# Novel Aspects of an Application of 'Zero'-Ripple Techniques to Basic Converter Topologies

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**Abstract.** Based on a short summary of the theoretical basics of the zero-ripple current phenomenon a special zero input current ripple boost converter topology as presented in the literature is investigated. It is shown that the complete suppression of the input current ripple of the system is only given in a theoretical extreme case. For a practical realization only such a ripple reduction of the input current of the basic converter structure is obtained as corresponds to a simple low-pass input filter. This is proven by a detailed analysis also for a zero-ripple Cuk and for a zero-ripple SEPIC converter structure. Furthermore, it is shown that the realization of a zero-ripple Cuk or zero-ripple SEPIC converter is not linked to a magnetic coupling of the input and output inductors, but can also be achieved by a simple rearrangement of the elements of the basic converter structures. There one can see that the operating behavior of a zero input current ripple SEPIC converter is equivalent to the operating behavior of a buck-boost converter stage with LC input filter. Finally, the advantages and disadvantages of the different realization approaches of zero-ripple topologies are compared. Also, an outlook towards the planned further treatment of the topic is given.

## 1 Introduction

As shown in Fig.13 of [1], ideally identical voltages $u_{L_1} = u_{L_2}$ are present across the input and output inductors $L_1$ and $L_2$ of a basic DC-to-DC Cuk converter structure. This allows to realize $L_1$ and $L_2$ by windings which are situated on a common magnetic core (cf. Fig.1(a)). Then, according to [2] (cf. Fig.10), a proper choice of the leakage of the magnetically coupled windings and/or a proper choice of the turns ratio $\frac{N_1}{N_2} \sim \sqrt{\frac{L_1}{L_2}}$ can lead to suppression of a ripple in the input current $i_1$ or in the output current $i_2$. According to [3] and [4], in equal manner a suppression of the input current ripple can be achieved also for a SEPIC converter (cf. Fig.1(b)).

An application of this concept (to be called in general a *zero-ripple technique*) to a buck and a boost converter structure is described in [5] (besides other zero-ripple converter topologies). Because buck and boost converters have (basically) only one inductive component, the basic converter structure is extended (cf. Fig.3) by a coupling capacitor and by an inductor which is coupled in a defined manner with the inductor on the input side (boost converter) or output side (buck converter). A closer analysis of the converter topologies resulting thereby is given in [6], [7] and [8].

For a basic consideration it seems to be strange that only by extending a basic DC-to-DC converter structure by passive components or by a defined magnetic coupling of the input and output inductors of a converter a complete elimination of the input or output current ripple can be obtained (as being implied by the designation *zero-ripple converter*) and not only a reduction of the ripple as, e.g., for conventional filtering. This motivates a closer investigation of the zero-ripple converter topologies as being the topic of this paper.

In **section 2** of this paper the basics of the zero-ripple technique are discussed briefly for the example of a DC-to-DC Cuk converter. For a clear explanation of the phenomenon an equivalent circuit of a transformer is used for the magnetically coupled input and output inductors $L_1$ and $L_2$. Alternatively, the superposition principle is applied. Based on these introductory considerations in **section 3** a zero input current ripple boost converter is investigated. It is shown that the system is equivalent to a conventional boost converter stage with an LC-filter connected in series at the input. Therefore, the ripple of the input current is not completely eliminated. It is only reduced according to a passive LC-filtering. This is checked in the second part of this paper also for a zero-ripple Cuk and a zero-ripple SEPIC converter structure (cf. **sections 4 and 5**). There, zero-ripple Cuk and SEPIC converters show an advantage insofar, however, as the filter to be provided additionally for the zero-ripple buck and boost converters is already a natural part of the basic converter structures. Furthermore, it is shown that the realization of a zero-ripple Cuk or zero-ripple SEPIC converter is not linked to a magnetic coupling of the input and output inductors. It can also be obtained by rearranging of the circuit elements of the basic converter structures by not coupled inductors. Thereby, new converter topologies result which have inherently very low ripple of the input or output currents. In conclusion (cf. **section 6**), the advantages and disadvantages of the different realization forms of zero-ripple converter topologies are summarized. Furthermore, an outlook towards the planned further treatment of the topic is given.

## 2 Basic Considerations

In order to clearly explain the effect called *zero-ripple phenomenon* in [5], in the following we want to consider briefly the relationships given for magnetic coupling of the input and output inductors of a Cuk converter (cf. **Fig.1**). It is shown that the suppression of a ripple of the input or output current is linked to a defined ratio of the inductive voltage divider formed by the main and stray inductances of the coupled inductors (cf. section 2.1). Furthermore, an alternative analysis of the zero-ripple phenomenon is given based on the application of the superposition principle (cf. section 2.2).

### 2.1 Zero-Ripple Phenomenon as Result of the Balancing of an Inductive Voltage Divider

By the magnetic coupling of the input inductor $L_1$ and output inductor $L_2$ of a Cuk converter (arrangement of the windings on a common magnetic core) a transformer with two windings $N_1$ and $N_2$ is formed (cf. **Fig. 2(a)**). Contrary to the familiar operation of a transformer (with impressed primary voltage and with passively terminated secondary side, i.e. by a load resistor) the primary voltage $u_{L_1}$ *and* the secondary voltage $u_{L_2} = u_{L_1}$ (cf. Fig.13 in [1]) are impressed thereby, however. (Furthermore, the magnetizing current is determined by the sum of the primary and secondary amperewindings

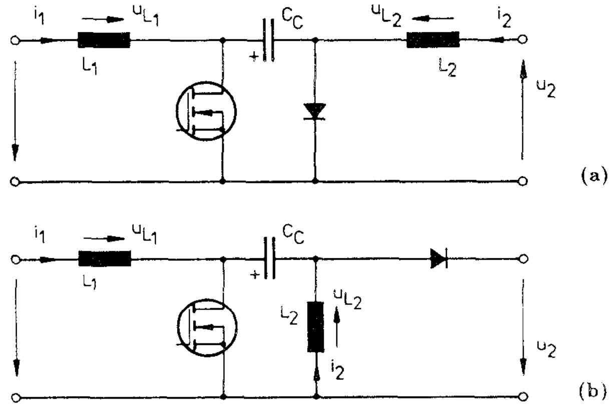

**Fig.1:** Basic structure of the power circuit of a DC-to-DC Cuk converter (cf. (a)) and of a DC-to-DC SEPIC converter (cf. (b)).

