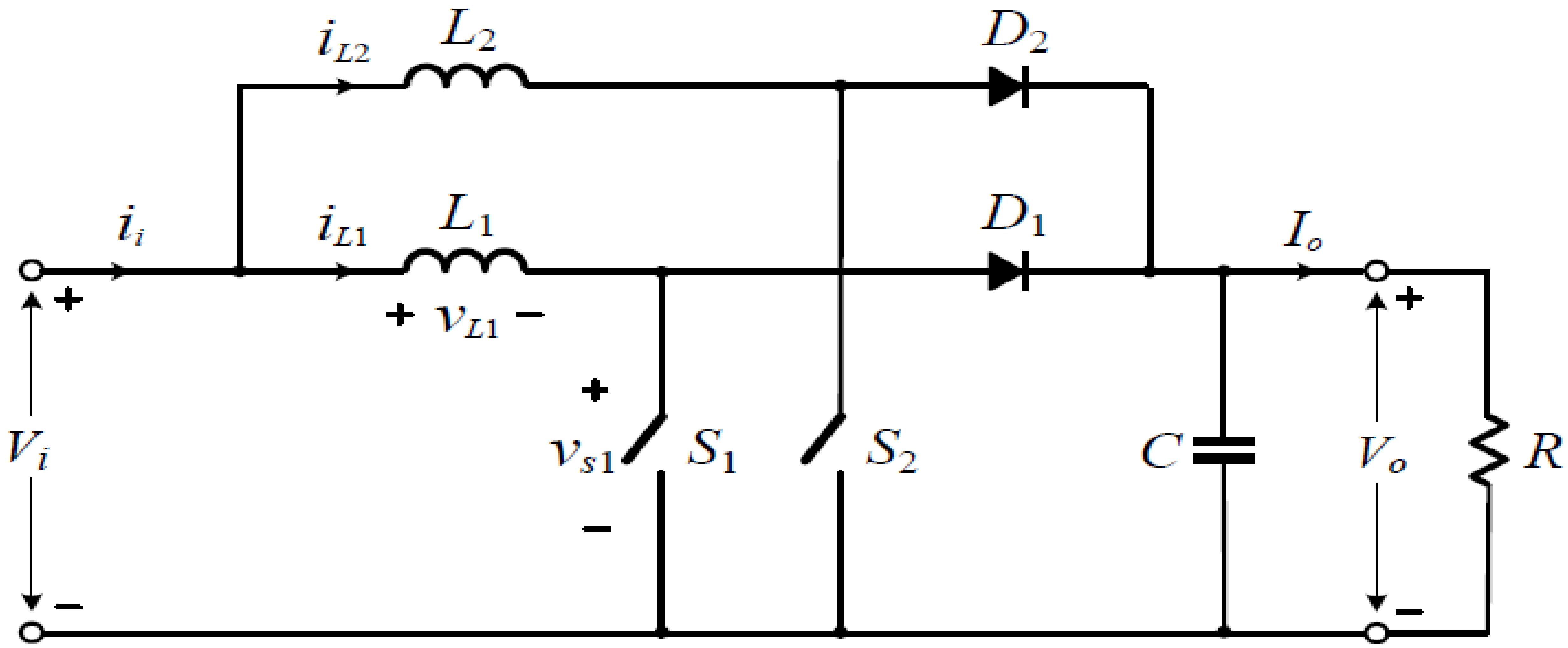
Lecture#

4.3.2 Two-channel Interleaved Boost Converter

4.3.3 Multi-channel Interleaved Boost Converters

