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Interleaved DC/DC Converter with Coupled Inductor – Theory and Application

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ABSTRACT: *This paper deals with the analysis of buck interleaved DC-DC converter with a coupled inductor on the same magnetic core. The advantage of the coupled inductor over the non-coupled case is investigated. The current ripple equations as an output current for the buck operation mode and the ripple current in individual phase of the interleaved converter using coupled inductor are explained analytically and supported by simulation and experimental results. The novelty of the paper is an investigation of current ripples of interleaved buck converter operated over 50 % of duty ratio and utilization of the converter in the application of electric drive vehicle.*

KEYWORDS: *Coupled inductor, interleaved converter,bidirectional converter*

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I. NOMENCLATURE

d	Time interval for calculation of current ripple
D	Duty cycle
i_{C1}	Output current of noncoupled converter
i_{C2}	Output current of coupled converter
i_{L1}, i_{L2}, i_{L3}, i_{L4}	Inductor L_1, L_2, L_3, L_4 current
$i_{out,}$	Output current
i_m	Magnetizing current
ΔI_{L1}, ΔI_{L2}	Inductor L_1, L_2 current ripple
ΔI_{L1pp}, ΔI_{L2pp}	Inductor L_1, L_2 current ripple in analyzed interval
ΔI_{out}	Output current ripple
K	Coupling coefficient
L	Inductance
L_m	Magnetizing inductance
L_{lk}	Leakage inductance
PFC	Power factor corrector
S_{1H} , S_{2H}, S_{1L}, S_{2L}	Power switches
T_S	Switching period
$V_{CE(SAT)}$	Transistor collector-emitter voltage
V_{out}	Output voltage
V_{in}	Input voltage
V_1, V_2	Input voltage
V_{lk1}, V_{lk2}	Leakage inductance
V_m	Magnetizing voltage
VRM	Voltage regulator module

II. INTRODUCTION

Nowadays, the interleaved topologies are widely used due to their advantageous properties such as lowered current ripple and volume reduction [1]- [3]. For the higher power applications, there are more possibilities how to perform higher power density regarding the efficiency of the converter. The first choice is to utilize of the paralleling of the power switches, shown in Fig. 1a. This converter includes only one inductor and parallel connected two half-bridge legs. This is done for reasons of obtaining higher current ratings, thermal improvements, and sometimes for redundancy. If losses are not equally shared, the thermal differences between the devices will lead to other problems and the possible failure of the transistors. Therefore, the thermal coefficient of the collector-emitter voltage $V_{CE(SAT)}$ is an important parameter when paralleling IGBTs. It must be a positive to allow current sharing. On the other hand, the higher positive thermal coefficient brings the higher conductive losses because at high temperature the $V_{CE(SAT)}$ is increased.

The second option how to share the current is to use the interleaved bidirectional topology, Fig. 1b [5]. The same problem as in the previous topology with current sharing is eliminated because the current is divided into two parallel buck converters. The advantageous of this connection is in improved power density, the interleaved effect reduces the total input and output current ripple, so this means the smaller input and output filters (bulk capacitor), better distribution of power with lower current stress for semiconductor devices [3].

In the high current application, there are used the interleaved topologies even with the coupled inductors. The advantageous of the coupled inductor is in lowered current ripple direct on the inductors not only in the output or input current of the converters. The interleaved buck converter with coupled inductance is used in VRM application where voltage about 1V and current of hundreds of amps are applied. On the other side, utilization of coupled inductor in higher voltage application does not have any limitation as is seen in PFC application [6]- [10]. Therefore, the advantageous features of the coupled inductor will be analyzed for the converter, which serves for recovery energy at the time of regenerative braking of the traction motor [11].

The analysis includes investigation of current ripple – on the output of the converter and change of the inductor current ripple in case of the coupled inductor in comparison with the non-coupled case.