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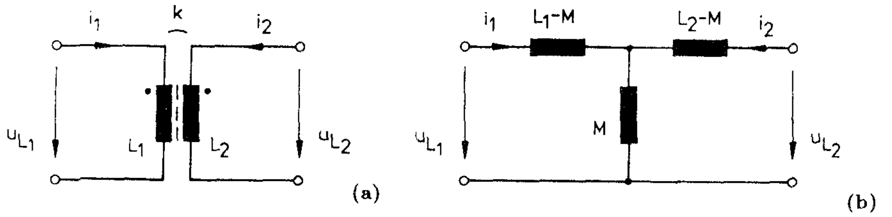

**Fig.2:** Transformer resulting from coupling of the input and output inductors of a Ćuk or SEPIC converter (cf. **(a)**); $u_{L_1}$ and $u_{L_2} = u_{L_1}$ are to be considered impressed according to the (ideal) converter function; **(b)**: equivalent circuit of the winding arrangement shown in (a).

$i_1 N_1$ and $i_2 N_2$ and not by their difference, as for a conventional transformer operation.)

The winding arrangement shown in Fig.2(a) can be described mathematically by

$$\begin{aligned} u_{L_1} &= L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \\ u_{L_2} &= L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} \end{aligned} \tag{1}$$

where

$$M = k\sqrt{L_1 L_2} \tag{2}$$

(the ohmic losses occurring in $N_1$ and $N_2$ and the hysteresis losses of the magnetic core are neglected). $M$ is the mutual inductance and $k$ the coupling coefficient of the windings. From Eq.(1), there follows immediately the equivalent circuit given in Fig.2(b) (cf. [1], p. 339). It shows according to

$$\begin{aligned} u_{L_1} &= (L_1 - M)\frac{di_1}{dt} + M(\frac{di_1}{dt} + \frac{di_2}{dt}) \\ u_{L_2} &= (L_2 - M)\frac{di_2}{dt} + M(\frac{di_1}{dt} + \frac{di_2}{dt}) \end{aligned} \tag{3}$$

equal behavior at the terminals as the circuit shown in Fig.2(a). As the further considerations show, isolation of the input and output circuits given for Fig.2(a) has no influence on the zero-ripple phenomenon and , therefore, is not considered in the following.

**Remark:** The equivalent circuit (shown in Fig.2(b)) replaces 2 coupled coils by 3 not coupled inductors. The order of the system (number of independent energy storage elements) remains unchanged, however, because the sum $i_1 + i_2$ of the state variables $i_1$ and $i_2$ flows through $M$. Therefore, $M$ does not represent an independent energy storage device. Furthermore, one has to point out that the inductors $L_1 - M$ and $L_2 - M$ in general may not be linked to a division of the stray flux of the transformer into a primary and secondary part. (Splitting up the stray flux of a general transformer is basically impossible based on an analysis of the terminal behavior of the transformer. For the sake of brevity, this shall not be treated in more detail here, however.) Therefore, Fig.2(b) serves exclusively for a clear representation of the mathematical relations given by Eq.(1).

If we have now

$$u_{L_1} = u_{L_2} \tag{4}$$

(cf. Eq.(43) in [1]) as already mentioned in section 1 the possibility becomes clear by a simple consideration to obtain, e.g., an ideally constant shape of the input current $i_1$ for this operation of the winding arrangement, according to

$$\frac{\mathrm{d}i_1}{\mathrm{d}t} = 0 \tag{5}$$

(cf. [2], p. 353). Eq.(5) is ideally fulfilled in the case where the voltage occurring across $L_1 - M$ becomes 0. Therefore, if one wants to avoid a ripple of the input current one has to guarantee

$$u_M = u_1 \tag{6}$$

for the voltage occurring across $M$ (cf. Fig.2(b)). This can be obtained by proper choice of the division ratio of the inductive voltage divider formed by $M$ and $L_2 - M$ (being open-circuited dynamically for $\frac{\mathrm{d}i_1}{\mathrm{d}t} = 0$; cf. also p. 353 and 354 in [2] or Fig.2 in [9]). By considering

$$u_M = \frac{M}{M + (L_2 - M)} u_2 \ . \tag{7}$$

there follows as balancing condition of the inductive voltage divider for ripple-free input current

$$L_2 = M \tag{8}$$

newpage (this relation can be gained also immediately from Fig.2(b)). Considering Eq.(2) one can see that $\frac{\mathrm{d}i_1}{\mathrm{d}t} = 0$ is obtained for given inductances $L_1$ and $L_2$ for

$$k = \sqrt{\frac{L_2}{L_1}} \ . \tag{9}$$

The reduction (caused by $k < 1$) of the voltage coupled from the secondary $L_2$ into the primary $L_1$ is then exactly compensated by the turns ration $\frac{N_1}{N_2} \approx \sqrt{\frac{L_1}{L_2}} > 1$. This results in an equilibrium between inner voltage (coupled into $N_1$) and voltage $u_1$ lying on the outside; this does not admit a current change in the primary (cf. Eq.(2) in [10]).

In analogy to the considerations related to the input current $i_1$ (as given so far) one also can derive a condition for the suppression of the ripple of the output current (according to $\frac{\mathrm{d}i_2}{\mathrm{d}t} = 0$). For a ripple-free output current we have to set

$$L_1 = M \tag{10}$$

and/or

$$k = \sqrt{\frac{L_1}{L_2}} \ . \tag{11}$$

In summary one has to note that

- the ripple suppression can be achieved only on the input side *or* on the output side. (A suppression of the input *and* output ripple is only possible if a further transformer is inserted into the Ćuk converter structure and/or for an isolation of the input and output (cf. Fig. 16 in [11]). This shall be not treated in more detail here, however;
- the (ideal) supression of the input or output current ripple is not linked to a specific time behavior of $u_{L_1}$ and/or $u_{L_2}$ but only to $u_{L_1} = u_{L_2}$ and vanishing DC component of the voltages;
- the inductance being in effect on the output side for vanishing current ripple is equal to the open-circuit inductance and/or self-inductance $L_2$ of the output circuit because $\frac{\mathrm{d}i_1}{\mathrm{d}t} = 0$ acts dynamically equally to an open-circuit on the primary side. **Remark:** The reduction of the amplitude of the current ripple to $\Delta i_i \rightarrow 0$ is *not* determined by the inductance $L_1 - M$ lying on the input side (as one could possibly assume for a superficial consideration of the circuit) *but* by an effectively acting inductance $L_{1,\mathrm{eff}} \rightarrow \infty$. For vanishing output current ripple we have, in analogy, $L_{2,\mathrm{eff}} \rightarrow \infty$ (cf. Eq.(18) in [1]);
- due to the physical limitation $k < 1$ we have to guarantee for the realizability of $\frac{\mathrm{d}i_1}{\mathrm{d}t} = 0$ $L_1 > L_2$ (cf. Eq.(9) and $L_1 < L_2$ for the realizability of $\frac{\mathrm{d}i_2}{\mathrm{d}t} = 0$ (cf. Eq.(11)).

