The Use of Tapped Inductors and Autotransformers in DC/DC Converters Shown for the SEPIC

FELIX A. HIMMELSTOSS, HELMUT L. VOTZI
Faculty of Electronic Engineering and Entrepreneurship
University of Applied Sciences Technikum Wien
Hoechstaedtplatz 6, 1200 Wien
AUSTRIA

Abstract: - Studying the function of DC/DC converters is an important topic when organizing a course in Power Electronics. The use of tapped inductors or autotransformers changes the behavior of the converter and also the stress of the semiconductors. In this paper, a simple way to teach these converters is shown and demonstrated for two variants of the well-known SEPIC converter. Suggestive drawings and simple calculations and simulations are used to demonstrate the operation of the converters. The large signal and the small signal models for one variant are calculated.

Key-Words: - DC/DC converter, SEPIC, autotransformer, coupled coils, tapped inductor, large signal model, small signal model, simulations.

Received: September 9, 2023. Revised: May 5, 2024. Accepted: June 11, 2024. Published: August 6, 2024.

1 Introduction

Replacing a coil of a DC/DC converter with a tapped inductor or an autotransformer changes the voltage transformation ratio, changes the stress of the semiconductors, and gives an additional degree of freedom for the design. The input and the output voltages can be adapted in such a way that the duty ratio of the active switch has no extreme values near zero or near one. So the efficiency can be increased. Here we discuss in a didactical way the function of a Sepic converter, when the first coil is replaced by two coupled windings. The best way to understand the function of a converter is by sketching the voltages across and the currents through the components. So the comprehension of converters is deepened. Both variants used here are done for the first inductor, and in the first case, the coupled coils behave like a transformer, and in the second variant as a tapped inductor. First, a look at the literature concerning tapped coils used in DC/DC converters, especially the SEPIC converter is done.

A short paper describing basic bidirectional converters with tapped inductors is [1]. In [2] tapped inductor technology-based DC-DC converters are shown. The modeling of the tapped inductor SEPIC converter by the TIS-SFG approach is treated in [3]. A high step-up tapped inductor SEPIC converter with a charge pump cell can be found in [4]. [5], treats an analysis and design of a charge pump-assisted high step-up tapped inductor SEPIC converter with a regenerative snubber. The analysis of a bidirectional SEPIC/Zeta converter with a coupled inductor [6] uses the coupling of both inductors of the original topologies. A family of high step-up soft-switching integrated Sepic converters with a Y-source coupled inductor is discussed in [7]. Other applications with tapped inductors are shown in [8] and [9]. It should be mentioned that the original SEPIC topology is treated in the textbooks on Power Electronic, e.g. [10], [11], [12].

In its basic form, the Sepic converter consists of an active (S) and a passive switch (D), two coils (L1, L2), and two capacitors (C1, C2). The circuit diagram is shown in Figure 1. During the steady state the voltages across the inductors are zero in the mean, so it is easy to see that the voltage across C1 must be equal to the input voltage U1. With the help of the voltage-time balance, the voltage transformation ratio is equal to a Buck-Boost converter according to

$$M = \frac{U_2}{U_1} = \frac{d}{1-d} \tag{1}$$

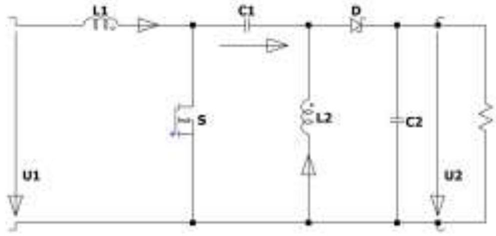

Fig. 1: Circuit diagram of the Sepic converter

The variants will be studied for ideal components (no parasitic resistors, ideal switching), in the continuous mode, in steady-state, and with capacitors so large that the voltages across them are constant during one period. In the continuous mode, only two modes within a period follow each other in a repeated way. In the first mode, M1 the active switch S is on and the passive switch D is off, in the second mode M2 the electronic switch S is off and the diode D is conducting. When the converter is in the discontinuous mode a third mode M3, when both semiconductor components are off, occurs. The drawings are done for a winding ratio of one to one but lettered with the exact winding ratio.

2 Variant I

In the first variant, the first coil of the Sepic converter is replaced by a tapped inductor which acts as an autotransformer. Figure 2 shows the circuit diagram.

2.1 Connection between the Voltages

When inspecting the circuit diagram one can immediately see that in the steady state, the voltage across C1 must be equal to the input voltage

$$U_{C1} = U_1 . \tag{2}$$

During M1 the input voltage U1 is across the winding N11 and during M2 the input voltage minus the output voltage minus the voltage across C2 is across the complete winding of the autotransformer (N11+N12). Only the corresponding part

$$u_{N11,M2} = \frac{N_{11}}{N_{11}+N_{12}}\left(U_1 - U_2 - U_{C1}\right) \tag{3}$$

is across the first winding during M2. With an arbitrarily chosen input voltage of two divisions, one can now draw the voltage across N11 (Figure 3, left).

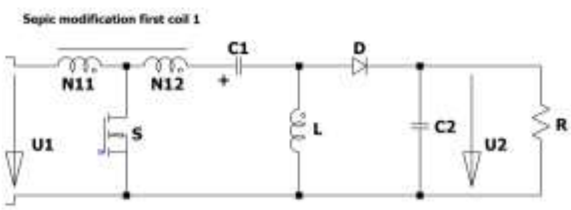

Fig. 2: Variant I

The charge balance across N11

$$U_1 \cdot d = \frac{N_{11}}{N_{11}+N_{12}}\left|U_1 - U_2 - U_{C1}\right|(1-d) \tag{4}$$

leads to the voltage transformation ratio

$$M = \frac{U_2}{U_1} = \frac{N_{11}+N_{12}}{N_{11}}\frac{d}{1-d} \tag{5}$$

In the same way, one gets the voltage across the second winding N12 of the autotransformer (Figure 3, right).

