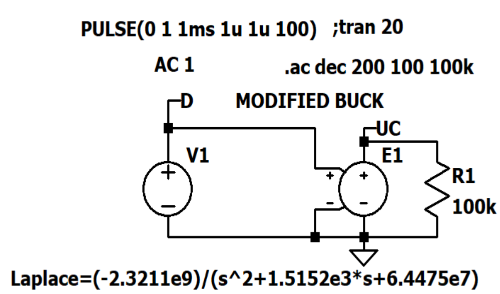
For all four transfer functions the same denominator is valid, as in equation (18),

$$\text{Den} = \begin{vmatrix} s & -\frac{1}{L} \\ \frac{1}{C} & s + \frac{1}{CR}\end{vmatrix} = s^2 + s\frac{1}{CR} + \frac{1}{CL} \tag{18}$$

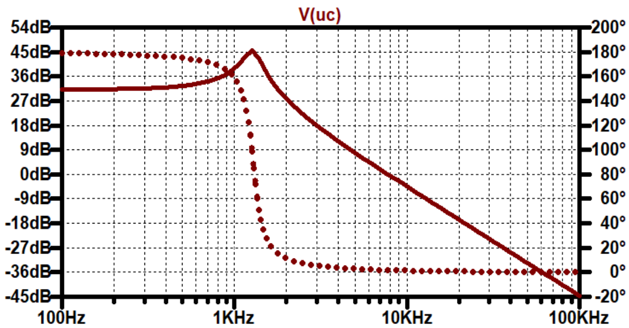
The system is stable and has a conjugate complex pole pair on the left side of the complex plane. The most important transfer function is that of the voltage across the capacitor referenced to the duty cycle. So one can calculate and control the output voltage. The numerator of this transfer function can be found by changing the second column of the state matrix by the second column of the input matrix and so calculate this determinant mentioned in Eq. (19), (Crammer's law is very useful for the calculation of the transfer functions.)

$$\text{NUM\_UC/D} = \begin{vmatrix} s & \frac{U_{10}}{L} \\ \frac{1}{C} & 0\end{vmatrix} = -\frac{U_{10}}{CL} \tag{19}$$

All Bode plots are calculated by the typical components we use in our laboratory L=47 µH, C=330 µF, U1=36 V, RC=10 mΩ, RL=4 mΩ, a duty cycle of one third, and a load resistor of R=2 Ω (RC and RL are the parasitic resistors of the capacitor and the coil, respectively and are later used in section 4).



(a)



(b)

Fig. 4: Transfer function between the capacitor voltage and the duty cycle: (a) simulation circuit (b) Bode plot, gain: solid line, phase: dotted line

Fig. 4 shows the Bode plot between the capacitor voltage and the duty cycle calculated directly with the help of LTSpice. Increasing the duty cycle, reduces the voltage across the capacitor. Fig. 5 shows another possibility to calculate the Bode plots with the help of LTSpice, leading to the same result as in Fig. 4 (b).

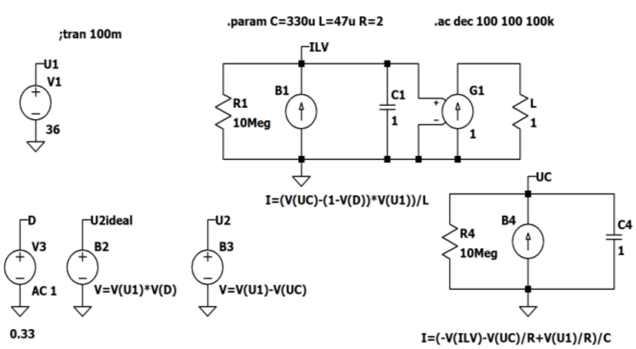


Fig. 5: Simulation circuit to calculate the transfer function between the capacitor voltage and the duty cycle using the nonlinear differential equations

The nonlinear state space model Eq. (8) is implemented and solved. The derivatives are written by arbitrary current sources which are integrated with capacitors of 1 F. To get a current for the first variable ILV (which is a voltage in the simulation), a voltage-controlled current source G1 is used which supplies a resistor of 1 Ω. This current is displayed. The input voltage is kept constant and the duty cycle is the AC source. In the same way one can calculate the other numerators of the other transfer functions.

Laplace transformation of the output equation leads to (20),

$$U_2(s) = \begin{bmatrix} 0 & -1 \end{bmatrix} \cdot \begin{pmatrix} I_L(s) \\ U_C(s) \end{pmatrix} + \begin{bmatrix} 1 & 0 \end{bmatrix} \cdot \begin{pmatrix} U_1(s) \\ D(s) \end{pmatrix} \qquad (20)$$

For the transfer function between the output voltage and the duty cycle we get (21),

$$\frac{U_2(s)}{D(s)} = -\frac{U_C(s)}{D(s)} + \frac{U_1(s)}{D(s)} \qquad (21)$$

The second term of the sum is zero. Therefore, the dynamics of the output is equal to the dynamics of the voltage across the capacitor (but now with a positive sign and the phase starts at zero and goes down to -180°) as in equation (22)

$$\frac{U_2(s)}{D(s)} = -\frac{U_C(s)}{D(s)} = \frac{\dfrac{U_{10}}{CL}}{s^2 + s\dfrac{1}{CR} + \dfrac{1}{CL}} \qquad (22)$$

3. Signal flow graph

A second way to calculate the transfer functions is by using the signal flow graph. Now the matrix calculus is bypassed (that may be helpful for modern students) and figures always help towards understanding. The design of the signal flow graph is now shown step by step. The MBuC is described by the small signal model according to the Eqs. (12) and (13). The signal graph consists of nodes, which are the variables and edges, which are labeled by the connections between the variables.

3.1 Design of the signal flow graph of the MBuC

To get the state variable, the state equation must be integrated. The integration has 1/s as transfer function between the signal and its derivative. The right nodes are the state variables, and the left nodes are labeled by their derivatives as shown in Fig. 6.

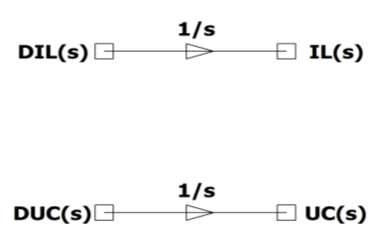


Fig. 6: Step 1, integration

The derivative of the current through the coil is the weighted sum of the capacitor voltage as shown in Fig. 7,

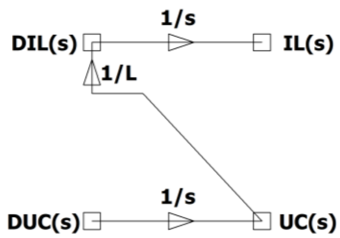


Fig. 7: Step 2

the input voltage (Fig. 8),

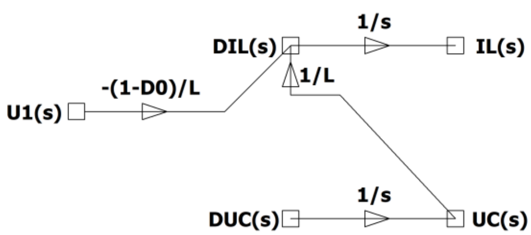


Fig. 8: Step 3

and the duty cycle (Fig. 9).

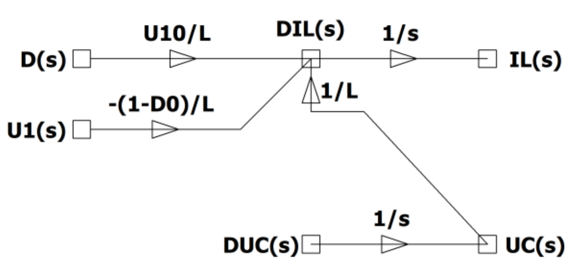


Fig. 9: Step 4

In the same way one has to construct the second equation. The derivative of the voltage across the capacitor is the weighted sum of the current through the coil (Fig. 10), the voltage across the capacitor (Fig. 11), and the input voltage (Fig. 12).