## 2.2 Explanation of the Zero-Ripple Phenomenon Based on the Principle of Superposition

An explanation of the ripple compensation being equally clear, but alternate to the considerations of the previous section, can be gained by applying the principle of superposition. There, the elimination of the ripple of the input or output current is represented as a mutual cancellation of 2 ficticious ripple components (superposition of ripple components of equal amplitude but of opposite phase). E.g., the input current ripple occurring for not coupled inductors is thought to be compensated by a further ripple component being coupled by a transformer action via $N_2$ (cf. [12], p. 241). This conception shall be substantiated also briefly mathematically in the following.

If one assumes $u_2 = 0$ for the first superposition step there follows under consideration of Eq.(1) for the change of the input current (after a short calculation)

$$\frac{\mathrm{d}i_{1,1}}{\mathrm{d}t} = \frac{L_2}{L_1 L_2 - M^2} u_1 \ . \tag{12}$$

On the other hand, due to $u_2$ there results an input current change for $u_1 = 0$

$$\frac{\mathrm{d}i_{1,2}}{\mathrm{d}t} = -\frac{M}{L_1 L_2 - M^2} u_2 \ . \tag{13}$$

The elimination of the ripple of the total input current $i_1$

$$\frac{di_1}{dt} = \frac{di_{1,1}}{dt} + \frac{di_{1,2}}{dt} = 0 \; , \tag{14}$$

is, therefore, given for equal absolute value of the current changes $\frac{di_{1,1}}{dt}$ and $\frac{di_{1,2}}{dt}$ (with opposite phases) and/or (under consideration of Eq.(4)) for $L_2 = M$. Thereby, one obtains once more Eq.(8) as condition for ripple-free operation.

By an appropriate consideration (related to the output side) also the condition Eq.(10) to be met for ripple-free output current is checked.

## 3 Zero Input Current Ripple Boost Converter

### 3.1 Analysis of the Circuit

The initially analyzed basic principle of ripple elimination can now (as described in [5] (cf. p. 282, Fig.12-14)) also be applied to a simple DC-to-DC boost converter structure (cf. **Fig.3**(a)). Because a boost converter has only one inductive element $L_1$, the basic converter structure has to be extended by a winding $N_2$ being magnetically coupled to $N_1$ (the windings $N_1$ and $N_2$ are arranged on a common magnetic core). Furthermore, a coupling capacitor $C_C$ has to be provided in order to suppress the occurrence of a DC voltage component across $L_2$.

As one can consider easily, the voltage across $C_C$ will be in the stationary case such that its average value balances the (constant) input voltage $u_1$. If the capacitance $C_C$ is selected sufficiently large, identical voltages across $L_1$ and $L_2$ will result, therefore. Therefore, the assumptions mentioned in section 1 are present for suppressing the ripple of the input current $i_1$ by proper choice of the coupling $k$ between $L_1$ and $L_2$ (cf. Eq.(9)).

For a closer analysis of the circuit one can replace (analogous to the considerations in section 1) the coupled inductors $L_1$ and $L_2$ by a T-equivalent-circuit (cf. Fig.2(b)). This results in Fig.3(b). If one considers here the condition of Eq.(8) which has to be met for vanishing ripple of $i_1$ then the inductance $L_2 - M$ (resulting for the general coupling $k$ in series to the filter capacitor $C_C$) becomes 0. (This represents also clearly a condition being sensible for lowest possible ripple of the input current.) Thereby, as somewhat surprising result, this leads to the converter structure shown in Fig.3(c).

According to Fig.3, a zero-ripple boost converter represents (concerning its operational behavior) only an alternate realization of a conventional boost converter stage with input filter! Therefore, the designation *'zero-ripple'* boost converter (used in the literature) which suggests a complete suppression of the input current ripple seems to be not correct, because a complete elimination of the input current ripple cannot be obtained thereby. On the contrary, there will always remain an input current ripple due to the ripple of the coupling capacitor voltage resulting across $L_1 - M$ for ideally constant input voltage. $\frac{di_1}{dt} = 0$ will be obtained (for proper coupling $k$) only for the theoretical limiting case $C_C \to \infty$.

For a practical system realization a capacity value $C_C$ as small as possible is desired (cf. p. 6-3 in [4]) in order to minimize size and weight of the converter and due to controls-oriented considerations; therefore, the system shown in Fig.3(a) should be labeled better *low*-ripple boost converter and not *zero*-ripple boost converter. For the sake of clearness, the designation *zero-ripple converter* is maintained in the following, and only *'zero'* is put in quotation marks.

The impossibility of a complete suppression (independent of duty cycle, mode of operation, load condition, switching frequency, etc.) of the input current ripple of the converter according to Fig.3(a) becomes clearly understandable also by the following: a circuit consisting of passive elements $L_1$, $L_2$ and $C_C$ cannot have an infinitely high effective input inductance for all frequencies (which would be required for $\frac{di_1}{dt} = 0$).

Analogous considerations for a 'zero' output current ripple buck converter (cf. Fig.12-13 in [5]) shall be omitted here for the sake of brevity. We only want to point out that also in this case the 'zero'-ripple extension corresponds to a simple low-pass filter (connected in series on the output side)..

### 3.2 Advantages and Disadvantages of the Realization Variants of a 'Zero' Input Current Ripple Boost Converter

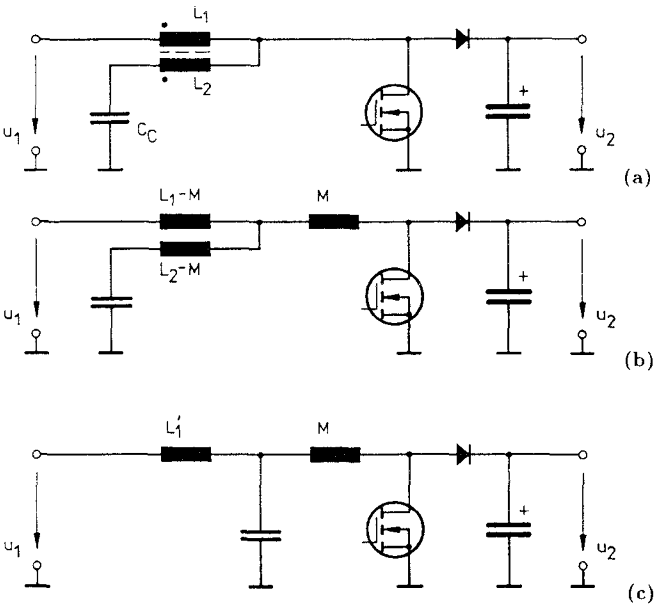

**Fig.3:** Basic structure of the power circuit of a 'zero' input current ripple boost converter according to [5] (cf. (a)); (b): circuit structure resulting for replacing the coupling of $L_1$ and $L_2$ by the T-equivalent-circuit as given in Fig.2(b); (c): converter structure resulting for meeting the condition $L_2 = M$ (cf. Eq.(8)) required for (ideally) zero input current ripple.