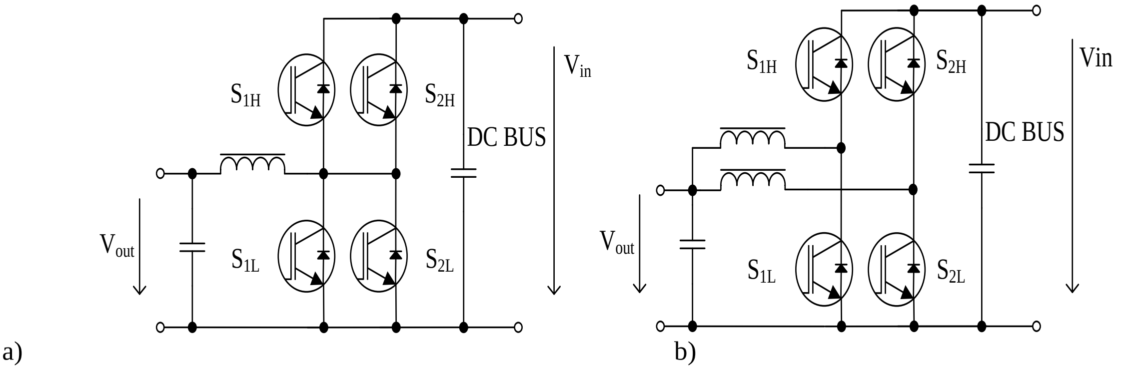

Fig. 1 a) Buck DC/DC converter for higher power application, b) Interleaved buck DC/DC converter for battery/ultracapacitor application

III. CURRENT RIPPLE REDUCTION EFFECT OF COUPLED INDUCTOR

The intention of the current ripple reduction in case of battery application is to prolong the battery lifetime because is sensitive to high dynamic current stress. Therefore, the buck interleaved topology with reduced output current ripple is proposed to solve this issue. The outputs of the converters shown in Fig. 1a, bare connected to the battery/ultracapacitor pack and input to the DC BUS of the three-phase inverter.

This section is divided into two parts. Firstly, an impact of the non-coupled inductor on buck topology is investigated. Then, in some following subheads, the advantage of coupled inductor is analyzed with emphasis to the reduced inductor current ripple.

In the two-phase interleaved converter, the four different operating modes occur as shown in Fig. 2. The first interval begins when the switch S_{1H} and S_{2L} are closed, the second interval when S_{1L} and S_{2L} are on. In the third interval, S_{2H} and S_{1L} are turn on. It means that the curve of the current i_{L2} in the second phase is same as the current i_{L1} in the first interval, but phase-shifted by 180°. Therefore, the ripple of currents in the third interval is same as in first one (exchange of current i_{L2} with i_{L1} and vice versa). From the Fig. 2 is seen that ripples ΔI_{L1} and ΔI_{L2} are the same. But, the output current ripple is dependent on ΔI_{L1} and ΔI_{L2pp}, not $\Delta I_{L2.}$ Then, an appropriate equation for inductor current ripples in a first interval can be obtained, (1) and (2).