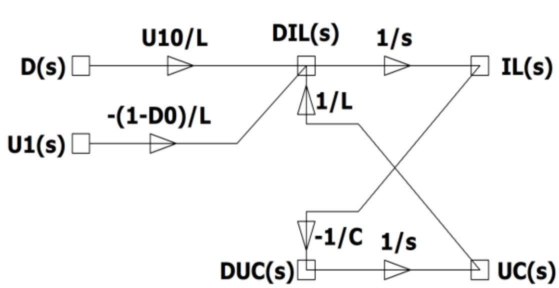


Fig. 10: Step 5

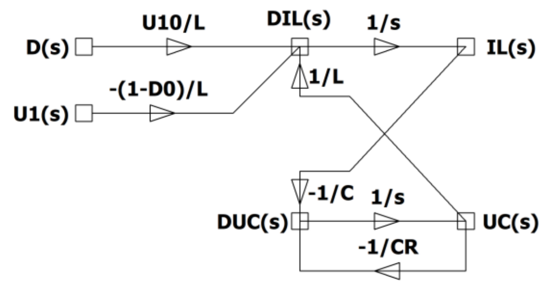


Fig. 11: Step 6

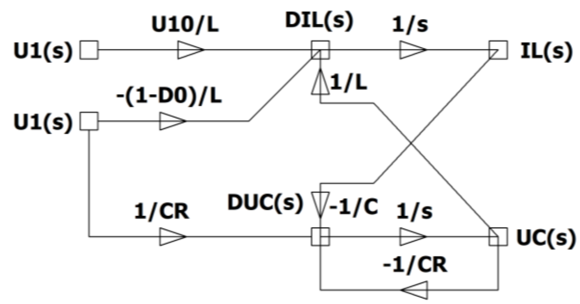


Fig. 12: Step 7

Now one has to construct the output equation. The output voltage is equal to the sum of the input voltage (Fig. 13) minus the voltage across the capacitor (Fig. 14).

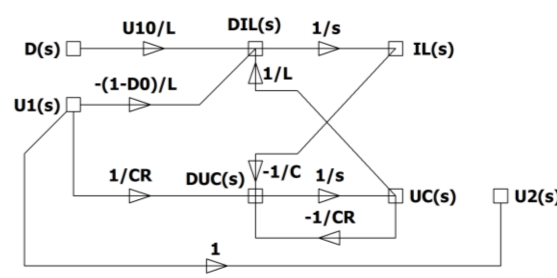


Fig. 13: Step 8

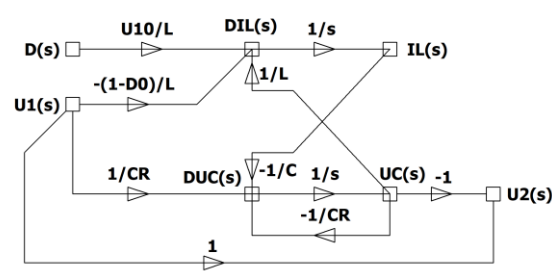


Fig. 14: Step 9, complete signal flow graph of the MBuC

3.2 Signal flow graph for basic second order converters and their modifications

With the small signal model, it can be represented in shown in equation (23 - 24)

$$\frac{d}{dt}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}=\begin{bmatrix}A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}+\begin{bmatrix}B_{11} & B_{12}\\ B_{21} & B_{22}\end{bmatrix}\begin{pmatrix}\hat{u}_1\\ \hat{d}\end{pmatrix}, \tag{23}$$

$$\hat{u}_2=\begin{bmatrix}C_1 & C_2\end{bmatrix}\cdot\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}+\begin{bmatrix}D_1 & D_2\end{bmatrix}\cdot\begin{pmatrix}\hat{u}_1\\ \hat{d}\end{pmatrix} \tag{24}$$

the signal flow graph is depicted in Fig. 15.

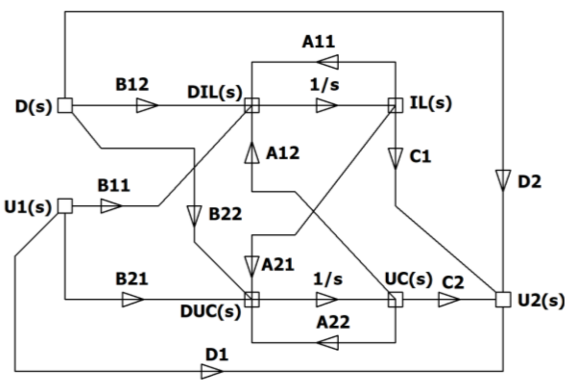


Fig. 15: Signal flow graph of a second order converter

3.3 Transfer function between the output voltage in reference to the duty cycle

The transfer function in equation (25),

$$\frac{U_2(s)}{D(s)}=? \tag{25}$$

can easily be found by using Mason's equation shown in equation (26) and (27) (A short explanation can be found in the appendix).

There are four forward paths

$$\text{F1: } B_{12}\cdot\frac{1}{s}\cdot A_{21}\cdot\frac{1}{s}\cdot C_2,\qquad \text{F2: } D_2,$$

$$\text{F3: } B_{12}\cdot\frac{1}{s}\cdot C_1,\qquad \text{F4: } B_{22}\cdot\frac{1}{s}\cdot C_2, \tag{26}$$

and three loops

$$\text{L1: } \frac{1}{s}\cdot A_{11},\quad \text{L2: } \frac{1}{s}\cdot A_{21}\cdot\frac{1}{s}\cdot A_{12},\quad \text{L3: } \frac{1}{s}\cdot A_{22} \tag{27}$$

All loops touch the forward path F1, all loops do not touch F2, L3 does not touch F3, and L1 does not touch F4. L1 and L3 do not touch each other. So, one gets with Mason's equation (28),

$$\frac{U_2(s)}{D(s)}=\frac{F_1+F_2\left[1-(L_1+L_2+L_3)+L_1L_3\right]+ +F_3\left[1-(L_3)\right]+F_4\left[1-(L_1)\right]}{1-(L_1+L_2+L_3)+L_1L_3} \tag{28}$$

Inserting Eq. (26) and Eq. (27) leads to (29),

$$\frac{U_2(s)}{D(s)}=\frac{\frac{A_{21}B_{12}C_2}{s^2}+D_2\left[1-\left(\frac{A_{11}}{s}+\frac{A_{12}A_{21}}{s^2}+\frac{A_{22}}{s}\right)+\frac{A_{11}A_{22}}{s^2}\right]+\frac{B_{12}C_1}{s}\left[1-\frac{A_{22}}{s}\right]+\frac{B_{22}C_2}{s}\left[1-\frac{A_{11}}{s}\right]}{1-\left(\frac{A_{11}}{s}+\frac{A_{12}A_{21}}{s^2}+\frac{A_{22}}{s}\right)+\frac{A_{11}A_{22}}{s^2}} \tag{29}$$

After solving the compound fraction and sorting it one gets equation (30),

$$\frac{U_2(s)}{D(s)}=\frac{D_2s^2+(B_{12}C_1+B_{22}C_2-A_{11}D_2-A_{22}D_2)s+\left(A_{21}B_{12}C_2+A_{11}A_{22}D_2-A_{12}A_{21}D_2-A_{22}B_{12}C_1-A_{11}B_{22}C_2\right)}{s^2-(A_{11}+A_{22})s+(A_{11}A_{22}-A_{12}A_{21})} \tag{30}$$