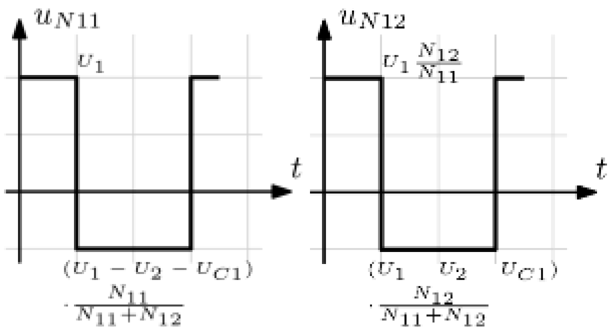

Fig. 3: Voltages across the autotransformer: first winding (left), second winding (right)

With a duty cycle of one-third the output voltage is equal to the input voltage for N11=N12. Figure 4 on the left side shows the input and the output voltages, and the voltage across the first capacitor.

The voltage across the coil L must be zero in the mean. During mode M1 the sum of the transformed voltage across N11 plus the voltage across C1

$$u_{L,M1} = U_1 \cdot \frac{N_{12}}{N_{11}} + U_{C1} \tag{6}$$

lies across the coil and during M2 the negative output voltage (Figure 4 right).

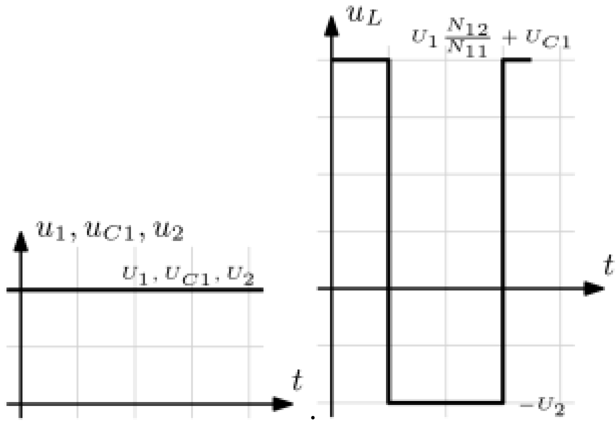

Fig. 4: Input voltage and voltages across the capacitors (left), voltage across the coil (right)

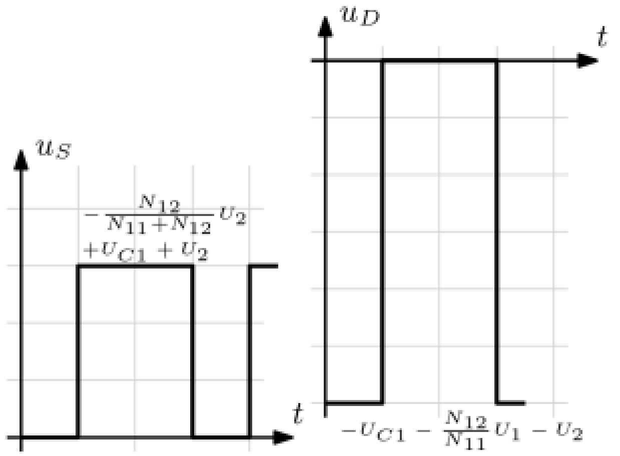

Fig. 5: Voltages across the electronic switch S (left) and the diode (right)

For the design of the converter the voltage maxima across the semiconductors are important (Figure 5). With the help of KVL one gets:

$$\frac{U_{S,\max}}{U_1}=\frac{1}{1-d}, \tag{7}$$

$$\frac{U_{D,\max}}{U_1}=\frac{N_{11}+N_{12}}{N_{11}}\frac{1}{1-d}. \tag{8}$$

2.2 Connection between the Currents

We start arbitrarily with a load current of two divisions (Figure 6, left).

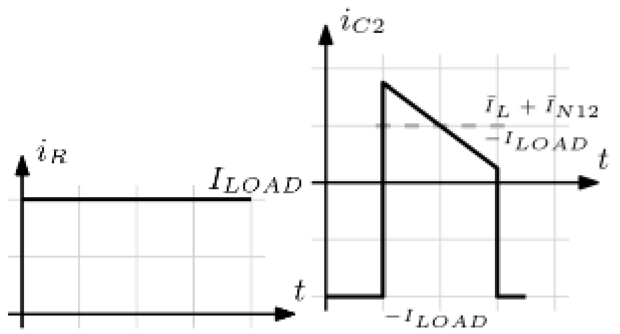

Fig. 6: Currents through the load (left) and through the output capacitor (right)

The charge balance of the output capacitor C2 can easily be drawn (Figure 6, right) and leads to

$$I_{LOAD}\cdot d=\left(\bar{I}_L+\bar{I}_{N12,M2}-I_{LOAD}\right)\cdot(1-d). \tag{9}$$

$\bar{I}_{N12,M2}$ is the mean value of the current through the winding N12 referred to as the duration of mode M2. The charge balance of the first capacitor C1 is given by

$$\bar{I}_L\cdot d=\bar{I}_{N12,M2}\cdot(1-d). \tag{10}$$

Solving

$$\begin{bmatrix}1-d & 1-d\\ 1-d & -d\end{bmatrix}\cdot\begin{pmatrix}\bar{I}_{N12,M2}\\ I_L\end{pmatrix}=\begin{pmatrix}1\\0\end{pmatrix}\cdot I_{LOAD} \tag{11}$$

leads to

$$\frac{\bar{I}_{N12,M2}}{I_{LOAD}}=\frac{d}{1-d}, \tag{12}$$

$$\frac{\bar{I}_{L2}}{I_{LOAD}}=1. \tag{13}$$

Figure 7, left shows the current through the winding N12 which is equal to the current through the capacitor C1. To distinguish the currents through L and N12 the current ripple is chosen differently, one division for the coil and half division for the autotransformer winding. The current through coil is shown in Figure 7, right.