This section treats the question as how the application of a 'zero'(or low)-ripple current technique for a simple boost (or buck) converter can be judged in comparison to a conventional passive filtering of the converter input current.

Advantages of the converter structure according to Fig.3(a) are as follows:

+ only one magnetic core is required for the realization of the filter inductor and of the input inductor of the converter

+ only a current ripple flows through inductor $L_2$ and not, as for conventional filtering (cf. Fig.3(c)), the full load current; this results in a relatively small rated power of the magnetic core and in low ohmic losses in the winding. Therefore, for equal losses a smaller wire gauge can be chosen (cf. p. 491 in [11]).

Overall, a relatively small realization effort and a relatively high power density (W/in$^3$) are given.

On the other hand, the following disadvantages have to be mentioned:

- a defined, reproducible value of the coupling between $L_1$ and $L_2$ can be guaranteed regarding manufacturing possibly only by an external balancing inductor lying in series to $L_2$ (cf. p. 282, Fig.12-14 in [5] and/or section 7 in [13]). Then, the advantage of having only one inductive device will be lost. Also, the balancing of the winding turns ratio $\frac{N_1}{N_2}$ being possible alternatively to balancing of $k$ is connected with a relatively high manufactoring effort (cf. p. 6-17 in [13]). There, also a basic limitation is given (called *integer number problem* in [10]; cf. p. 266 in [10]) which only can be avoided by a special geometry of the magnetic circuit (cf. Fig.1(c) in [10]);

- as compared to a series connection of independent inductors $L_1 - M$ and $M$ (cf. Fig.3(e)) the magnetic integration of $L_1$ and $L_2$ leads possibly to a higher parasitic coupling capacitance of the windings (and, therefore, to a less efficient suppression of high-frequency electromagnetic influences). The arrangement of $L_1$ and $L_2$ has to be realized, therefore, such that the capacitive coupling from the output to the converter input is kept as small as possible.

Furthermore (as Fig.3 shows clearly) a 'zero'-ripple boost converter does not have advantages from a controls point-of-view as compared to a conventional filtering of the input current.

In summary, one has to point out that the decision between different reali-

*zation variants of a 'zero'-ripple boost converter has to be made especially* on the basis of manufacturing points of view. It is not predetermined by basically different operating behavior.

# 4 Novel 'Zero'-Ripple Cuk-Type Converter Topologies Comprising No Coupled Inductors

Zero-ripple Cuk converter topologies are realized in the literature (cf. [3], [5], [6], [12], [14]) always (as proposed in [1]) based on a magnetic coupling of the input and output inductors. By extending the considerations given so far, the following questions arise, however:

- can a zero-ripple Cuk converter structure be realized also without magnetically coupled inductors according to the description of the coupling of the input and output inductors $L_1$ and $L_2$ by an equivalent circuit formed by independent inductors?
- does there result also for a zero-ripple Cuk converter only a limited suppression of the input current or output current ripple?

*These questions will be discussed in more detail in the following sections.*

## 4.1 Derivation of Novel Zero-Ripple Cuk Converter Topologies

If the basic structure of a Cuk converter is modified according to **Fig.4**(b) in such a way that $L_1$ and $L_2$ branch from the same circuit node (which does not influence the basic function), one can introduce the equivalent circuit according to Fig.2(b) in place of the coupling of the windings. This leads to the circuit structure as shown in Fig.4(c). If now a suppression of the input current ripple is required (and/or $L_2 = M$ is set according to Eq.(8)), there follows with Fig.4(d) a new zero input current ripple Cuk-type converter topology. On the other hand, (ideally) ripple free output current shape *is being obtained by the circuit according to Fig.4(e) (which also has not* been described in the literature so far). The realization of a zero-ripple Cuk converter therefore is basically *not* linked to a magnetic coupling between the input and output inductors! Alternative forms of realization of the circuits according to Figs.4(d) and (e) are shown in Fig.5(a)-(d) and/or Fig.5(e)-(h).

One has to point out that (ideal) vanishing of the input or output current ripple constitutes a property being immanent to the new converter topologies. Therefore, this property is independent (such as the suppression of the ripple by magnetic coupling of $L_1$ and $L_2$) especially of the mode of operation of the converter (discontinuous or continuous inductor current mode).

**Remark:** For the sake of scientific exactness one has to point out that for a modeling of the magnetic coupling of $L_1$ and $L_2$ by realiziation of the equivalent circuit given in Fig.2(b) only values of the mutual inductance $M \leq L_1$ and/or $M \leq L_2$ can be represented. This is the case because for $M > L_1$ and/or $M > L_2$ not realizable values $L_1 - M < 0$ and/or $L_2 - M < 0$ (using passive components) of the inductances result. For the further considerations this limitation is of no consequence, however. On the contrary, the model of the magnetic coupling of the inductors of a conventional Cuk converter structure by discrete inductors as shown here could be applied in fully analogous manner also to a step-down coupled inductor Cuk converter (cf. Fig. 2(b) in [14]) and to further converter structures as given in in Fig.5 of [14].

All zero input current ripple Cuk converters shown in **Figs.5**(a)-(d) have identical operating behavior. The same is true for the zero output current ripple converter structures as shown in Figs.5(e)-(h). A digital simulation of the stationary shapes of the converter input and output currents is shown in **Figs.6**(a) and (b). The comparison to the conditions (cf. Fig.6(c)) given for a conventional Cuk converter structure (cf. Fig.1(a)) shows clearly the improvement of the system behavior obtained by an only small circuit modification.

## 4.2 Analysis of the Effect of a Coupling Capacitor Voltage Ripple on the Zero Ripple Condition

Considering the results of an analysis of a 'zero'-ripple boost converter (cf. section 3.1) also for a zero-ripple Cuk converter the supposition is obvious that for a finite capacitance $C_C$ only a limited suppression of the input and/or output current ripple is possible, corresponding to a passive filtering.