For the idealized modified Buck (Eqs. (12), (13)) one gets equation (31) to (33),

$$A_{11}=0,\ A_{12}=\frac{1}{L},\ A_{21}=-\frac{1}{C},\ A_{22}=-\frac{1}{CR} \tag{31}$$

$$B_{11}=-\frac{1-D_0}{L},\ B_{12}=\frac{U_{10}}{L},\ B_{21}=\frac{1}{CR},\ B_{22}=0 \tag{32}$$

$$C_1=0,\ C_2=-1,\ D_1=1,\ D_2=0 \tag{33}$$

resulting in equation (34),

$$\frac{U_2(s)}{D(s)}=\frac{(-\frac{1}{C})\frac{U_{10}}{L}(-1)}{s^2-\left(-\frac{1}{CR}\right)s+\left(-\frac{1}{L}\left(-\frac{1}{C}\right)\right)}=\frac{\frac{U_{10}}{CL}}{s^2+\frac{1}{CR}s+\frac{1}{CL}} \tag{34}$$

It is obvious that this can also be calculated directly from Fig. 14. There is only one forward path, as in equation (35)

$$F=\frac{U_{10}}{L}\cdot\frac{1}{s}\cdot\left(-\frac{1}{C}\right)\cdot\frac{1}{s}\cdot(-1)=\frac{U_{10}}{s^2CL} \tag{35}$$

and two loops equation (36),

$$L_1 = \frac{1}{s}\cdot\left(-\frac{1}{C}\right)\cdot\frac{1}{s}\cdot\left(\frac{1}{L}\right) = -\frac{1}{s^2 CL},$$

$$L_2 = \frac{1}{s}\cdot\left(-\frac{1}{CR}\right) = -\frac{1}{CRs} \tag{36}$$

Both loops touch each other and also touch the forward path. Therefore, one gets equation (37) and (38),

$$\frac{U_2(s)}{D(s)} = \frac{F_1}{1-(L_1+L_2)}, \tag{37}$$

$$\frac{U_2(s)}{D(s)} = \frac{\frac{U_{10}}{s^2 CL}}{1+\frac{1}{s^2 CL}+\frac{1}{sCR}} = \frac{U_{10}R}{s^2 CLR + sL + R}$$
$$= \frac{U_{10}}{s^2 CL + s\frac{L}{R} + 1} = \frac{\frac{U_{10}}{CL}}{s^2 + s\frac{1}{CR} + \frac{1}{CL}} \tag{38}$$

The method to obtain the transfer function with the help of the signal flow graph is easy and leads to fast and correct results.

4. Model with parasitics

Fig. 16 shows the equivalent circuit during mode M1 when the electronic switch is on.

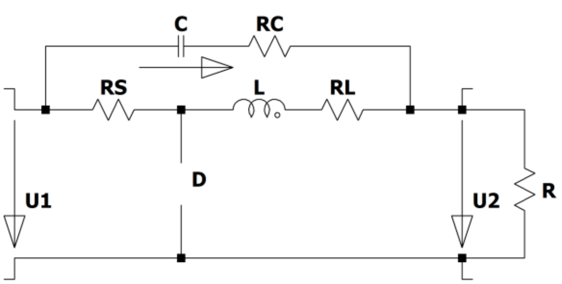


Fig. 16: MBuC with parasitic during M1

The voltage across the ideal inductor L is the negative voltage across the active switch plus the voltage across the ideal capacitor C plus the voltages across the parasitic resistance RC of the capacitor and of the capacitor C minus the voltage across the parasitic resistor RL of the coil L. One gets equation (39),

$$\frac{di_L}{dt} = \frac{1}{L}\left\{-R_S i_L + u_C + R_C i_C - R_L i_L\right\} \tag{39}$$

The current through the capacitor is neither a state variable nor an input variable and must therefore be replaced. KCL shows that this current is equal to the load current reduced by the current through the inductor as in equation (40),

$$i_C = \frac{-i_C R_C - u_C + u_1}{R} - i_L,\ \Rightarrow i_C = \frac{-u_C + u_1 - R i_L}{R + R_C} \tag{40}$$

Inserting into (39) results in equation (41),

$$\frac{di_L}{dt} = \frac{1}{L}\left\{\begin{matrix} -(R_L + R_S + R//R_C)i_L + \frac{R}{R+R_C}u_C \\ +\frac{R_C}{R+R_C}u_1 \end{matrix}\right\} \tag{41}$$

The change of the voltage across the capacitor C is equal to the current through the capacitor divided by the capacitor value C as in equation (42),

$$\frac{du_C}{dt} = \frac{-u_C + u_1 - R i_L}{C(R+R_C)} \tag{42}$$

The output voltage that is due to the parasitic loss not equal to the input voltage minus the voltage across the capacitor is given by (43),

$$u_2 = -R_C i_C - u_C + u_1 \tag{43}$$

Fig. 17 shows the equivalent circuit during operational mode M2, when the active switch S is off and the passive switch D is on. The voltage across the inductor L is equal to the negative knee-voltage VD minus the voltage across the differential resistor RD of the diode minus the voltage across the load R and minus the voltage across the parasitic resistor RL of the coil L. This leads to the derivative of the current through the inductor according to (44),

$$\frac{di_L}{dt} = \frac{1}{L}\left\{-V_D - R_D i_L - R(i_C + i_L) - R_L i_L\right\} \tag{44}$$

The current through the capacitor is again equal to Eq. (40). The differential state equation of the coil is now given by equation (45),

$$\frac{di_L}{dt}=\frac{1}{L}\left\{\begin{matrix}-\left(R_D+R_L+R//R_C\right)i_L\\ +\frac{R}{R+R_C}u_C-\frac{R}{R+R_C}u_1-V_D\end{matrix}\right\} \tag{45}$$

The second state equation is equal to the one in mode M1. This is also valid for the output equation. Combining the two modes by the state space averaging method leads to equation (46) and (47),

$$\frac{d}{dt}\begin{pmatrix}i_L\\u_C\end{pmatrix}=\begin{bmatrix}-\frac{\left(R_S-R_D\right)d+R_D+R_L+R//R_C}{L} & \frac{R}{L\left(R+R_C\right)}\\ -\frac{R}{C\left(R+R_C\right)} & -\frac{1}{C\left(R+R_C\right)}\end{bmatrix}\begin{pmatrix}i_L\\u_C\end{pmatrix}+\begin{bmatrix}\frac{-R(1-d)+R_Cd}{L\left(R+R_C\right)}\\ \frac{1}{C\left(R+R_C\right)}\end{bmatrix}\left(u_1\right)+\begin{pmatrix}-\frac{V_D(1-d)}{L}\\0\end{pmatrix} \tag{46}$$

$$u_2=\begin{bmatrix}R//R_C & -\frac{R}{R+R_C}\end{bmatrix}\begin{pmatrix}i_L\\u_C\end{pmatrix}+\begin{bmatrix}\frac{R}{R+R_C}\end{bmatrix}\left(u_1\right) \tag{47}$$

Linearization around the working point gives the small signal model in the state space description. The small signal output equation is equal to Eq. (47) with hatted variables in equation (48),

$$\hat{u}_2=\begin{bmatrix}R//R_C & -\frac{R}{R+R_C}\end{bmatrix}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}+\begin{bmatrix}\frac{R}{R+R_C} & 0\end{bmatrix}\begin{pmatrix}\hat{u}_1\\ \hat{d}\end{pmatrix} \tag{48}$$

and the state equation according to (49),

$$\frac{d}{dt}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}=\begin{bmatrix}-\frac{R_SD_0+R_D(1-D_0)+R_L+R//R_C}{L} & \frac{R}{L\left(R+R_C\right)}\\ -\frac{R}{C\left(R+R_C\right)} & -\frac{1}{C\left(R+R_C\right)}\end{bmatrix}\cdot\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}+\begin{bmatrix}\frac{-R(1-D_0)+R_CD_0}{L\left(R+R_C\right)} & \frac{\left(R_D-R_S\right)I_{L0}+V_D+U_{10}}{L}\\ \frac{1}{C\left(R+R_C\right)} & 0\end{bmatrix}\begin{pmatrix}\hat{u}_1\\ \hat{d}\end{pmatrix}. \tag{49}$$