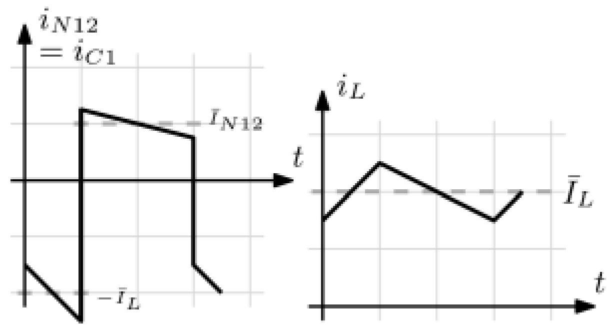

Fig. 7: Current through the second winding (left) and the current through the coil (right)

During M2 the transformer has no output current, so the current through N12 is only the magnetizing current i_{mag}. This current must also flow through N11. During M1 the magnetizing current flows only through the first winding N11 and must be therefore higher. The ampere windings must be the same:

$$N_{11}\cdot i_{mag,M1}=(N_{11}+N_{12})\cdot i_{mag,M2} \tag{14}$$

therefore, the magnetizing current must be

$$i_{mag,M1}=\frac{N_{11}+N_{12}}{N_{11}}\cdot i_{mag,M2} \tag{15}$$

higher in mode M1. The current through N11 is in M1 equal to this higher magnetizing current and the current which is the transformed current through the coil L. The current turns are:

$$N_{12}\cdot i_L=N_{11}\cdot i_{L,N11}. \tag{16}$$

So the current caused by the current through the coil in N11 (Figure 8, left) can be obtained by:

$$i_{L,N11}=\frac{N_{12}}{N_{11}}\cdot i_L \tag{17}$$

The magnetizing current is shown in Figure 8 on the right side.

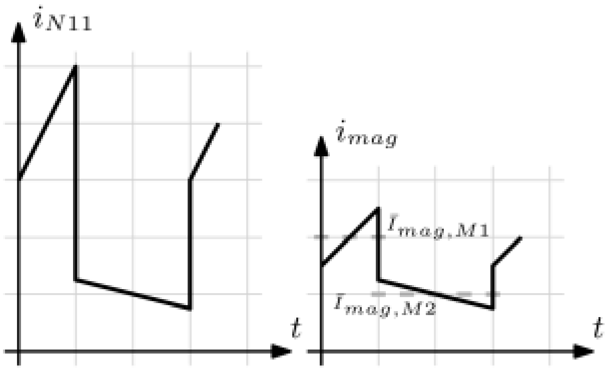

Fig. 8: Current through the first winding (left), magnetizing current (right)

Now one can construct the current through the semiconductor devices. The current through the electronic switch (Figure 9, left) is

$$i_S = i_{N11} - i_{C1} \tag{18}$$

and through the diode (Figure 9, right)

$$i_D = i_L + i_{C1} \tag{19}$$

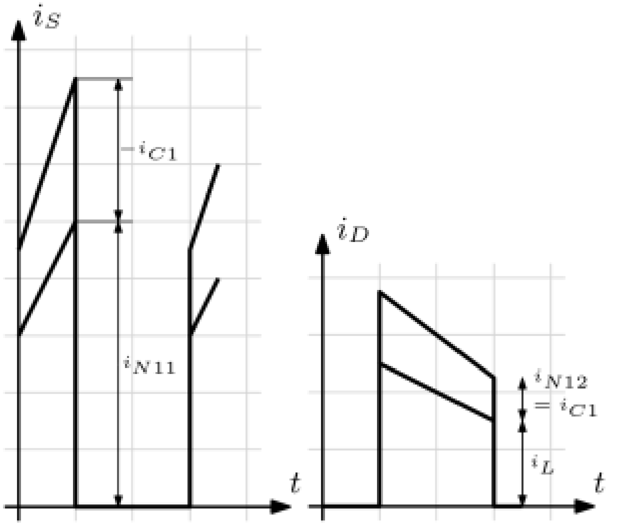

Fig. 9: Currents through the semiconductors, active switch (left), passive switch (right)

3 Variant II

Not only the first inductor is replaced by a tapped inductor, also the connections of the electronic switch S and of the intermediate capacitor C1 are changed (Figure 10).

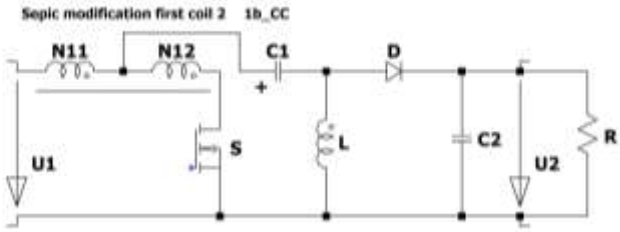

Fig. 10: Variant II

In this case, we can interpret the tapped inductor as coupled coils.