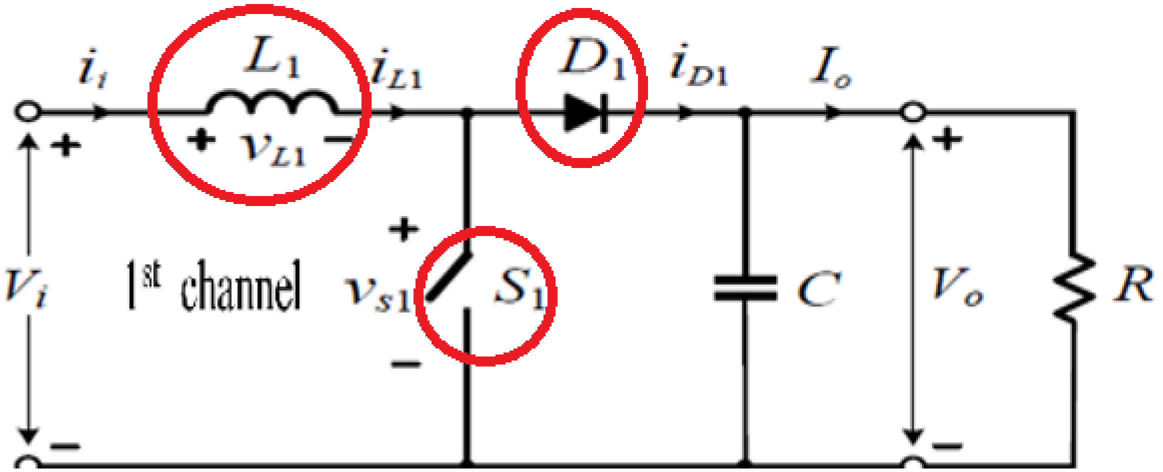
Numericals:

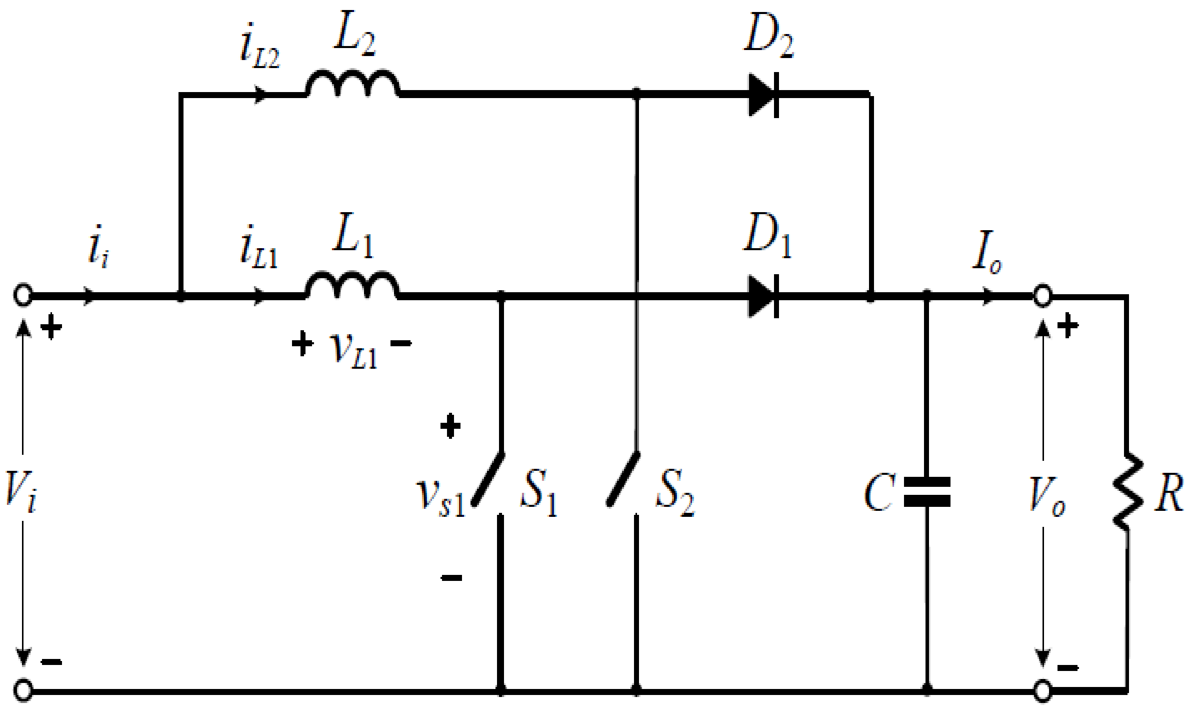
4.3.2 Two-channel Interleaved Boost Converter