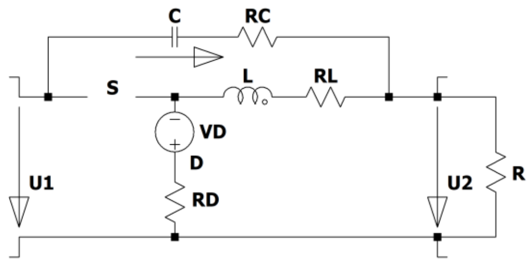


Fig. 17: MBuC with parasitic during M2

There is no direct influence on the output voltage by the duty cycle. When the perturbation ansatz Eqs. (9, 10) is inserted, the sum of the working point values on the right side of Eq. (46) must be zero leading to the connections of the operating point values as in equation (50) and (51),

$$U_{C0}=\frac{\left[R_SD_0+R_D\left(1-D_0\right)+R_L+R//R_C\right]\left(R+R_C\right)}{R}\cdot I_{L0}-\frac{R_CD_0-R\left(1-D_0\right)}{R}U_{10}+V_D\left(1-D_0\right)\frac{R+R_C}{R} \tag{50}$$

$$I_{L0}=\frac{U_{10}-U_{C0}}{R} \tag{51}$$

Including the data of the circuit leads to (52),

$$\frac{d}{dt}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}=\begin{bmatrix}-5.1255e2 & 2.1171e4\\ -3.0152e3 & -1.5076e3\end{bmatrix}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}+\begin{bmatrix}-1.4149e4 & 7.7604e5\\ 1.5076e3 & 0\end{bmatrix}\begin{pmatrix}\hat{u}_1\\ \hat{d}\end{pmatrix} \tag{52}$$

With abbreviations of the elements of the state matrix A_{ij} and of the input matrix B_{ij} gives (53)

$$\frac{d}{dt}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}=\begin{bmatrix}A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix}\begin{pmatrix}\hat{i}_L\\ \hat{u}_C\end{pmatrix}+\begin{bmatrix}B_{11} & B_{12}\\ B_{21} & 0\end{bmatrix}\begin{pmatrix}\hat{u}_1\\ \hat{d}\end{pmatrix} \tag{53}$$

and after Laplace transformation it will produce (54),

$$\begin{bmatrix}s-A_{11} & -A_{12}\\ -A_{21} & s-A_{22}\end{bmatrix}\begin{pmatrix}I_L(s)\\ U_C(s)\end{pmatrix}+\begin{bmatrix}B_{11} & B_{12}\\ B_{21} & 0\end{bmatrix}\begin{pmatrix}U_1(s)\\ D(s)\end{pmatrix} \tag{54}$$

one gets for the denominator as equation (55)

$$\text{Den} = \begin{vmatrix} s-A_{11} & -A_{12} \\ -A_{21} & s-A_{22} \end{vmatrix}$$
$$= s^2 - s(A_{11}+A_{22}) + (A_{11}A_{22} - A_{12}A_{21}) \qquad (55)$$
$$= s^2 + 2.0202\cdot 10^3 + 6.3835\cdot 10^7$$

The numerator of the transfer function between the voltage across the capacitor and the duty cycle is given by equation (56),

$$\text{NUM\_UC/D} = \begin{vmatrix} s-A_{11} & B_{12} \\ -A_{21} & 0 \end{vmatrix} = (A_{21}B_{12}) = \qquad (56)$$
$$= -2.3399\cdot 10^9$$

In the same way all other transfer functions can be calculated. To achieve the transfer functions of the output voltage, the output equation (57) in the Laplace domain must be used

$$U_2(s) = \begin{bmatrix} R // R_C & -\dfrac{R}{R+R_C} \end{bmatrix} \begin{pmatrix} I_L(s) \\ U_C(s) \end{pmatrix} + \qquad (57)$$
$$+ \begin{bmatrix} \dfrac{R}{R+R_C} & 0 \end{bmatrix} \begin{pmatrix} U_1(s) \\ D(s) \end{pmatrix}$$

For the output voltage one has to combine different transfer functions. It is easier to use the signal flow graph. For the MBuC with parasitics one gets the graph according to Fig. 18.

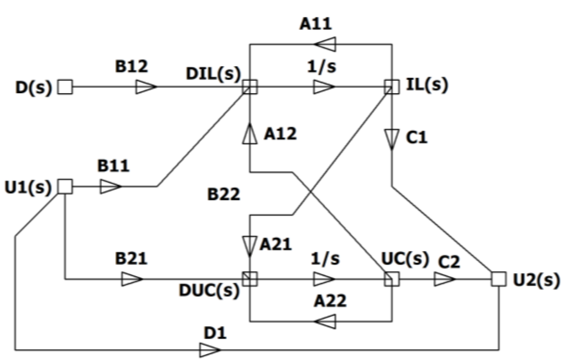


Fig. 18: MBuC with losses

There are two forward paths and two loops as (58 -59),

$$F_1 = B_{12}\cdot\frac{1}{s}\cdot A_{21}\cdot\frac{1}{s}\cdot C_2\,,\; F_2 = B_{12}\cdot\frac{1}{s}\cdot C_1 \qquad (58)$$

$$L_1 = \frac{1}{s}\cdot A_{11}\,,\; L_2 = \frac{1}{s}\cdot A_{21}\cdot\frac{1}{s}\cdot A_{12}\,,\; L_3 = \frac{1}{s}\cdot A_{22} \qquad (59)$$

All three loops touch the forward path F1, only the first and the second loops touch the second forward path F2. The loops L1 and L3 do not touch each other. So, one can write for the transfer function as equation (60) and (61),

$$\frac{U_2(s)}{D(s)} = \frac{F_1 + F_2[1-L_3]}{1-(L_1+L_2+L_3)+L_1L_3} \qquad (60)$$

$$\frac{U_2(s)}{D(s)} = \frac{\dfrac{B_{12}A_{21}}{s^2} + \dfrac{B_{12}C_1}{s}\left[1-\dfrac{A_{22}}{s}\right]}{1-\left(\dfrac{A_{11}}{s}+\dfrac{A_{12}A_{21}}{s^2}+\dfrac{A_{22}}{s}\right)+\dfrac{A_{11}A_{22}}{s^2}} \qquad (61)$$

leading to the result (62),

$$\frac{U_2(s)}{D(s)} = \frac{B_{12}C_1 s + (A_{21}B_{12} - A_{22}B_{12}C_1)}{s^2 - (A_{11}+A_{22})s + (A_{11}A_{22} - A_{12}A_{21})} \qquad (62)$$

Inserting the parameters leads to equation (63),

$$\frac{U_2(s)}{D(s)} = \frac{+7.7216e3s + 2.3399e9}{s^2 + 2.0202e3s + 6.4608e7} \qquad (63)$$

Fig. 19 shows the Bode plot drawn with the help of LTSpice using Eq. (63)

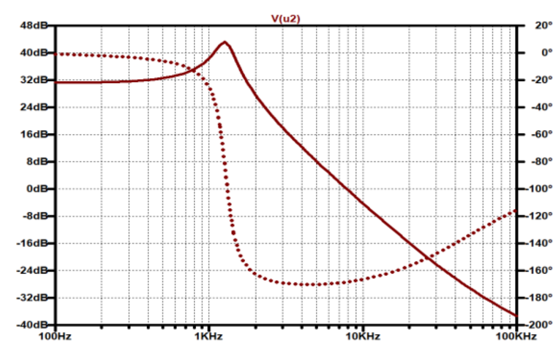


Fig. 19: Bode plot: solid line: gain, dotted line: phase

Using the Bode nominal form, will gives (64),

$$\frac{1}{\dfrac{s^2}{\omega_0^2} + 2\dfrac{d}{\omega_0}s + 1} \qquad (64)$$

one gets equation (65),

$$\frac{U_2(s)}{D(s)} = \frac{1.1952e-4\cdot s + 3.6217e1}{\dfrac{s^2}{6.4608e7} + 3.1269e-5\cdot s + 1} \qquad (65)$$