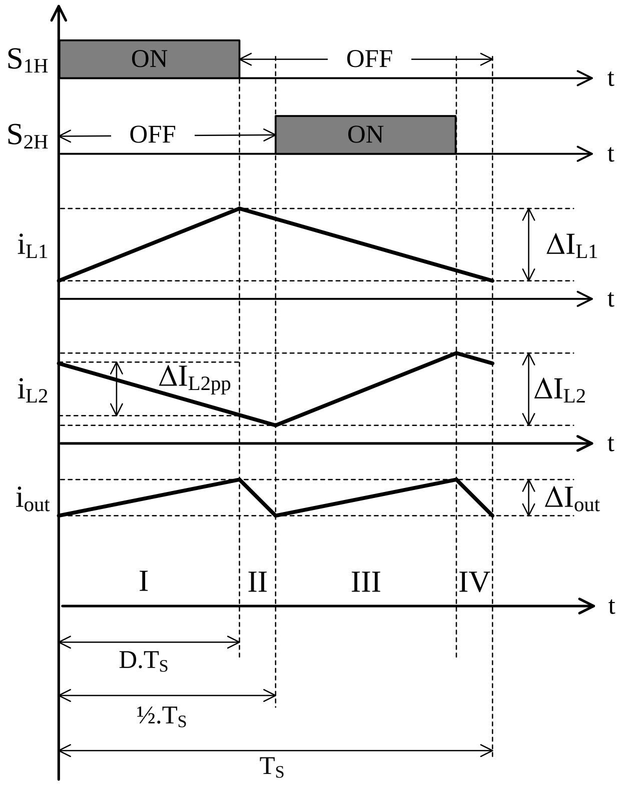

Fig. 2 Current ripples of interleaved non-coupled buck converter

$$\Delta I_{L1} = \frac{V_{in}}{L}(1-D)DT_S \tag{1}$$

$$\Delta I_{L2pp} = -\frac{V_{in}}{L}(D)DT_S \tag{2}$$

Then, by summing (1) and (2) the equation for output current ripple reduction is

$$\Delta I_{out} = \Delta I_{L1} + \Delta I_{L2pp} = \frac{V_{in}}{L}(1-2D)DT_S \tag{3}$$

Using the same procedure, it can be achieved the output current ripple calculation for all intervals. On the other hand, in case of steady state it is not necessary, because the current ripple in all intervals is the same.

A. Dual Interleaved Coupled Buck Converter

A simplified schematic for a coupled buck converter is depicted in Fig. 3. Two-phase coupled buck converter is divided into four intervals same as in non-coupled case, Fig. 4, Fig. 5.

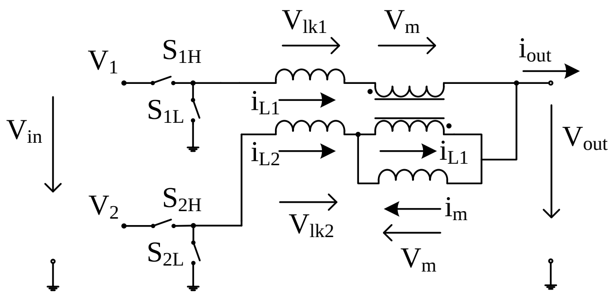

Fig. 3A schematic of dual buck converter using coupled inductor

According Kirchhoff's law the following equation for two-phase coupled buck converter in first interval can be written (4) - (8):

$$i_{out} = i_{L1} + i_{L2} \quad (4)$$

$$i_m = i_{L1} - i_{L2} \quad (5)$$

$$V_{lk1} = V_{in} - V_{out} - V_m \quad (6)$$

$$V_{lk2} = V_m - V_{out} \quad (7)$$

$$V_m = \frac{L_m}{L_{lk} + 2L_m} V_{in} \quad (8)$$

Using the mathematical apparatus, the following equations refer to the first interval of operation are given, (9) – (11):

$$\Delta I_{L1} = \frac{V_{in}}{L_{lk}} \left(1 - D - \frac{L_m}{L_{lk} + 2L_m} \right) DT_S \quad (9)$$

$$\Delta I_{L2\_I} = \frac{V_{in}}{L_{lk}} \left(\frac{L_m}{L_{lk} + 2L_m} - D \right) DT_S \quad (10)$$

$$\Delta I_{out} = \Delta I_{L1} + \Delta I_{L2\_I} = \frac{V_{in}}{L} (1 - 2D) DT_S \quad (11)$$

These equations also apply for the third interval with the difference that ΔI_{L1} is ΔI_{L2} and vice versa. Using Kirchhoff's laws, the equations for the second interval are as follows, (12) - (14).

$$V_{lk1} = -V_{out} - V_m \quad (12)$$

$$V_{lk2} = V_m - V_{out} \quad (13)$$

$$V_m = 0 \quad (14)$$

Using the same procedure as in interval I and III we can obtain current ripples in interval II and IV. The given equations are as follows:

$$\Delta I_{L1\_II} = \Delta I_{L2\_II} = -\frac{V_{in}}{L_{lk}} (0.5 - D) DT_S \quad (15)$$

$$\Delta I_{out} = \Delta I_{L1\_II} + \Delta I_{L2\_II} = -\frac{V_{in}}{L_{lk}} (1 - 2D) DT_S \quad (16)$$

For the second and fourth interval of operation, the ripple is same for both phase currents. If we want to determine the total inductor current ripple we must sum the ripple currents in interval II, III and IV or calculate the ripple in interval I. For the ripple current in the second phase we can apply the same approach with the difference that we must calculate the ripple in III interval. On the other hand, the output current ripple is the sum of inductor current ripples corresponding to each time interval.