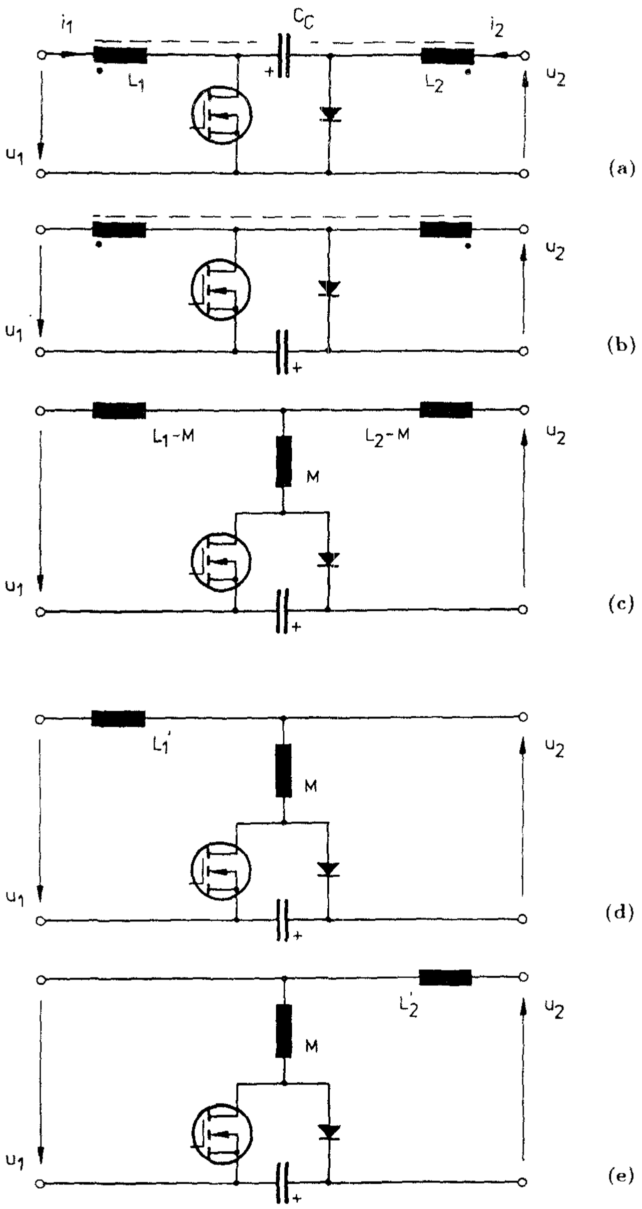

**Fig.4:** Derivation of the basic structure of a zero input current ripple and of a zero output current ripple Cuk-type converter topology based on a conventional zero ripple Cuk converter structure (cf. **(a)**); **(d)**: converter structure for $L_2 = M$ and/or (ideally) vanishing ripple of the input current. **(e)**: converter structure for $L_1 = M$ and/or (ideally) vanishing ripple of the output current.

For an analysis of the influence of $C_C$ on the current ripple remaining on the input or output side we have to reconsider once more the condition $u_{L_1} = u_{L_2}$ (cf. Eq.(4)) which has been assumed so far as being met exactly and/or we have to observe the ripple $\Delta u_{C_C}$ of the voltage of the coupling capacitor $C_C$ (and the voltage drops of the valves).

The average value $U_{C_C}$ of the voltage of the coupling capacitor

$$u_{C_C} = U_{C_C} + \Delta u_{C_C} \tag{15}$$

is equal to the sum of input and output voltages

$$U_{C_C} = u_1 + u_2 \tag{16}$$

in the stationary case. Then, there follows (e.g., for the converter structure shown in Fig.4(d) and/or for the conventional zero input current ripple Cuk converter structure according to Fig.4(a)) for the voltage across $L_1' = L_1 - M$

$$u_{L_1}' = \Delta u_{C_C} \ , \tag{17}$$

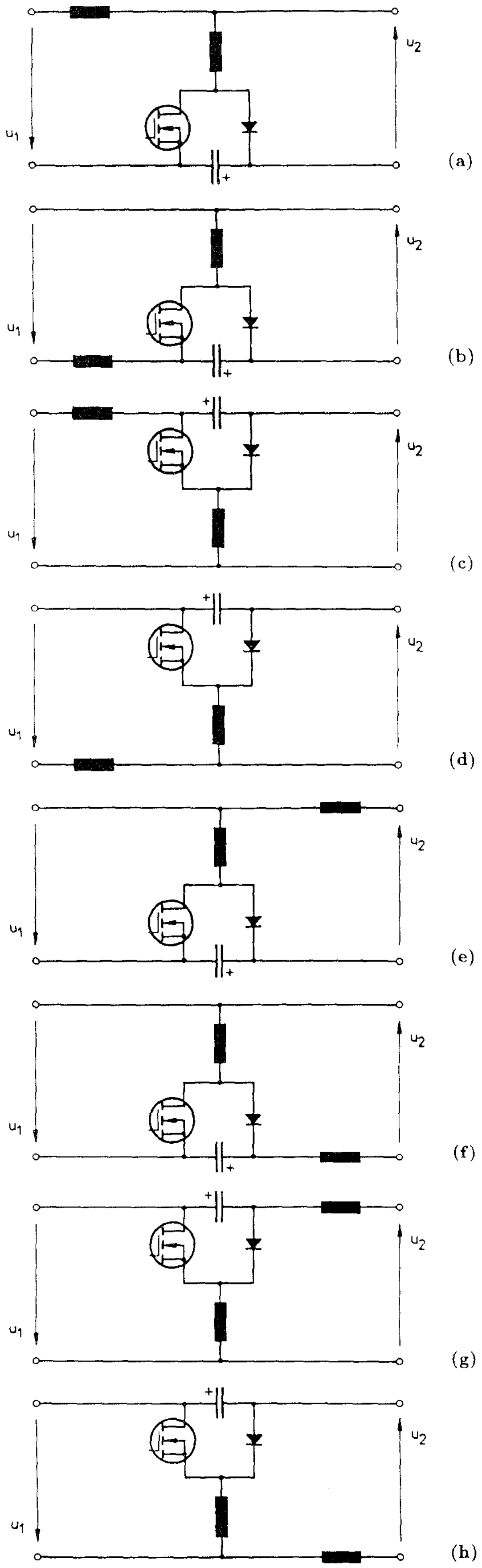

**Fig.5:** Zero-ripple Cuk-type converter topologies as obtained by rearrangement of the elements of the circuits shown in Figs.4(c) and (d); **(a)-(d)**: zero-input current ripple converters, **(e)-(h)**: zero-output current ripple converters.

independently of the switching state of the converter (and, therefore, independently of the on-state voltage drops across the valves). Therefore, as shown in **Fig.7**, a finite ripple of the input current

$$\Delta i_1 \approx \frac{\Delta u_{C_C}}{\omega_P L_1'} \qquad \omega_P = 2\pi f_P \qquad (18)$$

results. There, $f_P$ denotes the pulse frequency of the converter. The supposition formulated at the beginning of this paper is checked thereby. An analysis of a zero output current ripple Cuk converter leads to an analogous result. Therefore, for a zero input or zero output current ripple Cuk converter there is in reality *no* ideal elimination of the input or output current ripple!