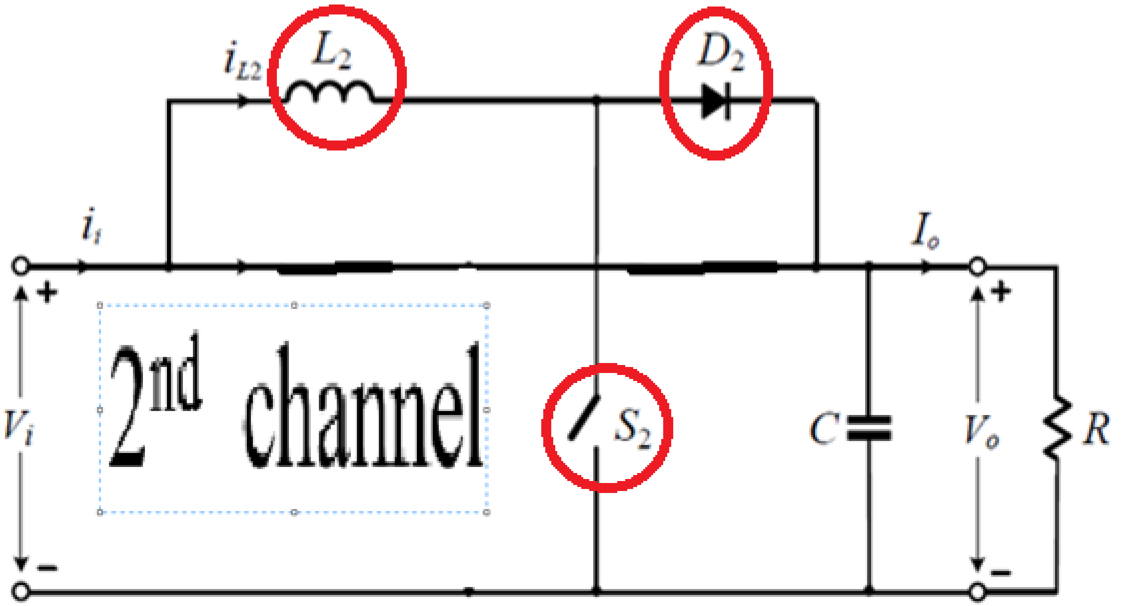


02 parallel converter channels in circuit

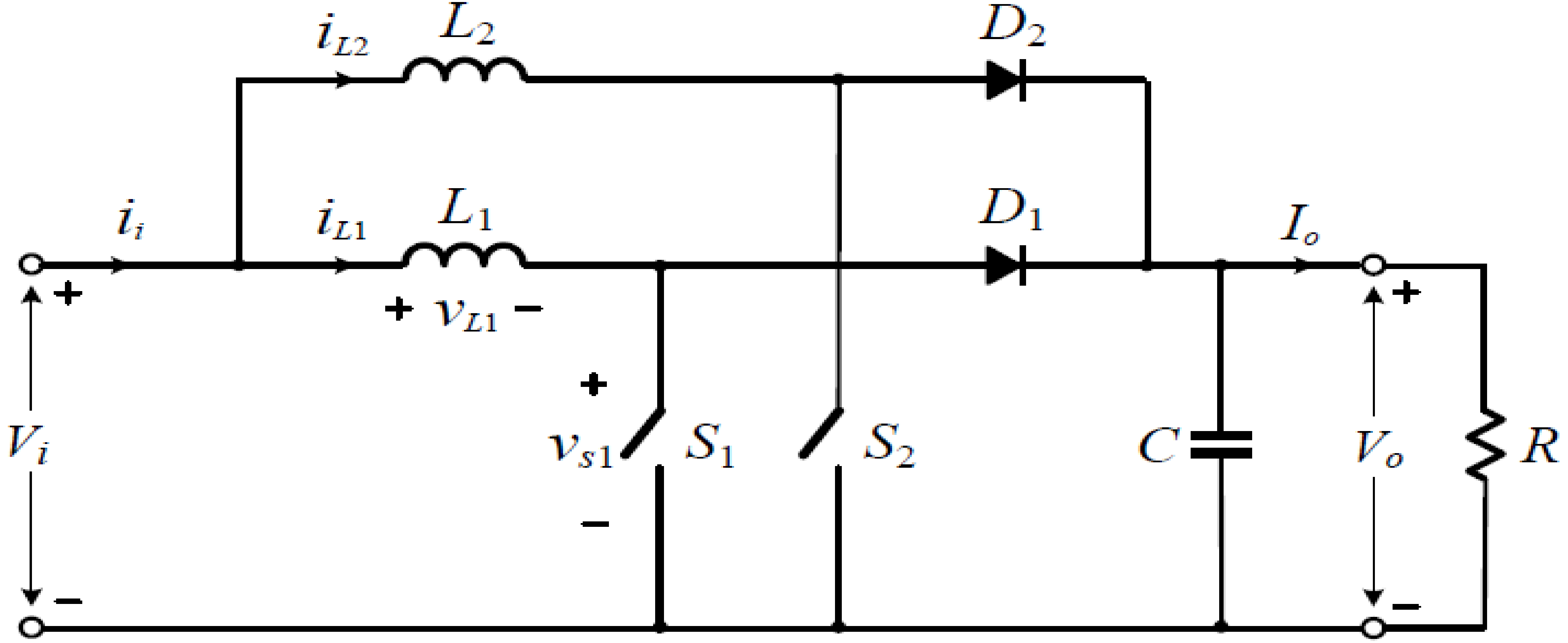
- 1^{st} channel has inductor L_1, switch S_1 & diode D_1,
- 2^{nd} channel has of L_2, S_2 & D_2 .