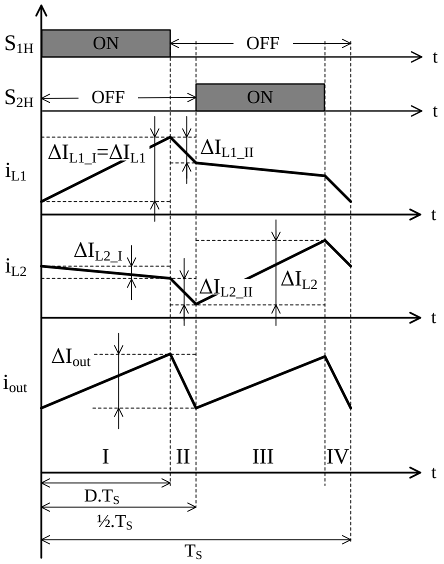

Fig. 4 Current ripples of interleaved coupled buck converter for D < 0.5

The operation of buck interleaved converter with duty ratio over 0.5 is shown in a Fig. 5. From this figure is seen that upper switches of the converter can be switched on at once (interval I and III). It means that in this interval the magnetizing voltage V_m equals zero. Analytically, it is stated in some following equations (17) – (23).

$$V_{lk1} = V_{in} - V_{out} - V_m \tag{17}$$

$$V_{lk2} = V_{in} + V_m - V_{out} \tag{18}$$

$$V_m = 0 \tag{19}$$

$$d = D - 0.5 \tag{20}$$

$$\Delta I_{L1\_I} = \frac{V_{in}}{L_{lk}}(1-D)(D-0.5)T_S \tag{21}$$

$$\Delta I_{L2\_I} = \frac{V_{in}}{L_{lk}}(1-D)(D-0.5)T_S \tag{22}$$

$$\Delta I_{out} = \Delta I_{L1\_I} + \Delta I_{L2\_I} = \frac{V_{in}}{L_{lk}}(2-2D)(D-0.5)T_S \tag{23}$$

Similarly, for the II and IV interval the following equation apply (24) – (30).

$$V_{lk1} = V_{in} - V_{out} - V_m \tag{24}$$

$$V_{lk2} = V_m - V_{out} \tag{25}$$

$$V_m = \frac{L_m}{L_{lk} + 2L_m} V_{in} \tag{26}$$

$$d = 1 - D \tag{27}$$

$$\Delta I_{L1\_II} = \frac{V_{in}}{L_{lk}}\left(1 - D - \frac{L_m}{L_{lk} + 2L_m}\right) DT_S \tag{28}$$

$$\Delta I_{L2\_II} = \frac{V_{in}}{L_{lk}}\left(\frac{L_m}{L_{lk} + 2L_m} - D\right) DT_S \tag{29}$$

$$\Delta I_{out} = \Delta I_{L1\_II} + \Delta I_{L2\_II} = \frac{V_{in}}{L_{lk}}(1-2D)(1-D)T_S \tag{30}$$