**Remark:** Similarly to $\Delta u_{C_C}$ also a ripple of $u_1$ and/or of $u_2$ as well as voltage drops across the winding resistances etc. lead to a finite ripple of the input or output current of a 'zero'-ripple Cuk converter. Because the consideration of

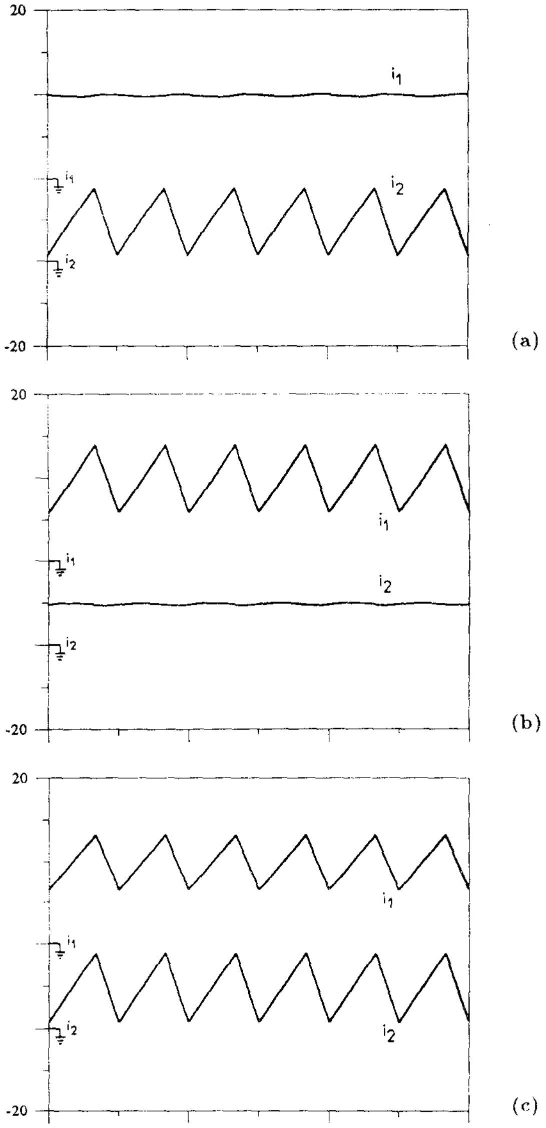

**Fig.6:** Digital simulation of the input and output currents of the converter circuits shown in Figs.4(d) and (e) and/or Figs.5(a)-(d) and Figs.5(e)-(h); **(a)**: zero input current ripple Cuk-type converter; **(b)**: zero output current ripple Cuk-type converter; also shown: conditions for a conventional Cuk converter according to Fig.1(a) (cf. **(c)**). Simulation parameters: $u_1 = 12\,\mathrm{V}$ (impressed by a voltage source), $u_2 = 24\,\mathrm{V}$, $R_L = 5\,\Omega$ (load resistance), $L_1 = 60\,\mu\mathrm{H}$, $L_2 = 50\,\mu\mathrm{H}$ (for the circuits according to Figs.5(e)-(h) $L_2 = 60\,\mu\mathrm{H}$ and $L_1 = 50\,\mu\mathrm{H}$ are chosen), $C_C = 400\,\mu\mathrm{F}$, $C_2 = 1\,\mathrm{mF}$, $f_P = 20\,\mathrm{kHz}$ (system operation in continuous conduction mode). Scales: 10 A/div, 100 µs/div. Current shapes identical to (a) and (b) are also obtained for the conventional zero-ripple Cuk converter structure shown in Fig.4(a); there, one has to set for coupling $k = 0.91287$ (= $\sqrt{\frac{L_2}{L_1}}$ or $\sqrt{\frac{L_1}{L_2}}$).

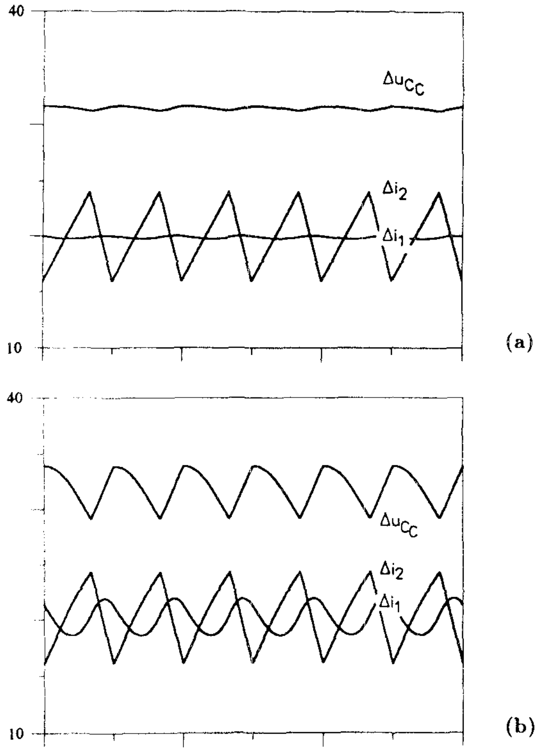

**Fig.7:** Digital simulation of the shape of the voltage ripple $\Delta u_{C_C}$ across the coupling capacitor $C_C$ of a 'zero' input current ripple Cuk converter and of the input current ripple $\Delta i_1$ caused thereby; furthermore shown: ripple of the output current $\Delta i_2$. Simulation parameters: $C_C = 400\,\mu\mathrm{F}$ (cf. **(a)**) and $C = 40\,\mu\mathrm{F}$ (cf. **(b)**), remaining simulation parameters equal as for Fig.6. $\Delta u_{C_C}$ has a triangular shape due to the (in a first approximation) rectangular shape of $i_{C_C}$; the quasi-sinusoidal shape of $\Delta i_1$ corresponds to the integration of this voltage ripple by $L_1' = L_1 - M$. Scales: 10A/div, 10V/div, 100 $\mu$s/div.

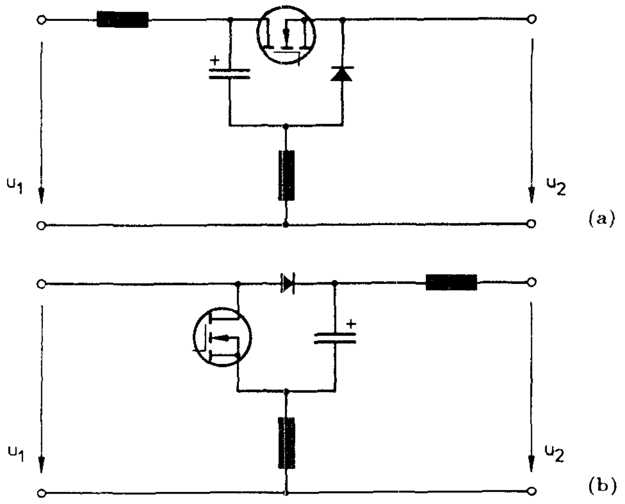

**Fig.8:** Basic structure of a continuous input&output current buck (cf. **(a)**) and of a continuous input&output current boost converter (cf. **(b)**) according to Fig.2 in [15]. The input current of the buck converter shown is not interrupted with pulse frequency contrary to a conventional buck converter topology. The same is valid for the output current of the boost converter according to (b). For a more detailed description of the boost converter structure we want to refer the reader also to [17] and [18].

the ripple contributions $\Delta u_1$ and $\Delta u_2$ does not lead to basically new results we will not treat this matter here in more detail for the sake of brevity, however.