The resonant frequency f_0 (66) and the damping d are (67),

$$\omega_0 = 8.0379 \cdot 10^3 \ \mathrm{s}^{-1} \qquad f_0 = 1.2793 \cdot 10^3 \ \mathrm{Hz} \qquad (66)$$

$$2\frac{d}{\omega_0} = 3.1269 \cdot 10^5 \qquad d = 0.123 \qquad (67)$$

The resonant overshot is at the angular frequency is (68),

$$\omega_{\max} = \sqrt{1-d^2}\,\omega_0\,, \qquad (68)$$

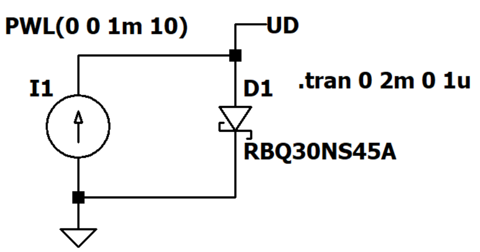
in our case nearly equal to ω_0 ($0.9924 \cdot \omega_0$, $f_{\max}$=1270 Hz) and has the value as equation (69),

$$20\lg\frac{1}{2d\sqrt{1-d^2}} = 12.3 \ \mathrm{dB} \qquad (69)$$

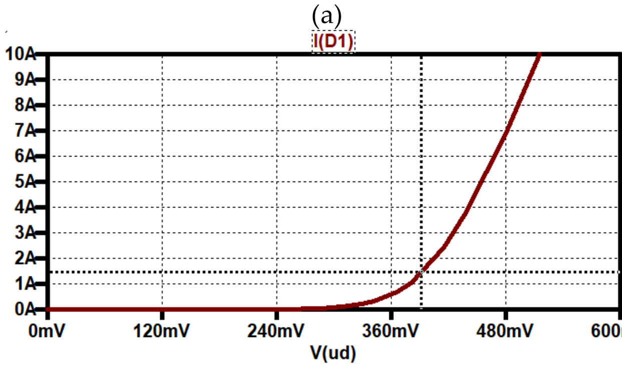
The stationary gain is G_0=36.2 (31.2 dB).

5. Simulations

The equivalent values of the diode are found in Fig. 20, where the simulation circuit to draw the characteristics of the diode and the characteristics are shown. RD is the differential resistor and VD is the knee-voltage of the used Schottky diode.



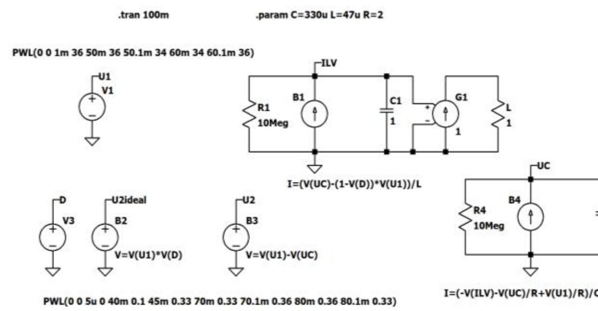
(a)



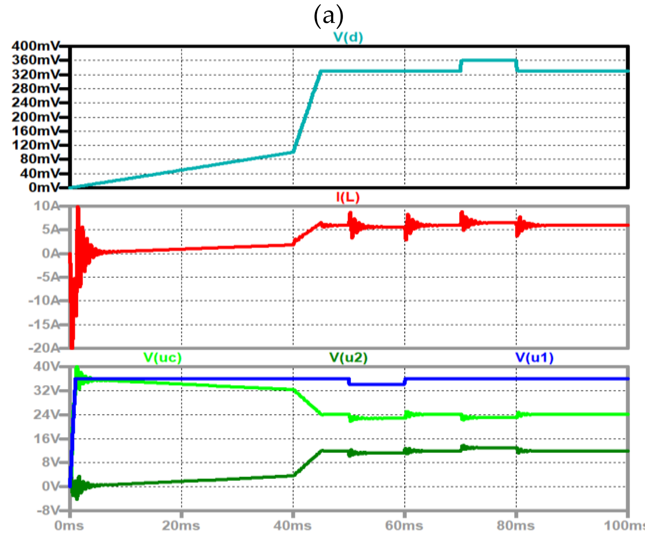
(b)

Fig. 20: Characteristics of the diode: (a) simulation circuit; (b) characteristics

The results from Fig. 20 are RD=124 mV/10 A= =12.4 mΩ, VD=0.39 V. The on-resistor of the used active switch is given by RS=5.4 mΩ. (Symbols written like in Fig. 21). Fig. 21 shows the results of the idealized model. The differential equations are solved by using arbitrary current sources to model the derivatives. The integration is done by feeding these currents into capacitors of 1 F.



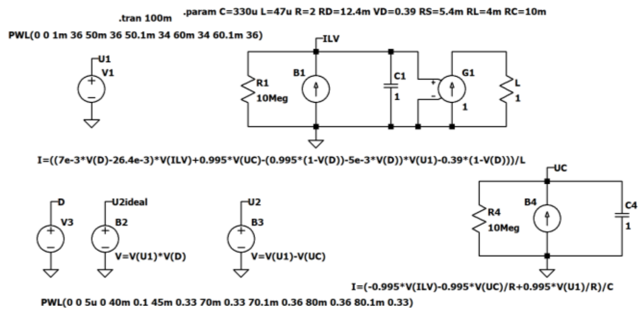
(a)



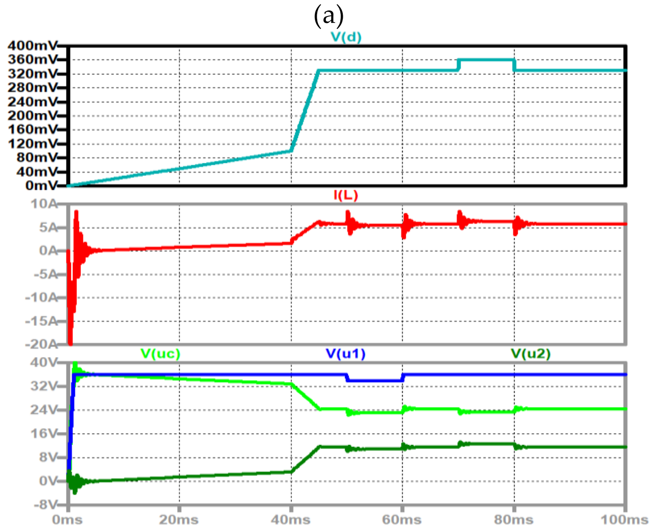
(b)

Fig. 21: idealized model: inrush, start-up, duty cycle steps, input voltage steps: (a) simulation circuit; (b) top to bottom: duty cycle (turquoise); current through the coil (red); input voltage (blue), voltage across the capacitor (green), output voltage (dark green)

The duty cycle is increased from zero by two ramps, stays in the steady state, makes a jump to a higher value, and after some time it steps back. The current through the coil is shown in the next graph. When the system starts, there is a large ringing. The model is not correct at the beginning, because the model cannot correctly describe the beginning, but after a short time it describes the system correctly. The graph at the bottom shows the input voltage which makes a step down and a step up, the voltage across the capacitor, and the output voltage. The steps of the duty cycle and of the input voltage lead to a ringing in the current and at the capacitor voltage (and therefore also in the output voltage). Fig. 22, shows the same signals in the model with included parasitic resistors. The ringing is more damped compared to the idealized model.