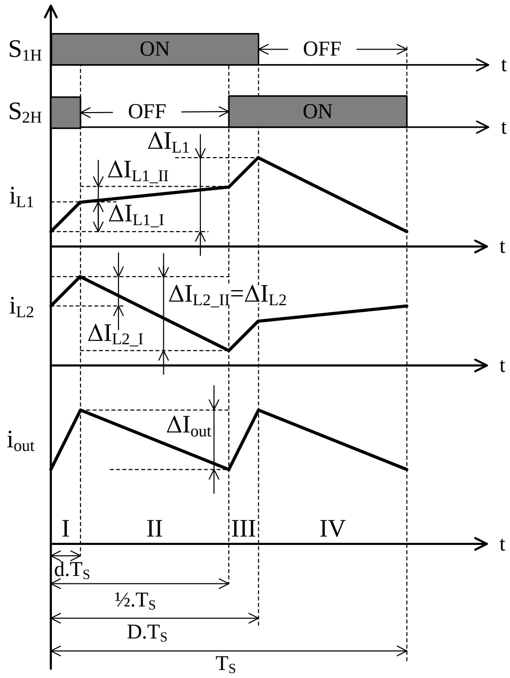

Fig. 5 Current ripples of interleaved coupled buck converter for D > 0.5

From (3), (11) and (16) is evident that output current ripple is the same (except the negative sign in (16)) under the condition that leakage inductance L_{lk} L is equaled to non-coupled inductance. If we fit into the equations (24) and (30) the value of duty ratio we find that the ripple is same as in the equation (3), (11) and (16). The condition of D < 0.5 for equation (24) and D > 0.5 for equation (30) must be fulfilled.

The coupling coefficient k is the most important parameter which affects inductor current ripple.

$$k = \frac{L_m}{L_{lk} + L_m} \qquad (31)$$

Using the high value of the coupling coefficient (near 1) then the leakage inductance is small and it leads to increasing of the output current ripple ΔI_{out}, but the ripple of the phase current ΔI_{L1} or ΔI_{L2} is minimized. Using the smaller value, then the magnetizing inductance is smaller and the ripple of the phase current is higher but the ripple of the output current is smaller and then the bulky output filter is reduced. Therefore, there is a trade-off between choosing coupling coefficient.

IV. SIMULATION RESULTS

As mentioned in section II, the inductor current ripple is strongly dependent on the coupling coefficient k of the coupled inductor. In order to have the maximum inductor current ripple reduction, the coupled inductor should have high k and also have enough leakage inductance to reduce output current ripple for the buck converter respectively.

The switching frequency of the one leg of the interleaved converter was set to 20 kHz, due to use of the inverter. Therefore, because of the interleaving effect, the output switching frequency is doubled, which is shown in Fig. 6, Fig.7 and Fig. 8. The self-inductance of the non-coupled inductor was set at 672 µH. In order to satisfy the condition of the ripple current equality, the leakage inductance was also set to 672 µH. Then, the coupling coefficient was set to value of 0.55 and it follows that the magnetizing inductance is 834 µH. The additional parameters of the converter are given in a Table 1. The simulation results are done for duty ratio 28% (minimum output voltage), 50% (almost zero current output ripple) and 58% (maximum output voltage).

TABLE I. SETUP CONDITIONS

PARAMETER	COUPLED INDUCTOR	NON-COUPLED INDUCTOR
Switching frequency	20 kHz	20 kHz
Leakage inductance	672µH	-
Magnetizing Inductance	834 µH	-
Self-inductance	-	672 µH
Duty cycle	0.28-0.58	0.28-0.58
Input voltage V_{in}	560 V	560 V
Output voltage	160 – 320 V	160 – 320 V

The time waveforms of ripple current for the minimum and maximum value of duty cycle are depicted in Fig. 6 and Fig. 7. From the simulation results in Fig. 7 and Fig. 8 is evident that the inductor current ripple of the converter with a coupled inductor (iL5, iL8) is smaller than the non-coupled case (iL2, iL3). In Fig. 9 are given time waveforms of ripple currents for non-coupled (iL5, iL8) coupled inductor (iL2, iL3) with the difference that the ripple of output current (ΔiC1 and ΔiC2) equals almost zero. The advantage is not in zero value of output current because same option occurs in interleaved connection with a non-coupled inductor, but the fact there is reduced inductor current ripple.