According to Eq.(18) $L_1'$ and $C_C$ act (with respect to forming the ripple $\Delta i_1$ of the input current) like a low-pass filter lying at the converter input. However, contrary to a 'zero' input current ripple boost converter topology the input filter is already an integral part of the basic converter structure. Therefore, it does not have to be realized by additional power components. One has to point out, however, that $C_C$ for the Cuk converter acts (besides as filter capacitor) also as an essential element of the energy transfer between the input and output sides. Therefore, the current stress on $C_C$ is basically different from that of a conventional filter capacitor.

The considerations made so far are being checked also clearly by a close topological relationship between the circuits (shown in Fig.5(c) and (g)) with the topologies (given in [15]) of a continuous input&output current buck- and a continuous input&output current boost converter (cf. **Fig.8**). As being described very clearly in [16] (cf. Figs.1 and 3 in [16]), the circuits given in Fig.8 can be developed by systematic redrawing of the series combination of an LC-filter on the input and/or output side and of the basic converter structures. Therefore, the circuits finally represent a buck-converter with integrated input filter and/or a boost converter with integrated output filter.

**Remark:** In [15] also the possibility is described that for the continuous input&output current boost converter the output current ripple (and/or for the continuous input& output current buck converter the input current ripple) can be reduced by coupling of the inductors $L_1$ and $L_2$ ('zero'-ripple balancing of the coupling). If now the inductors $L_1$ and $L_2$ of the converter are magnetically coupled in order to eliminate the ripple of the input or output current, then it becomes clear by introducing an equivalent circuit of the winding arrangement that thereby the continuous input&output current ripple converter topologies are finally again converted back into discrete series connections of the basic converter structure and an LC-filter! These have been the starting point for the considerations in [16]. Therefore, by the coupling between $L_1$ and $L_2$ again only an implicitely different representation of the converter topologies is obtained. The ripple of the input or of the output current is still suppressed according to a passive filtering, however.

### 4.3 Experimental Analysis

In order to verify the theoretical considerations of sections 4.1 and 4.2 an experimental analysis of the 'zero' input current ripple Cuk converter structure (shown in Fig.5(a)) has been carried out at the University of Minnesota. There, the realization of the laboratory model of the converter has been based on the following operating parameters.

$$\begin{array}{lll} U_1 = 25\,\mathrm{V} & U_2 = 35\,\mathrm{V} & P_O = 120\,\mathrm{W} \\ L_1' = 13\,\mu\mathrm{H} & L_2 = 63\,\mu\mathrm{H} & f_P = 22\,\mathrm{kHz}\,. \end{array}$$

Furthermore, filter capacitors $C_1 = C_2 = 1\,\mathrm{mF}$ have been provided at the input and output sides. For investigating the influence of the capacitance value of the coupling capacitor on the ripple of the input current $i_1$ capacity values $C_C = 10\,\mu\mathrm{F}$ and $C_C = 420\,\mu\mathrm{F}$ have been used.

The results of the experimental analysis of the system are shown in **Fig.9**. They have a very good consistency with the signal shapes obtained for digital simulation (cf. Fig.7). This checks clearly the correctness of the results of the theoretical analysis. This is also valid for the current and voltage shapes measured on a further laboratory model of a conventional 'zero' input current ripple Cuk converter (cf. Fig.4(a)). (There, for the balancing of the coupling factor an external balancing inductor in series with $L_1$ has been applied.) Therefore, a more detailed discussion of this (well known) converter structure shall be omitted here.

### 4.4 Advantages and Disadvantages of the New Zero-Ripple Cuk Converter Topologies

In the following the advantages and disadvantages of the new 'zero'-ripple Cuk-type converter topologies (as shown in Fig.5) are summarized in brief.

Advantages:

\+ As compared to a conventional Cuk converter topology (without coupled inductors, cf. Fig.1(a)) the circuits have a substantially smaller ripple of the input or output current for equal circuit complexity. Thereby the filtering effort and/or the stress on the input or output capacitor are reduced. Furthermore, for a 'zero' input current ripple converter only a relatively low inductance value $L_1 - M$ for the input inductor (as compared to $L_1$) has to be provided. Similarly, for a 'zero' output current ripple converter only a relatively low inductance value $L_2 - M$ (as compared to $L_2$) for the output inductor has to be provi-

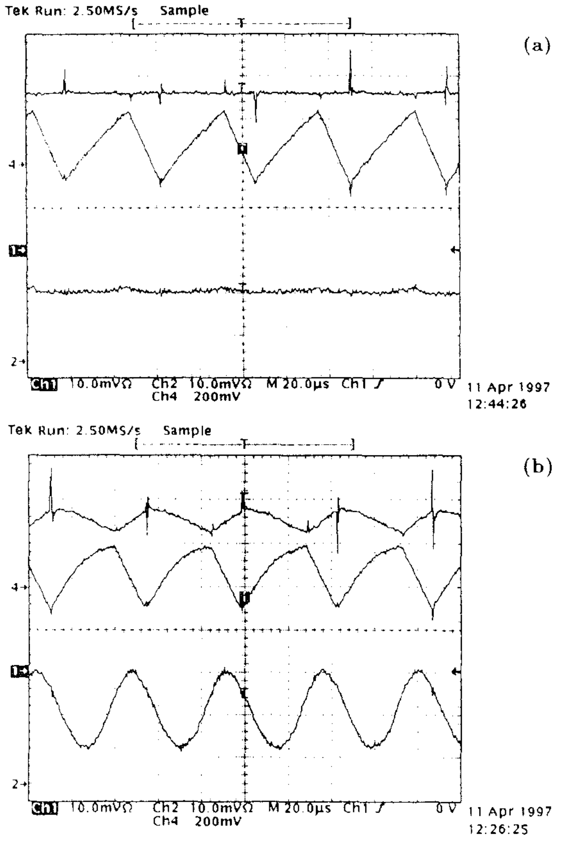

Fig.9: Experimental analysis of a 'zero' input current ripple Cuk converter structure according to Fig.5(a); upper trace: coupling capacitor voltage $u_{C_C}$ (the small signal spikes are caused by the stray inductance of $C_C$ and/or by parasitic lead inductances lying in series to $C_C$ in connection with the step changes of the current in $C_C$ in the switching instants); middle trace: current $i_{L_2}$ in $L_2$, lower trace: input current $i_1$; **(a):** $C_C = 420\,\mu$F, **(b):** $C_C = 10\,\mu$F; scales: 40 V/div, 5 A/div, 20 $\mu$s/div.

ded. Altogether, thereby the realization effort is substantially reduced in comparison to the circuit shown in Fig.1(a);

+ contrary to a conventional 'zero'-ripple Cuk converter structure no balancing of the coupling (and/or no special forming of the magnetic circuit [10]) and/or no balancing of a turns ratio of the converter inductors is required. This results in a better (and easier) realizability;
+ the circuits have (in a first approximation) equal power density as corresponding conventional 'zero'-ripple Cuk converters. This is valid for the case where external inductors (cf. $L_{\text{ext}}$ in Fig.12.12 of [5]) are provided for guaranteeing a defined value of the coupling coefficient.