3.1 Connection between the Voltages

During mode M1 (the active switch is turned on and the diode blocks) the input voltage is across the complete winding N1+N2. According to the transformation law (the voltages behave like the number of turns) only the part

$$u_{N11,M1} = \frac{N_{11}}{N_{11} + N_{N12}} U_1 \tag{20}$$

is across the winding N11. During M2 one gets the sum of the input voltage minus the output voltage and minus the voltage across C1 across N11 (Figure 11, left)

$$u_{N11,M2} = U_1 - U_2 - U_{C1}\,. \tag{21}$$

Inspecting the circuit of the converter, it is easy to see that in the steady state, the voltage across C1 must be equal to the input voltage U1 (the inductive components have zero voltage in the mean).

Now one can calculate the voltage transformation ratio according to

$$\frac{U_2}{U_1} = \frac{N_{11}}{N_{11} + N_{12}} \cdot \frac{d}{1-d}\,. \tag{22}$$

In Figure 11 on the right side the voltages across the input, the capacitor C1, and the output are depicted.

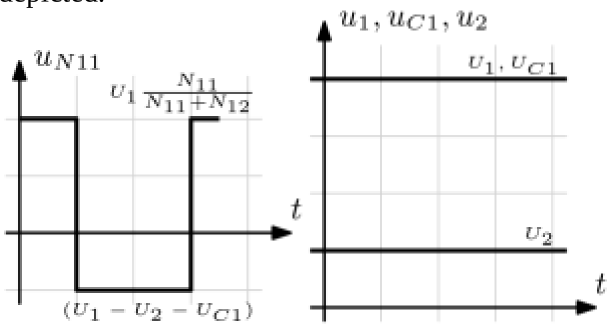

Fig. 11: Voltage across the first winding (left), voltages across the input, the intermediate capacitor and the output (right)

During mode M1 the voltage across the second winding N12 of the first magnetic element is:

$$u_{N12,M1} = \frac{N_{12}}{N_{11}+N_{12}} U_1 , \tag{23}$$

and the transformed voltage across N11 during M2 is:

$$u_{N12,M2} = \frac{N_{12}}{N_{11}} \left(U_1 - U_2 - U_{C1} \right). \tag{24}$$

The voltage across the second winding is drawn in Figure 12 on the left side.

The third magnetic winding is the coil L. During M2 the negative output voltage is across the coil and during M1 the sum of the negative voltage across N12 plus the voltage across C1 is there (Figure 12, right).

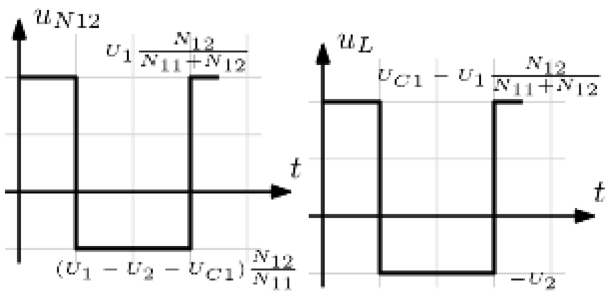

Fig. 12: Voltage across the second winding (left), voltage across the coil (right)

The maximum voltages across the semiconductors (Figure 13) are

$$U_{S,\max} = U_1 + U_2 \frac{N_{11}+N_{12}}{N_{11}} , \tag{25}$$

$$U_{D,\max} = -\left(U_1 \frac{N_{11}}{N_{11}+N_{12}} + U_2 \right) \tag{26}$$

$$\frac{U_{D,\max}}{U_1} = -\frac{N_{11}}{N_{11}+N_{12}} \frac{1}{1-d} \tag{26a}$$

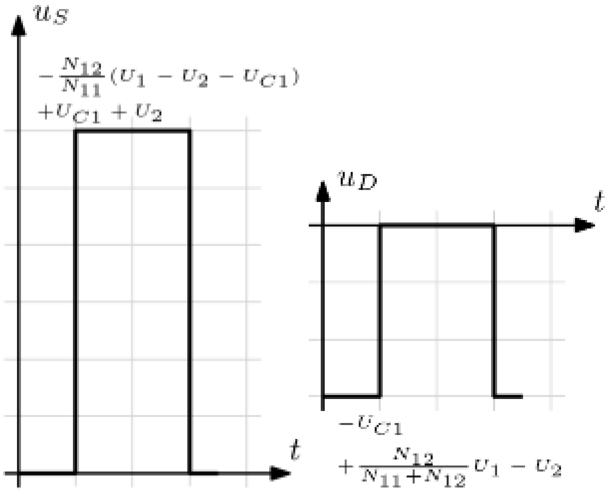

Fig. 13: Voltages across the electronic switch S (left) and the diode (right)

3.2 Connection between the Currents

The connections between the currents are more difficult to find. First one can write the charge balance of the two capacitors (in the steady state the mean current through a capacitor must be zero). During mode M1 the output capacitor supplies the load, and during mode M2 the diode transfers the current through the coil L and the current through the capacitor C1 to the output. The charge balance for the output capacitor is therefore

$$\left| -I_{LOAD} \right| \cdot d = \left(\bar{I}_{C1,M2} + \bar{I}_L - I_{LOAD} \right) \cdot (1-d) \tag{27}$$

where $\bar{I}_{C1,M2}$ is the current through C1 during mode M2 referred to the duration of mode M2. $\bar{I}_{L2}$ represents the mean value of the current through the coil L. The load current can be taken as constant because the output capacitor is dimensioned so large that the voltage across it stays nearly constant during a period. When one looks at the first capacitor one can see that the current through the coil L must flow (discharging) through the capacitor during M1, and during M2 a positive current flows through it which must be equal to the one through the first winding N1 (there is no current in the winding N2).