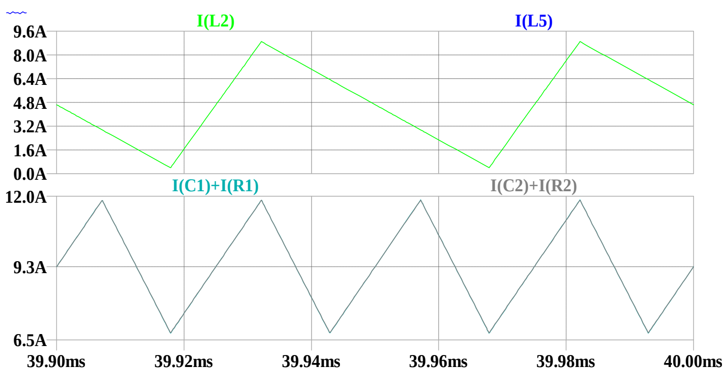

Fig. 6 Inductor current ripples with D = 28% for coupled (iL5) and non-coupled inductor (iL2)- up, output current ripples for coupled (I_{C2}+I_{R2}) and non-coupled inductor(IC1+IR1)-down

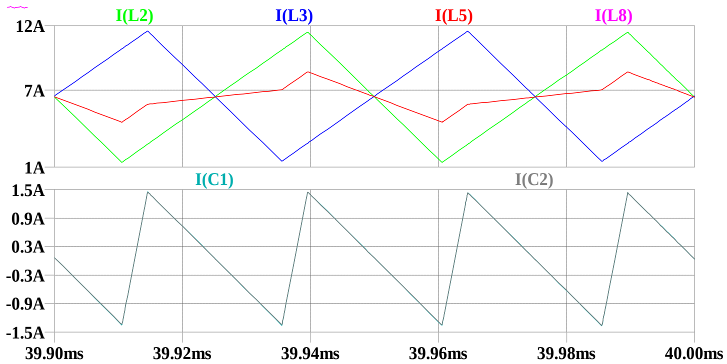

Fig. 7 Inductor current ripples with D = 58% for coupled (iL5) and non-coupled inductor (iL2)- up, output current ripples for coupled (I_{C2}+I_{R2}) and non-coupled inductor(IC1+IR1)-down

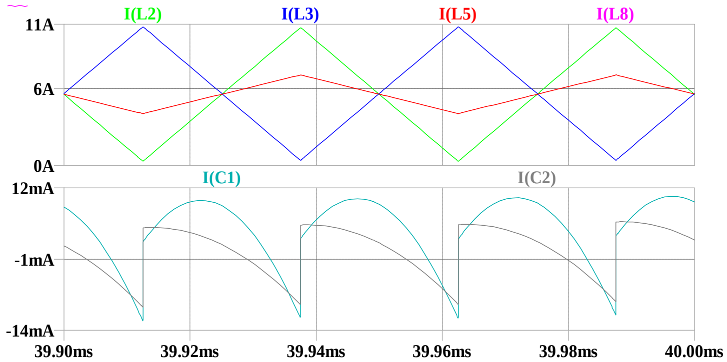

Fig. 8 Inductor current ripples with D = 50% for coupled (iL5) and non-coupled inductor (iL2)- up, output current ripples for coupled (I_{C2}+I_{R2}) and non-coupled inductor(IC1+IR1)-down

The comparison of the ratio between output and inductor current is depicted in Fig. 9. It is obvious, that the ratio is increased when the coupling effect is utilized. This means that the inductor current ripple is smaller in a whole range of duty cycle, instead of D = 0.5. Then, the ripples are equal. To satisfy the same ripple of the output current for the coupled and non-coupled case, the condition of the same leakage inductance must agree.

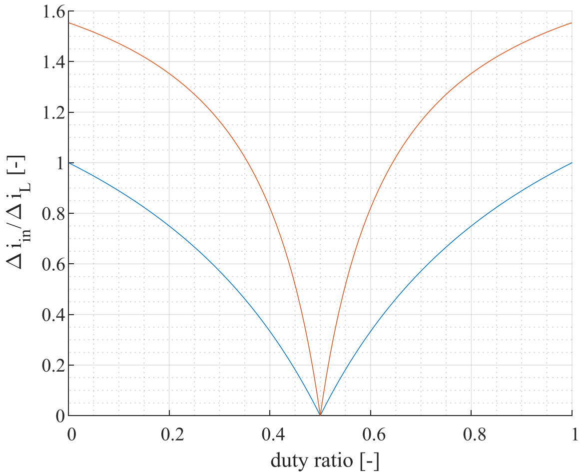

Fig. 9 The ratio of output current ripple and inductor current ripple for non- and coupled case