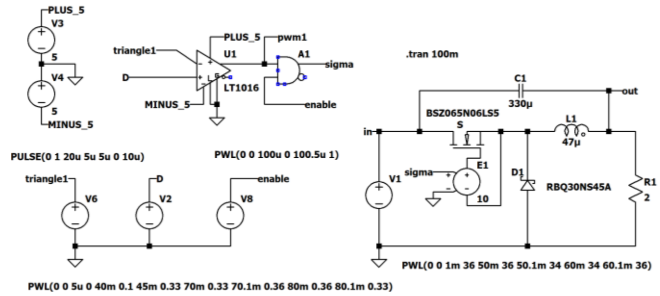
(a)



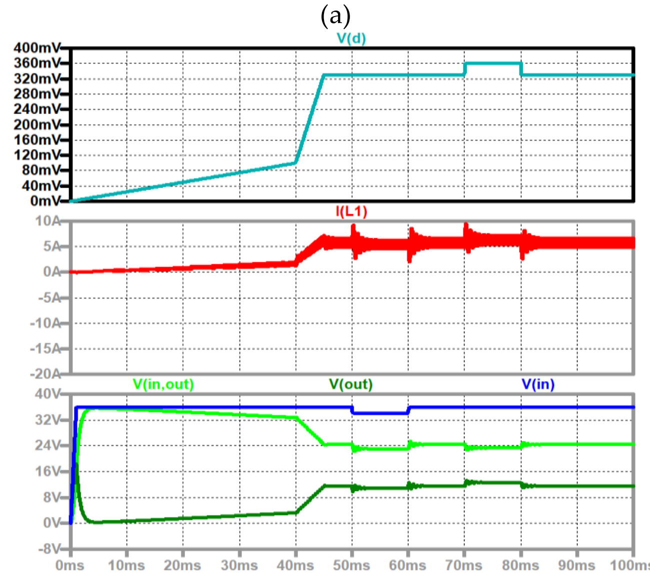
(b)

Fig. 22: idealized model: inrush, start-up, duty cycle steps, input voltage steps: (a) simulation circuit; (b) top to bottom: duty cycle (turquoise); current through the coil (red); input voltage (blue), voltage across the capacitor (green), output voltage (dark green)

To check the results of the models, the circuit is implemented in LTSpice. The simulation model is shown in Fig. 23 (a) and the same signals as in the Fig. 21 and Fig. 22 are shown in Fig. 23 (b). One can see a very good coincidence of the mathematical models and the circuit simulation. The main difference can be seen in the current through the coil. In the model only the mean value is calculated, but in the circuit simulation the current ripple is displayed.



(a)



(b)

Fig. 23: Circuit simulation: inrush, start-up, duty cycle steps, input voltage steps: (a) simulation circuit; (b) top to bottom: duty cycle (turquoise); current through the coil (red); input voltage (blue), voltage across the capacitor (green), output voltage (dark green)

6. Additional aspects of the converter

After the mathematical modelling we take a short look at the MBuC by an intuitive way. Afterwards we look at the differences between the normal Buck and the modified one, study the inrush current and finally we combine the MBuC with the traditional Buck.

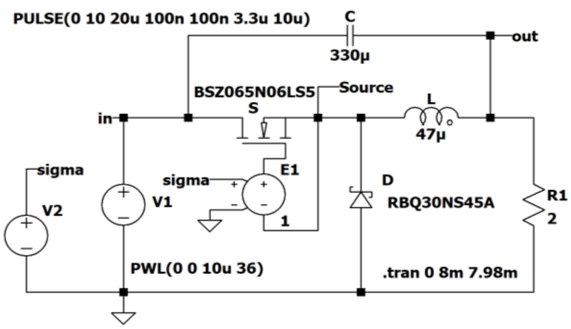
6.1 Intuitive description of the converter

The best way to study a DC/DC converter is with ideal components (that means they have no parasitic resistors and the switching takes no time) and to start with the voltage across the coil. In the steady state the voltage across the coil must be zero in the mean. During the on time of the switch, the difference between the input voltage and the output voltage (which is equal to the voltage across the capacitor) is across the coil. During the off-time of the switch (now the diode is conducting), the negative output voltage is across the coil as shown in Fig. 24. From the voltage-time balance (70),

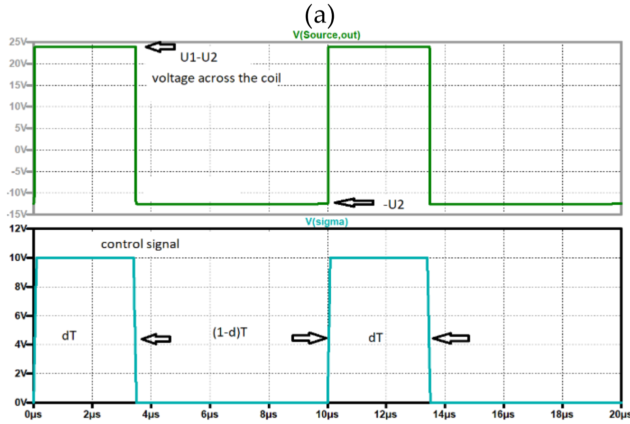
$$(U_1 - U_2)dT = |-U_2|(1-d)T \tag{70}$$

one can obtain the output voltage U_2 and the voltage transformation ratio M as (71),

$$U_2 = d \cdot U_1 \qquad M = \frac{U_2}{U_1} = d \tag{71}$$



(a)



(b)

Fig. 24: MBuC: (a) simulation circuit; (b) top to bottom: voltage across the coil (dark green); control signal (turquoise)

The output voltage is a linear function of the duty cycle, which is defined as the on-time of the active switch with reference to the period. During the on-time of the active switch, when a positive voltage is across the coil, the current through the coil increases, and during the off-time of the transistor the current decreases, because now a negative voltage is across the inductor. The output voltage and the input voltage can now be drawn. The voltage across the capacitor is the difference between the input voltage and the output voltage (Fig. 25). In the upper graph the current through the capacitor is shown. The capacitor delivers current, when the current through the coil is lower than the load current; when the current through the coil is higher than the load current, the capacitor is charged. In the steady state the current through the capacitor is zero in the mean. Inspecting the positive output node one can see that the mean value of the current through the coil must be equal to the load current as in equation (72).

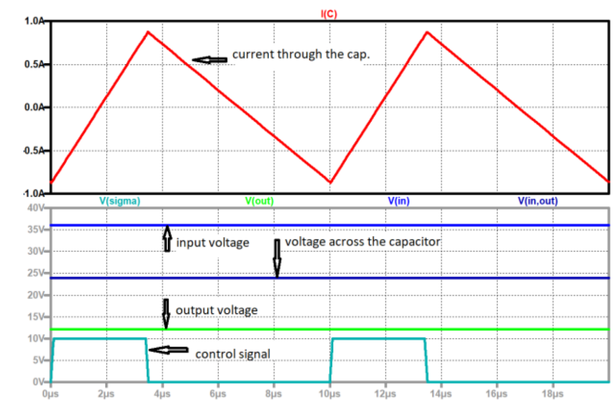


Fig. 25: MBuC: (a) top to bottom: current through the capacitor (red); input voltage (blue), voltage across the capacitor (dark blue), output voltage (green); control signal (turquoise)