$$\bar{I}_{C1,M2} = \bar{I}_{N11,M2} . \tag{28}$$

One can therefore write the charge balance according to:

$$\left| -\bar{I}_L \right| \cdot d = \bar{I}_{C1,M2} \cdot (1-d) . \tag{29}$$

One has to solve:

$$\begin{bmatrix} 1-d & 1-d \\ 1-d & d \end{bmatrix} \cdot \begin{pmatrix} \bar{I}_{C1,M2} \\ I_L \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot I_{LOAD} \tag{30}$$

leading to

$$\frac{\bar{I}_{C1,M2}}{I_{LOAD}} = \frac{d}{1-d} , \tag{31}$$

$$\bar{I}_L = I_{LOAD} . \tag{32}$$

We start to draw the signals with the load current (arbitrarily 3.5 divisions, Figure 14, left)

The current through the capacitor C2 is the negative load current during M1. The mean value of the current during M2 must be half as large as the load current (Figure 14, right).

DOI: 10.37394/23201.2024.23.10

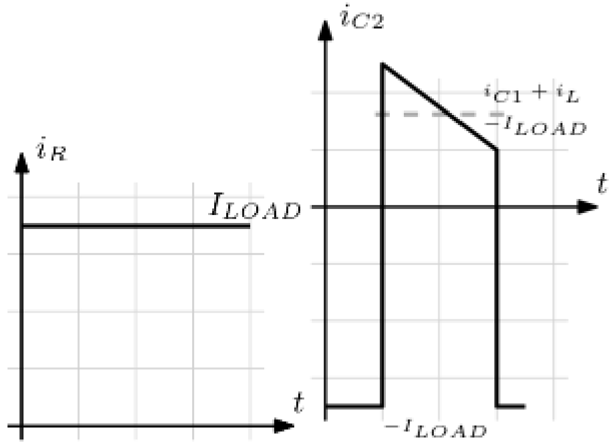

Fig. 14: Load current (left), current through the output capacitor (right)

From (32) one knows that the mean value of the current through L must be equal to the load current. With an arbitrarily chosen current ripple one gets Figure 15 on the left.

It is easy to draw the current through C1 (Figure 15, right). During M1 the current of the coil L must flow in a negative direction through the first capacitor. The mean value $\bar{I}_{C1,M2} = \bar{I}_{C1,2}$ of the current through C2 during M2 must be half as large.

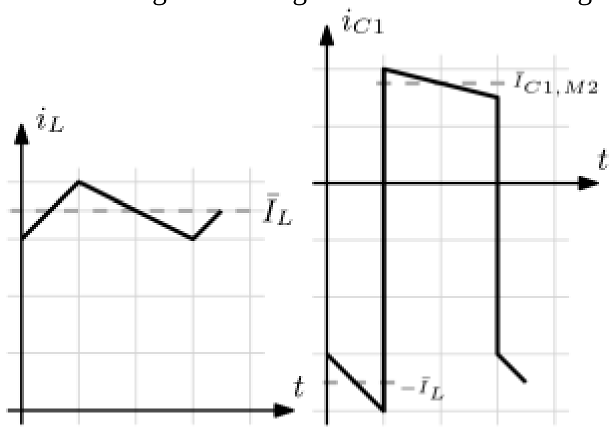

Fig. 15: Current through the coil (left), current through the intermediate capacitor (right)

In mode M2 no current flows through N12 and the current through the first capacitor must flow through N11. We can interpret this a magnetizing current. The magnetizing current through N11 during M1 must be smaller because more windings are available. The current turns (current linkage, magnetomotive force) must be equal immediately before $(dT-)$ and after the turn off $(dT+)$ of the electronic switch

$$i_{N11}(dT-)(N_{11} + N_{12}) = i_{N11}(dT+)N_{11} \qquad (33)$$

Now one can draw the magnetizing current. For a winding ratio of one to one we have half the values of iN11, and M2 at the beginning and the end of M2 to get the values of mode M1 (Figure 16).

Fig. 16: Magnetizing current

The current through the coil L flows to both windings and compensates them (according to the number of turns). The winding with a lower number of turns must correspondingly take more current.
With

$$i_L = i_{L,N11} + i_{L,N12}, \qquad (34)$$

$$N_{11} \cdot i_{L,N11} = N_{12} \cdot i_{L,N12} \qquad (35)$$

the currents through the windings caused by the current through L during mode M1 can now be calculated according to

$$\frac{i_{L,N11}}{i_L} = \frac{N_{12}}{N_{11} + N_{12}} \qquad (36)$$

$$\frac{i_{L,N12}}{i_L} = \frac{N_{11}}{N_{11} + N_{12}} \qquad (37)$$

The current through N11 (Figure 17, left) during M1 is the magnetizing current minus the current caused by L and the magnetizing current during M2. The current through N12 (Figure 17, right) is the sum of the magnetizing current and the current caused by L during M1 and zero during M2.

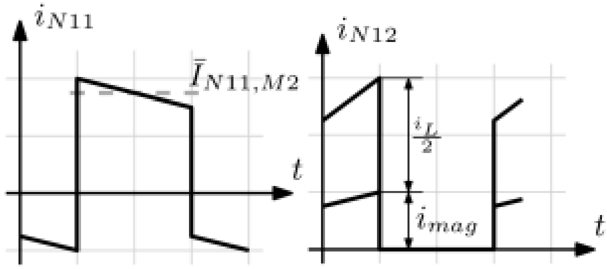

Fig. 17: Currents through windings: first (left), second (right)

The currents through the semiconductor devices can now be found. The current through the electronic switch is equal to the current through the second winding N12. It is the sum of the magnetizing current plus the current caused by the coil L according to (37) (Figure 18, left). The current through the diode is the current through the first winding N11 and the current through the coil (Figure 18, right).