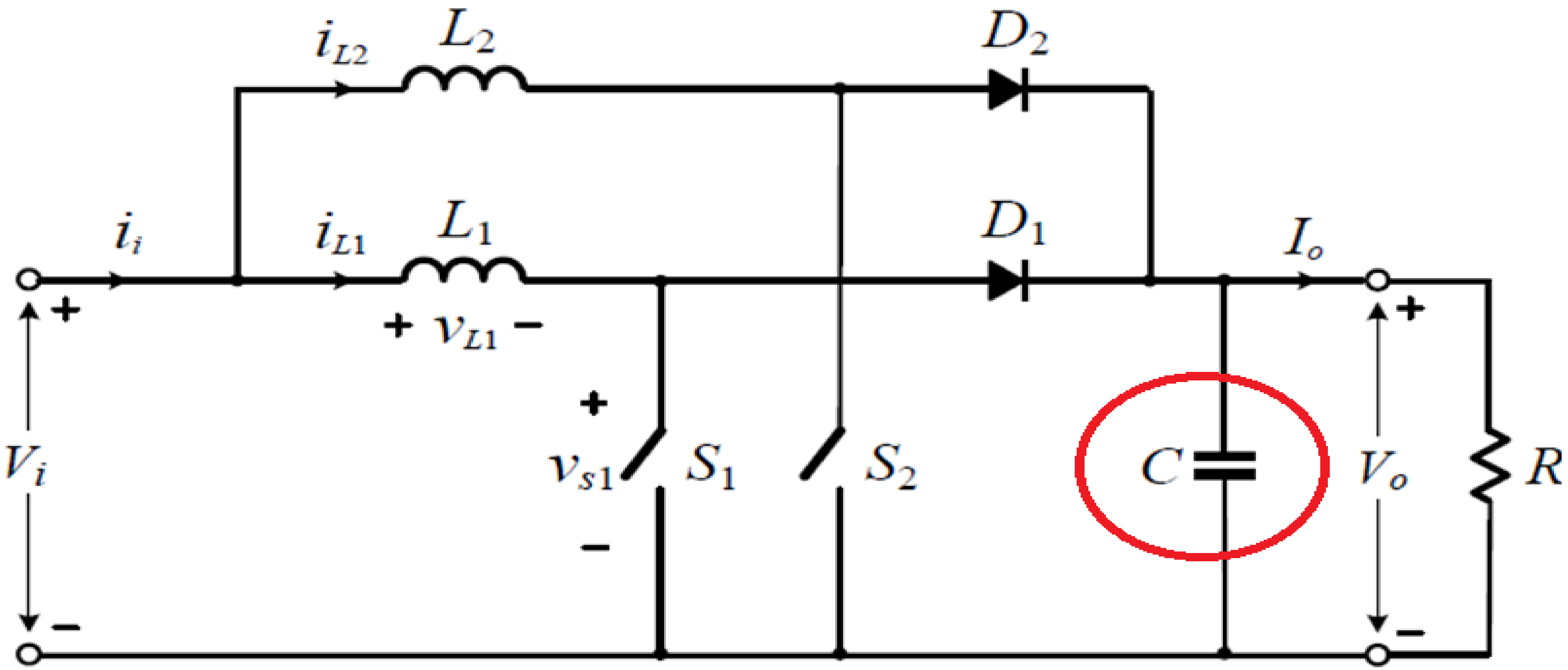




Q. Which element is shared at output?