$$\bar{I}_L = I_{LOAD} = \frac{U_2}{R} \tag{72}$$

6.2 The differences between the modified and the normal Buck converters

The eye catching difference is the position of the storage capacitor, so that the output voltage is the input voltage minus the voltage across the capacitor. A change of the input voltage has an immediate push-through on the output voltage. Therefore, the circuit should be used, when the input source is stable (batteries or a DC micro-grid). An interesting effect is that the voltage across the capacitor is the difference between the input voltage and the output voltage. When large step-down ratios are used, a significantly larger voltage is across the capacitor compared to the output voltage. The energy stored in a capacitor is proportional to the square of the voltage across it. So more energy is stored in the capacitor compared to a capacitor which is in parallel to the output terminals. For the same stored energy, a smaller capacitor can be used. With equation (73),

$$\frac{C_{OUT}U_{OUT}^2}{2}=\frac{C_{MODIFIED}\left(U_{IN}-U_{OUT}\right)^2}{2} \tag{73}$$

the capacitor in the modified converter, when the same stored energy is used, can be reduced by (74),

$$C_{MODIFIED}=\frac{U_{OUT}^2}{\left(U_{IN}-U_{OUT}\right)^2}C_{OUT} \tag{74}$$

Fig. 26 shows the used simulation circuit for Fig. 27 which shows in the most upper graph the input current and the load current of the normal Buck, in the middle graph the input current and the load current of the MBuC, and in the lowest graph the input voltage, the output voltage and the control signal for both converters. The efficiency and the current through the coils are equal in both concepts.

6.3 Inrush

A disadvantage of the MBuC in comparison with the normal Buck is that, when the converter is connected to a stable input source a large inrush current occurs. The transistor is turned off. When the input voltage is applied to the circuit, a current flows through the capacitor and the load. At the beginning no voltage is across the capacitor, so the output voltage is equal to the input voltage and the current is only limited by the load. This current charges the capacitor and decreases the output voltage. When the capacitor is fully charged, the output voltage is zero and so is also the current out of the source. Fig. 27 shows the input voltage, the output voltage, the voltage across the capacitor, and the input current. The simulation circuit is the upper part of Fig. 26.

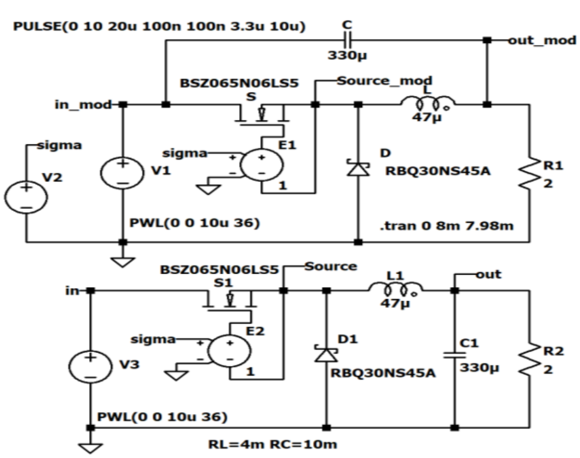


Fig. 26: simulation circuit

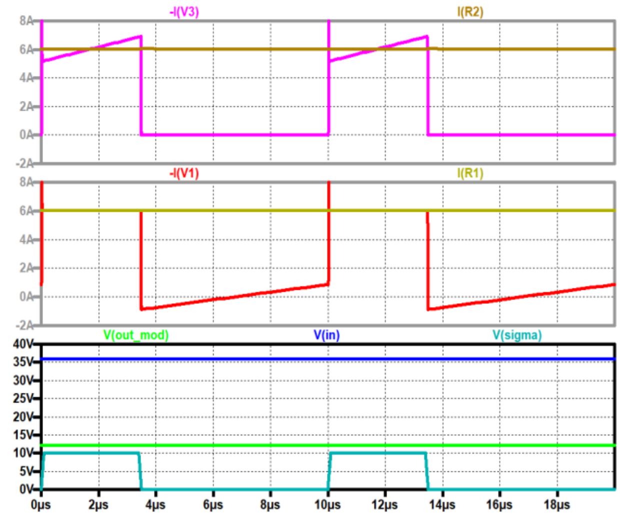


Fig. 27: Top to bottom: input current of the Buck (violet) and the load current (brown); load current (light brown) and input current (red) of the MBuC; input voltage (blue), output voltage (green), control signal (turquoise) of both types. (MBuC: Pin=75.36 W, Pout=73.1 W; ETA=97%; Buck: Pin=75.31 W, Pout=73.1 W, ETA=97 %)

The input current is described by the input voltage is U_1, C and R; the parasitic resistor of the capacitor can be simply added to the load resistor as (75),

$$U_1=\frac{1}{C}\int_0^t i_C dt+R\cdot i \tag{75}$$

With the help of the Laplace transformation one gets (76),

$$\frac{U_1}{s}=\frac{1}{Cs}I(s)+R\cdot I(s) \qquad i=\frac{U_1}{R}\exp\left(-\frac{1}{RC}\right) \tag{76}$$

The inrush also occurs in famous converters as the Boost, the Cuk or the SEPIC. A heat dependent resistor, or a resistor which is shunted by a contact of a relay or an additional electronic switch are used when necessary. A more elegant way, which can be used also as electronic fuse, is to connect a small Buck in series that is turned on all the time after the start-up.

6.4 Quadratic step-down converter with a modified Buck converter

The circuit diagram is shown in Fig. 28. The duty cycle of the switch starts from zero up to the desired value so slow that the capacitors are charged continuously without high current. So, the inrush is avoided and the input source and the components of the converter are treated gently. The voltage transformation ratio is the product of the voltage transformation ratios of the cascaded stages. In this case, the result gives equation (77),

$$M = \frac{U_2}{U_1} = d^2 \tag{77}$$

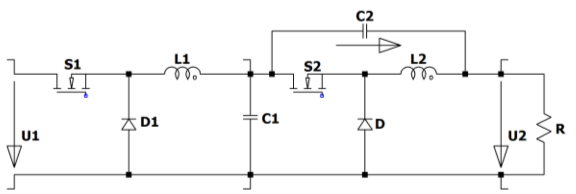


Fig. 28: Circuit diagram of a quadratic step-down converter

The switch S1 can be used as an electronic fuse in case of an error, e.g. a short circuit at the load, or an overcurrent. When S1 is turned on all the time, the voltage transformation ratio is linear to the duty cycle.

6.5 Summery

The MBuC behaves like a normal Buck. The input current and the voltage across the capacitor differ, however. This leads to an inrush current, when the converter is connected to a stiff supply. The energy stored in the capacitor, however, is higher when low output voltages are used. The ripple of the capacitor voltage and therefore the ripple of the output voltage are equal in both types. The efficiency is also equal. The voltage stress across the semiconductors is also equal for both topologies and must be equal to the input voltage (multiplied by a factor of 1.3 to 2 depending on the application).

7. Conclusion

There are two ways to analyze a new DC/DC converter topology. One way is to use a scattered paper and a pencil and sketch the signals across the components in the steady state. This helps to understand the operation of the converter. The second way is to use physics and mathematics. This is done in this paper. The operational modes of the converter are described by differential equations. These equations are weighted by the percentage of their validity leading to the nonlinear large signal model. By linearization e.g. by the perturbation ansatz, the small signal model is achieved. After the Laplace transformation the transfer functions can be calculated. It is shown that the application of the signal flow graph is an easy way to calculate the transfer functions and also helps to a better understanding of the converter, when e.g. state space control and two-loop control is used. With the help of LTSpice the models were solved and compared with the circuit simulation. The results show a fine coincidence. The here described converter can be used as a stage in a quadratic converter, e.g. with a traditional Buck converter (as a pre-stage, an inrush current is avoided, when the system is connected to a stiff input supply) or as a charger for batteries and super capacitors. The pre-stage serves also as an electronic fuse. As the energy stored in a capacitor is dependent on the square of the voltage, the storage capacitor can be reduced, when the output voltage is lower than half of the input voltage. The paper can also be used as a lecture note for teaching modelling of DC/DC converters.

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Data Availability Statement

The data are included in the paper.