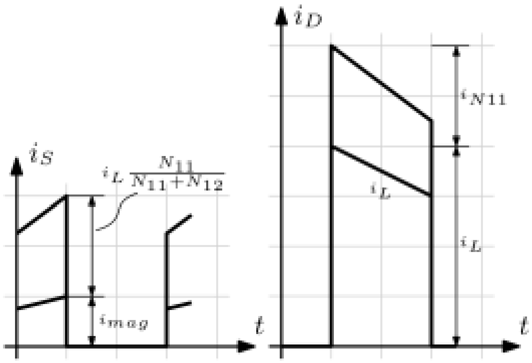

Fig. 18: Currents through the electronic switch (left) and the diode (right)

4 Simulations

For better understanding, a few simulations with the help of LTSpice are shown. The simulations show excellent conformity with the theoretical considerations in sections 2 and 3.

4.1 Variant I

Figure 19 shows the current through C1, the current through C2, the current through the coil L, the current through the load, the current through the first winding N11, the current through the second winding N12 of the autotransformer, the input voltage, the output voltage, and the control signal.

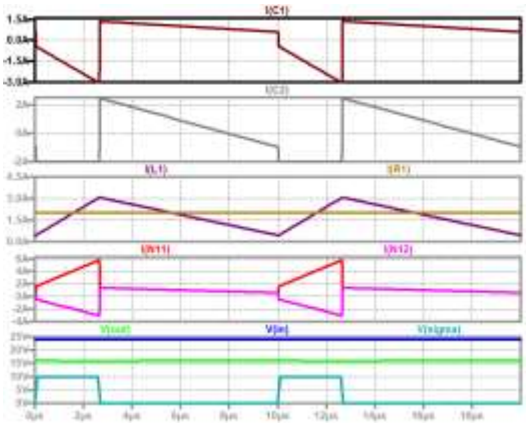

Fig. 19: Variant I, up to down: current through C1 (black); current through C2 (grey); current through the coil L (dark violet), current through the load (brown); current through N11 (red), and N12 (violet) of the autotransformer; input voltage (blue), output voltage (green), the control signal (turquoise)

4.2 Variant II

Figure 20 shows the voltage across the diode D, the voltage across the active switch S, the voltage across N12, the voltage across N11, the input voltage, the control signal, and the output voltage.

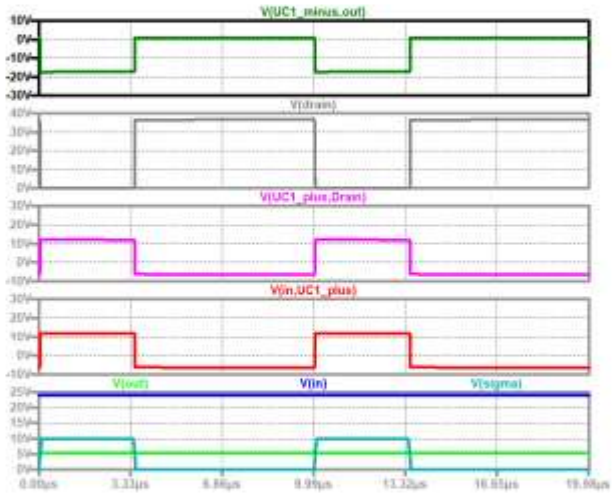

Fig. 20: Variant II voltages across the components, up to down: voltage across the diode D (dark green); voltage across the active switch S (grey); voltage across N12 (violet); voltage across N11 (red); input voltage (blue), control signal (turquoise), output voltage (green)

In Figure 21 the current through the output capacitor C2, the current through the intermediate capacitor C1, the current through L1, the current through the winding N12, and the current through winding N11 are depicted.

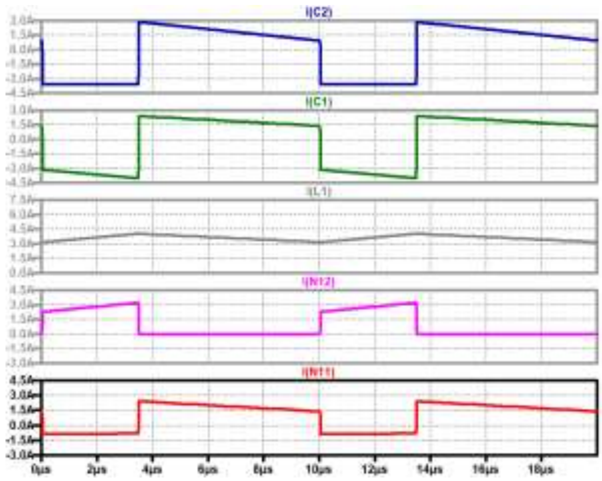

Fig. 21: Variant II currents through the components, up to down: current through the output capacitor C2; current through the intermediate capacitor C1; current through L1; current through the winding N12 (violet); current through winding N11 (red)

All simulations were done with 40 μH for the windings N11, and N12; 47 μH for L, and 330 μF for the capacitors.

5 Modelling

In this section, the modeling of the converter when a tapped inductor is used is sketched. Ideal components and continuous mode are proposed. Variant II (Figure 10) is taken as an example. A tapped inductor with the windings N11, and N12 replaces the first coil. The first state variable is now the flux. The basic equation is the induction law:

$$u = \frac{d\psi}{dt} = N\frac{d\phi}{dt}. \tag{38}$$

A voltage is induced when the flux ψ is changing. When discrete coils are employed, one can use the flux per winding Φ and the number of turns N.