Disadvantages:

- If a common reference potential of the input and output is required (direct connection of one input and one output terminal), the control of the power transistor has to be realized potential free with respect to the potential reference (cf. Figs.5(b) and (c) and Figs.5(f) and (g));
- there does not exist a simple possibility of a potential separation of the input and output circuits; especially, one cannot obtain at the same time a suppression of the input current ripple *and* of the output current ripple (contrary to the extended conventional 'zero' ripple Cuk converter structure as described, e.g., in [11] (cf. p. 495)).

## 5 'Zero' Input Current Ripple SEPIC Converter Topology

The development of alternate 'zero'-ripple converter topologies as described in section 4.1 for the example of a Cuk converter can be performed equally also for a SEPIC converter structure. Then, the circuit of a zero input current ripple SEPIC converter results as shown in **Fig.10(c)**. (A zero output current ripple SEPIC converter structure cannot be given due to the basically discontinuous output current shape of a SEPIC converter.)

Fig.10(c) does not represent a new converter topology in any way, however! On the contrary, this circuit is identical to a buck-boost converter with input filter concerning the operating behavior, as one can see by redrawing the circuit (cf. Fig.10(d)).

Accordingly, also for a zero input current ripple SEPIC converter (as for a 'zero' input current ripple boost or Cuk converter topology) only a reduction of the input current ripple and not an ideal suppression of the input current ripple is obtained.

The advantage of the 'zero'-ripple SEPIC converter structure according to Fig.10(a) consists, therefore, primarily in the fact that the filter inductor and the inductor of the buck-boost converter are realized by using only one magnetic circuit. Also, the measurement of the output voltage does not have to be potential free.

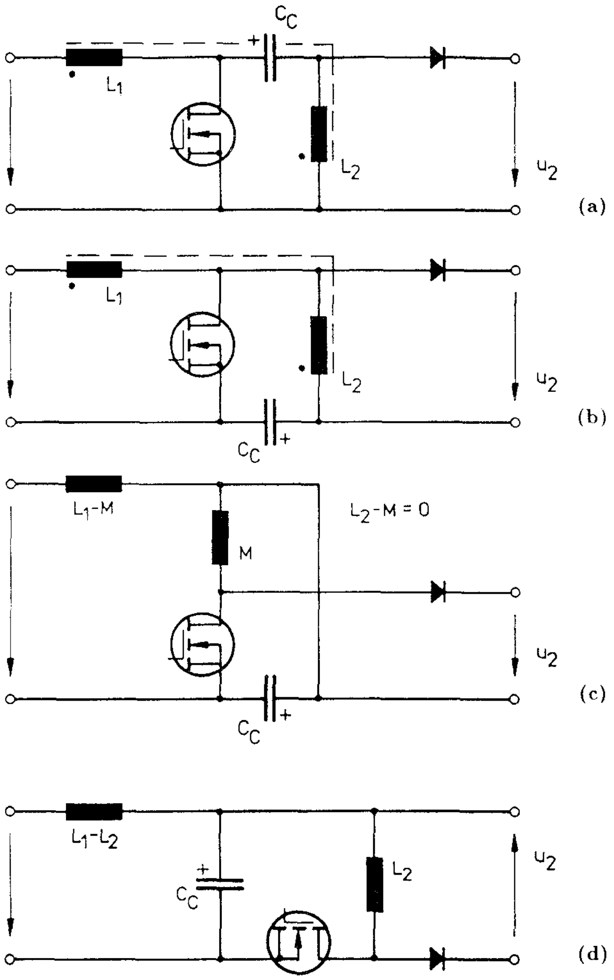

**Fig.10:** Proof of the equivalence of a 'zero' input current ripple SEPIC converter and of a buck-boost converter with LC input filter.

**Remark:** Figure 8(d) also makes clearly understandable the problem mentioned in [4] consisting of a resonance between the stray inductance of the coupled inductors $L_1$ and $L_2$ and the coupling capacitor $C_C$ (cf. p. 6-3 in [4]) of a 'zero' input current ripple SEPIC converter. The filter formed by the stray inductance $L_1 - M$ and $C_C$ of the 'zero'-ripple converter is only lightly damped. Therefore, step load changes or disturbances superimposed on the input voltage lead to the occurrence of only slowly decaying current and voltage oscillations.

## 6 Conclusions

In the literature the analysis of 'zero'-ripple converter structures is based on

$C_C \to \infty$ in most cases. A priori, this excludes the possibility of a deeper insight into the system behavior; the 'zero'-ripple phenomenon is then seen as scientific curiosity [5] in most cases.

In this paper it is shown that the 'zero'-ripple buck, boost, Cuk and SEPIC converter structures correspond to the integration of a (passive) LC-filter into the respective basic converter structure, regarding the operating behavior. The input current ripple or the output current ripple of this converters is substantially reduced, therefore, in comparison to a conventional realization. However, the ripples are not completely suppressed, as one could possibly presume in view of the designation *zero*-ripple converters. Therefore, the application of a zero-ripple converter seems to be advantageous especially due to the relatively high power density (related to the separate arrangement of filter and converter).

Furthermore, it is shown that the 'zero'-ripple phenomenon is not linked necessarily to a defined magnetic coupling and/or to a defined turns ratio between the input and output inductors of a Cuk converter. On the contrary it can be obtained also by a simple rearrangement of the elements of the basic converter structure. Thereby a new class of 'zero' ripple current Cuk converter topologies results having a very low input or output current ripple already being due to the structure.

At present, the topic of further research in this area is a detailed comparison of the realization effort of the newly introduced converter topologies with conventional 'zero' ripple current converter topologies. Furthermore, the controls behavior of the new 'zero' ripple converter structures shall be compared to the conventional converters. Also, the possibility of realizing the switching stage of a Switch-Mode Assisted Linear Amplifier [19] by a 'zero'-ripple Cuk converter structure shall be investigated.

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