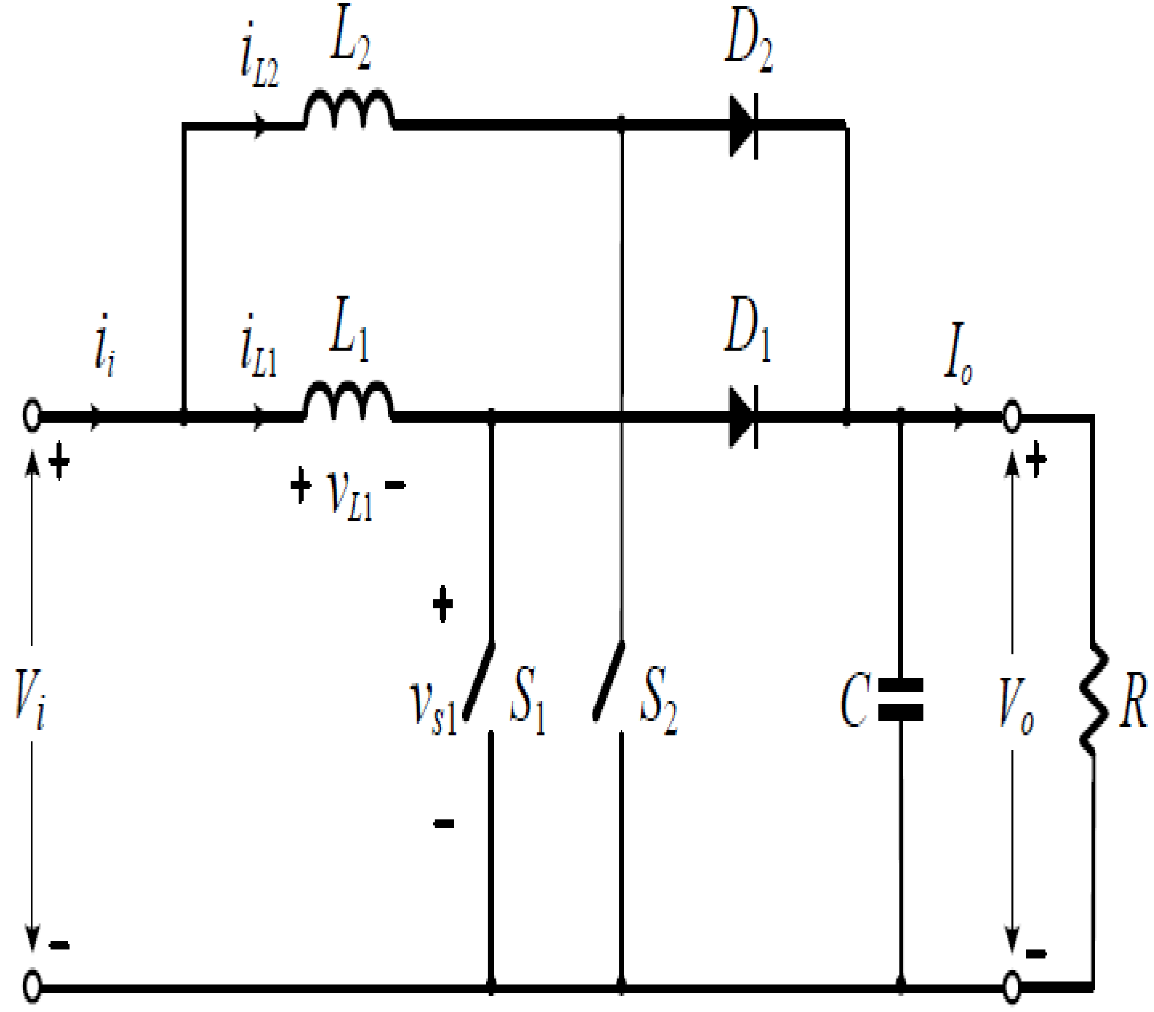


Answer: They share filter capacitor C



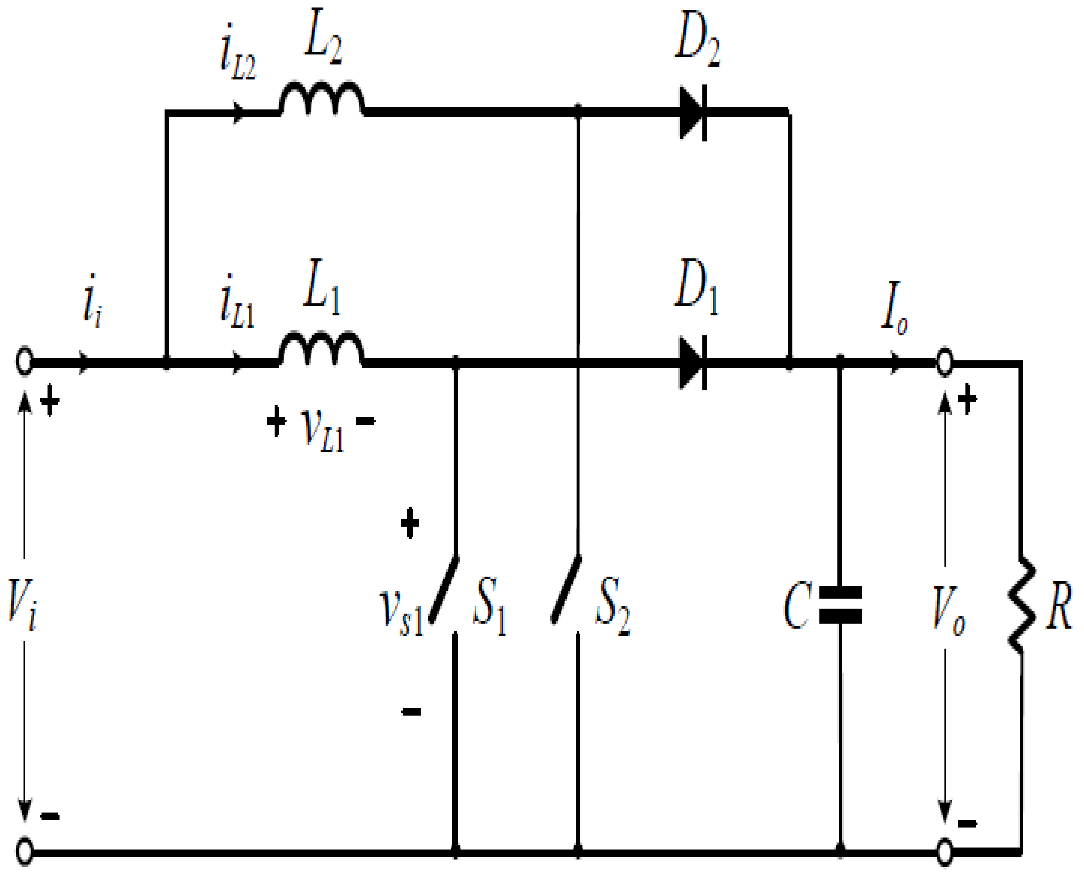
2 converter channels are connected in parallel but operate in an interleaved mode.