During mode M1, when the active switch S is turned on, the input voltage is across both windings

$$\frac{d\phi}{dt} = \frac{u_1}{N_{11}+N_{12}}. \tag{39}$$

With the help of KVL (Kirchhoff's voltage law) the voltage across the inductor L can be calculated. The voltage across the second winding is given by the transformer law (the voltages are proportional to the number of turns) according to:

$$\frac{du_L}{dt} = \frac{-u_1\frac{N_{12}}{N_{11}+N_{12}} + u_{C1}}{L}. \tag{40}$$

The changes in the voltages across the capacitors are produced by the currents flowing through them:

$$\frac{du_{C1}}{dt} = -\frac{i_L}{C_1}, \tag{41}$$

$$\frac{du_{C2}}{dt} = \frac{-\frac{u_{C2}}{R}}{C_2}. \tag{42}$$

The state equations can be combined with the matrix equation

$$\frac{d}{dt}\begin{pmatrix}\phi\\ i_L\\ u_{C1}\\ u_{C2}\end{pmatrix} = \begin{bmatrix}0 & 0 & 0 & 0\\ 0 & 0 & \frac{1}{L} & 0\\ 0 & -\frac{1}{C_1} & 0 & 0\\ 0 & 0 & 0 & -\frac{1}{RC_2}\end{bmatrix}\begin{pmatrix}\phi\\ i_L\\ u_{C1}\\ u_{C2}\end{pmatrix} + \begin{bmatrix}\frac{1}{N_{11}+N_{12}}\\ \frac{N_{12}}{(N_{11}+N_{12})L}\\ 0\\ 0\end{bmatrix}(u_1). \tag{43}$$

For mode M2, when the active switch S is off and the diode D is conducting, the sum of the input voltage and the negative voltages across the capacitors C1 and C2 is across the first winding leading to

$$\frac{d\phi}{dt} = \frac{u_1 - u_{C2} - u_{C1}}{N_{11}}. \tag{44}$$

The change of the current through L2 can be found with the help of KVL according to

$$\frac{du_L}{dt} = \frac{-u_{C2}}{L}. \tag{45}$$

To obtain the current through the capacitor the connection between flux and current is used. The flux is directly proportional to the current which produces it

$$\psi = Li \tag{46}$$

or using the flux per winding Φ

$$N\phi = Li. \tag{47}$$

The value of the inductor depends on the AL-value (this value can be found in the datasheet of the magnetic core which is used to build the coil; it depends on the air gap) and the square of the number of turns

$$L = A_L N^2. \tag{48}$$

The current can now be written as

$$i = \frac{\phi N}{A_L N^2}. \tag{49}$$

The third state equation is therefore

$$\frac{du_{C1}}{dt} = \frac{\phi}{A_L N_{11} C_1}. \tag{50}$$

The current through the output capacitor C2 is the sum of the current through the first winding and the current through the coil minus the load current

$$\frac{du_{C2}}{dt} = -\frac{\dfrac{\phi}{A_L N_{11}} + i_L - \dfrac{u_{C2}}{R}}{C_2 (N_1 + N_2) A_L} \tag{51}$$

leading to (52)

$$\frac{d}{dt}\begin{pmatrix}\phi\\ i_L\\ u_{C1}\\ u_{C2}\end{pmatrix} = \begin{bmatrix} 0 & 0 & -\dfrac{1}{N_{11}} & -\dfrac{1}{N_{11}} \\ 0 & 0 & 0 & -\dfrac{1}{L} \\ \dfrac{1}{C_1 N_{11} A_L} & 0 & 0 & 0 \\ \dfrac{1}{C_2 N_{11} A_L} & \dfrac{1}{C_2} & 0 & -\dfrac{1}{RC_2} \end{bmatrix}\begin{pmatrix}\phi\\ i_L\\ u_{C1}\\ u_{C2}\end{pmatrix} + .$$

$$+\begin{bmatrix}\dfrac{1}{N_{11}}\\ 0\\ 0\\ 0\end{bmatrix}(u_1)$$

Combined one gets ((43) is weighted by the duty cycle d and (52) weighted by 1-d and added) the large signal model of the converter (53)

$$\frac{d}{dt}\begin{pmatrix}\phi\\ i_L\\ u_{C1}\\ u_{C2}\end{pmatrix} = \begin{bmatrix} 0 & 0 & \dfrac{d-1}{N_{11}} & \dfrac{d-1}{N_{11}} \\ 0 & 0 & \dfrac{1-d}{L_2} & \dfrac{d-1}{L_2} \\ \dfrac{1-d}{C_1 N_{11} A_L} & -\dfrac{d}{C_1} & 0 & 0 \\ \dfrac{1-d}{C_2 N_{11} A_L} & \dfrac{1-d}{C_2} & 0 & -\dfrac{1}{RC_2} \end{bmatrix}\begin{pmatrix}\phi\\ i_L\\ u_{C1}\\ u_{C2}\end{pmatrix} +$$

$$+\begin{bmatrix}\dfrac{d}{N_{11}+N_{12}} + \dfrac{1-d}{N_{11}}\\ \dfrac{dN_{12}}{(N_{11}+N_{12})L}\\ 0\\ 0\end{bmatrix}(u_1) \tag{53}$$

Linearization leads to the small signal model (54). With the help of it, the transfer functions can be calculated and so a simple controller can be designed.