Conflict of Interest

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References

[1] N. Mohan, T. M. Undeland, W. Robbins, "Power electronics, converters, applications and design",

3rd edition, John Wiley & Sons, New York, USA, 2003. [CrossRef]

[2] F. Zach, "Power Electronics, in German: Leistungselektronik", *6th edition, Springer*: Frankfurt, Germany, 2022. https://doi.org/10.1007/978-3-658-31436-1

[3] Y. Rozanov, S. Ryvkin, E. Chaplygin, P. Voronin, "Power Electronics Basics" *CRC Press*: Boca Raton, FL, USA, 2016.

[4] D. Maksimovic, S. Cuk, "A general approach to synthesis and analysis of quasi-resonant converters", *IEEE Transactions on Power Electronics*, Vol. 6, No. 1, pp. 127-140, Jan 1991. https://doi.org/10.1109/63.65011

[5] B. W. Williams, "Generation and analysis of canonical switching cell DC-to-DC converters", *IEEE Transactions on Industrial Electronics*, Vol. 61, No. 1, pp. 329-346, January 2014. https://doi.org/10.1109/TIE.2013.2240633

[6] M. S. B. Ranjana, S. M. Badave, P. KiranMaroti, S. M. Mule and R. M. Kulkarni, "DC-DC current buck converter through duality approach and its DC transformer modelling for current based loads", *2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, Nagercoil, India, pp. 1-5, 2016. https://doi.org/10.1109/ICCPCT.2016.7530111

[7] H. Gholizadeh, S. A. Gorji and D. Sera, "A quadratic buck-boost converter with continuous input and output currents", *IEEE Access*, Vol. 11, pp. 22376-22393, 2023. https://doi.org/10.1109/ACCESS.2023.3253102

[8] H. Gholizadeh, S. A. Gorji and D. Sera, "A family of high-gain single-switch dc-dc converters for high-intensity discharge lamps", *IEEE Open Journal of Power Electronics*, Vol. 5, pp. 1534-1561, 2024. https://doi.org/10.1109/OJPEL.2024.3462715

[9] M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg and B. Lehman, "Step-up DC–DC converters: a comprehensive review of voltage-boosting techniques, topologies, and applications", *IEEE Transactions on Power Electronics*, Vol. 32, No. 12, pp. 9143-9178, 2017. https://doi.org/10.1109/TPEL.2017.2652318

[10] F. A. Himmelstoss, K. Edelmoser, T. Vienna "Modified Basic DC-DC Converters", *Power Conversion and Intelligent Motion PCIM*, Nuernberg, pp. 1076-1083, 2018.

[11] F. A. Himmelstoss and M. Jungmayer, "A family of modified converters with limited duty cycle", *2021 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) & 2021 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, Brasov, Romania, pp. 246-253, 2021. https://doi.org/10.1109/OPTIM-ACEMP50812.2021.9590064

[12] A. Rajaei, P. Yavari, H. Farsi and S. Safarloo, "Signal flowgraph model of a DAB converter with phase-shift modulation as an interlinking converter of two DC MGs", *2025 15th Smart Grid Conference (SGC)*, Shiraz, Iran, Islamic Republic of, pp. 1-7, 2025. https://doi.org/10.1109/SGC69320.2025.11372441

[13] D. Schulz, R. Schwendemann, T. Eckstein, A. Liske and M. Hiller, "Versatile converter impedance modeling with matrix signal flow graphs to include frequency coupling", *2025 Energy Conversion Congress & Expo Europe (ECCE Europe)*, Birmingham, United Kingdom, pp. 1-6, 2025. https://doi.org/10.1109/ECCE-Europe62795.2025.11238400

[14] E. R. C. Da Silva, D. A. Fernandes, A. K. P. de Macedo and A. Marcus N. Lima, "Signal flow graph modeling and control of the DC-DC multilevel boost converter", *2022 14th Seminar on Power Electronics and Control (SEPOC)*, Santa Maria, Brazil, pp. 1-6, 2022. https://doi.org/10.1109/SEPOC54972.2022.9976417

[15] M. Appikonda, K. Dhanalakshmi and P. S. V. Krishna, "Signal flow graph model and feed-forward control for a high voltage gain dual input boost DC-DC converter", *2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020)*, Cochin, India, pp. 1-6, 2020. https://doi.org/10.1109/PESGRE45664.2020.9070586

[16] Z. Xu, B. Li, S. Li, X. Wang and D. Xu, "MMC admittance model simplification based on signal-flow graph", *IEEE Transactions on Power Electronics*, Vol. 37, No. 5, pp. 5547-5561, May 2022. https://doi.org/10.1109/TPEL.2021.3126870

[17] S. Shah, P. Koralewicz, V. Gevorgian and L. Parsa, "Small signal modeling and design of

phase-locked loops using harmonic signal flow graphs", *IEEE Transactions on Energy Conversion*, Vol. 35, No. 2, pp. 600-610, June 2020. https://doi.org/10.1109/TEC.2019.2954112

[18] I. Jahn, G. Chaffey, E. Prieto-Araujo, M. Hoffmann, R. Alvarez and A. Monti, "On the partitioning of MMC control systems using graph theory", *IEEE Open Journal of Power Electronics*, Vol. 3, pp. 611-620, 2022. https://doi.org/10.1109/OJPEL.2022.3204558

[19] F. A. Himmelstoss and H. L. Votzi, "Converters to drive two brushed DC machines", *2021 IEEE 15th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, Florence, Italy, pp. 1-8, 2021. https://doi.org/10.1109/CPE-POWERENG50821.2021.9501190

[20] W. Ki, "Signal flow graph in loop gain analysis of DC-DC PWM CCM switching converters", *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, Vol. 45, No. 6, pp. 644-655, June 1998. https://doi.org/10.1109/81.678481

[21] F. A. Himmelstoss, "Design of State-Space Controllers with the Help of Signal Flow Graphs Shown for a Buck Converter", *WSEAS Transactions on Systems*, Vol. 21, pp. 421-429, 2022. https://doi.org/10.37394/23202.2022.21.46

Appendix

A1. Signal flow graphs - a short summery

The nodes of the signal flow graph represent the signals, and the branches which connect the nodes show the correlations between them. The transfer functions between the nodes are written above the branches One has to distinguish between forward paths which connect an input node as a starting point with an output node which represents an output signal, and between loops, which begin and end at the same node. To get the connection of a forward path (between an input node and an output node), one has to multiply the values of all the connecting branches. A loop begins at a node and ends at the same node. The result of the loop is found by the multiplication of the connection values of all branches which form the loop. The result of second-order loops is found by the product of two different loops which are not touching each other. Third order loops are formed from three loops which do not touch each other, and so on. Mason's equation helps to find the transfer functions of the described system. The denominator of the transfer functions is given by one minus the sum of all first order loops plus the sum of all second order loops minus the sum of all third order loops plus...etc. The numerator is given by the sum of all forward paths each multiplied by the denominator, but all loops which are touching the forward path are deleted.

A2. Linearization – an intuitive explanation

The linearization is done around an operating point. In the steady state the mean values of all signals are written as capital letters with a zero in the index and describe the operating point. When a signal e.g. the input voltage or the duty cycle are changing, all other variables will change, too. All variables are written by the sum of the operating point value plus a disturbance value (Eq. 9 and 10). Including these variables into the nonlinear equation (Eq. 11) does not change the contents of the equation, now it is only written in this special form. When the disturbances are small, the product of two disturbance values will be even smaller. So when the products of the disturbance values are deleted, the equation is now linear but not exact. So the assumption to use this process is that the changes are small (e.g. 10 %) compared to the operating point. The larger the disturbances, the more incorrect will be the result. The nonlinear model can be used to check the deviation. The linearization is necessary to calculate transfer functions and to draw Bode plots.

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