V. EXPERIMENTAL VERIFICATION

In coupled inductor design, there should be a problem how to maintain the required leakage inductance. The easiest way how to manage this issue, it is used the additional non-coupled inductor. The powder core is ideal for this inductor, which is capable to carry high dc current. Then the magnetizing inductance will wound as a coupled inductor and only the ac component of the current will flow through it because the dc current is canceled with the negative coupling of the inductors. It means, that the inductors are wound against each other and the magnetic flux of both inductors is canceled. Therefore, the solution with the ferrite core should be utilized. The proposed coupled inductor in this paper does not use an additional inductor. The coils consist of two EE cores, where each winding is wound on the outer leg of the core. This ensures a sufficiently large value of leakage inductor and magnetizing inductance is adjusted with a change of an air gap in the center leg or the outer legs.The final values of the leakage and magnetizing inductance are given in Table 1.

Subsequently, the experimental measurements of the converter with a coupled inductor were performed.

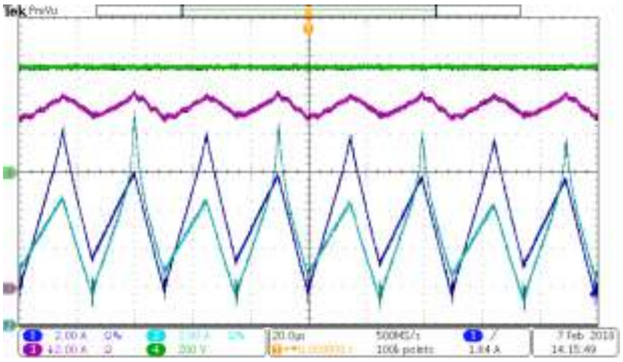

Fig. 10 The time waveforms of inductor current ripple (turquoise and blue one), output current (violet) and input voltage (green) for D <0.5

The oscilloscope waveform with the duty lower than 50% (minimum operating duty ratio – 28%) is shown in Fig. 11 and for duty higher than 50% (maximum operating duty ratio – 58%) in a Fig. 11.

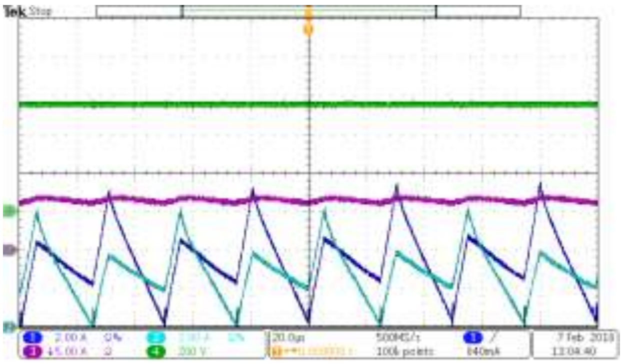

Fig. 11 The time waveforms of inductor current ripple (turquoise and blue one), output current (violet) and input voltage (green) for D >0.5

From the Fig. 10 and Fig. 11 is visible that the ripple of the output current is markedly reduced which allows to use smaller output capacitor value and extend the lifetime of the ultracapacitor/battery pack connected to the output of the converter.

VI. CONCLUSION

In order to reduce inductor current ripple as well as output current ripple respectively, the two inductors should be coupled to the same core. It is preferable to use coupled inductor topology in battery/ultracapacitor application due to less stress of these energy sources and lower conduction losses of the semiconductor switches because of the lower effective value of the inductor current ripple. To maintain the required ripples on the inductor and on the output respectively, the coupling coefficient must agree. For the output current, the leakage inductance is very important and it must be equal to the non-coupled inductance to maintain criterion. Then, for the high value of coupling coefficient, the mutual inductance increases and leakage inductance decreases and vice versa. The solution is to find an appropriate compromise between the output and inductor ripple value.

In the future work, the three and four phase converter with a coupled inductor will be investigated.

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