$$\frac{d}{dt}\begin{pmatrix}\hat{\phi}\\ \hat{i}_L\\ \hat{u}_{C1}\\ \hat{u}_{C2}\end{pmatrix} = \begin{bmatrix} 0 & 0 & \dfrac{D_0-1}{N_{11}} & \dfrac{D_0-1}{N_{11}} \\ 0 & 0 & \dfrac{1-D_0}{L} & \dfrac{D_0-1}{L} \\ \dfrac{1-D_0}{C_1 N_{11} A_L} & -\dfrac{D_0}{C_1} & 0 & 0 \\ \dfrac{1-D_0}{C_2 N_{11} A_L} & \dfrac{1-D_0}{C_2} & 0 & -\dfrac{1}{RC_2} \end{bmatrix}\begin{pmatrix}\hat{\phi}\\ \hat{i}_L\\ \hat{u}_{C1}\\ \hat{u}_{C2}\end{pmatrix} + \tag{54}$$

$$\begin{bmatrix} \dfrac{D_0}{N_{11}+N_{12}} + \dfrac{1-D_0}{N_{11}} & \dfrac{U_{C10}}{N_{11}} + \dfrac{U_{C20}}{N_{11}} - \dfrac{N_{12}U_{10}}{N_{11}(N_{11}+N_{12})} \\ \dfrac{D_0 N_{12}}{(N_{11}+N_{12})L} & \dfrac{-U_{C10}+U_{C20}}{L} - \dfrac{N_{12}U_{10}}{(N_{11}+N_{12})L} \\ 0 & -\left(\dfrac{\Phi_0}{A_L N_{11} C_1} + \dfrac{I_{L0}}{C_1}\right) \\ 0 & -\left(\dfrac{\Phi_0}{A_L N_{11} C_2} + \dfrac{I_{L0}}{C_2}\right)0 \end{bmatrix}\begin{pmatrix}\hat{u}_1\\ \hat{d}\end{pmatrix}$$

6 Conclusion

The application of two coupled coils instead of a coil in a DC/DC converter changes the behavior of the system. The voltage transformation ratio is changed. In the first variant of the SEPIC treated here, the voltage transformation ratio is increased, and in the second variant, it is decreased by the winding ratio. For the designer, this means an additional degree of freedom for adapting the output voltage to the input voltage. In the first variant, the magnetic component can be interpreted as an autotransformer, and in the second as a tapped inductor. The method to describe the converters shown here can be applied to other converters with a tapped inductor or an autotransformer replacing an inductor of the original topology. The text can be utilized for a lecture note using tapped inductors in a course concerning DC/DC converters.

References:

[1] F. A. Himmelstoss, and P.H.Wurm, Simple Bi-Directional DC-to-DC Converter with High Input to Output Voltage Ratio, *17th European Photovoltaic Solar Energy Conference and Exhibition*, Munich, Germany, 22-26 Oct. 2001, pp. 592-595, published 2002, (ISBN: 3-936338-08-6).

[2] V. R. Tintu and M. George, Tapped inductor technology based DC-DC converter, *2011 International Conference on Signal Processing, Communication, Computing and Networking Technologies*, Thuckalay, India, 2011, pp. 747-753, doi: 10.1109/ICSCCN.2011.6024650.

[3] J. Yao, J. Zhao and A. Abramovitz, Modeling of the Tapped Inductor SEPIC converter by the TIS-SFG approach, *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Yokohama, Japan, 2015, pp. 001674-001679, doi: 10.1109/IECON.2015.7392342.

[4] J. Yao, A. Abramovitz and K. Smedley, High step-up tapped inductor SEPIC converter with charge pump cell, *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Pittsburgh, PA, USA, 2014, pp. 2303-2309, doi: 10.1109/ECCE.2014.6953710.

[5] 5J. Yao, A. Abramovitz and K. M. Smedley, Analysis and Design of Charge Pump-Assisted High Step-Up Tapped Inductor SEPIC Converter With an “Inductorless” Regenerative Snubber, *IEEE Transactions on Power Electronics*, vol. 30, no. 10, pp. 5565-

5580, Oct. 2015, doi: 10.1109/TPEL.2014.2374992.

[6] Dimna Denny C and Shahin M, Analysis of bidirectional SEPIC/Zeta converter with coupled inductor, *2015 International Conference on Technological Advancements in Power and Energy (TAP Energy)*, Kollam, India, 2015, pp. 103-108, doi: 10.1109/TAPENERGY.2015.7229600.

[7] L. Chen, D. Rong and X. Sun, A Family of High Step-Up Soft-Switching Integrated Sepic Converter With Y-Source Coupled Inductor, *IEEE Access*, vol. 11, pp. 111752-111764, 2023, doi: 10.1109/ACCESS.2023.3322459.

[8] H. F. A. Barberena, Leveraging tapped-inductor architectures to increase power density of single and dual-polarity-output buck-boost converters, *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Fort Worth, TX, USA, 2011, pp. 1447-1450, doi: 10.1109/APEC.2011.5744782.

[9] P. Odo, A Comparative Study of Single-phase Non-isolated Bidirectional dc-dc Converters Suitability for Energy Storage Application in a dc Microgrid, *2020 IEEE 11th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Dubrovnik, Croatia, 2020, pp. 391-396, doi: 10.1109/PEDG48541.2020.9244351.

[10] N. Mohan, T. Undeland, W. Robbins, *Power Electronics, Converters, Applications and Design*, 3rd ed.; John Wiley & Sons: New York, NY, USA, 2003.

[11] (text in German) F. Zach, *Leistungselektronik*, 6th ed.; Springer: Frankfurt, Germany, 2022.

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

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Felix A Himmelstoss did the basic research, the simulations and wrote the text,
- Helmut L Votzi did the proof reading and draw the pictures Figures 3-9 and 11-19, and gave the presentation at the conference.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.