- It is assumed that parameters of 2 channels are identical.



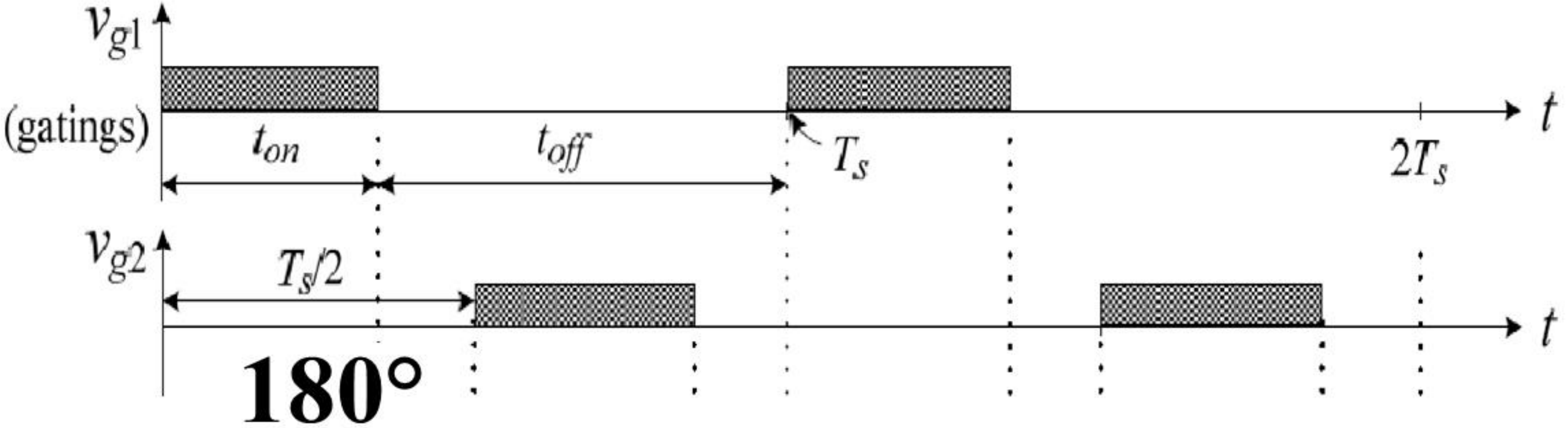
Q. Gating arrangement of converter?

- Now we have 2 switches S1 & S2.
- What should be their gating arrangement?
- Gating should be on both switches simultaneously?



Gating arrangement of converter

- With interleaving design, gating signals v_{g1} & v_{g2} for S_1 & S_2 are identical but shifted by 360°/N = 180°, where N is number of parallel converter channels.

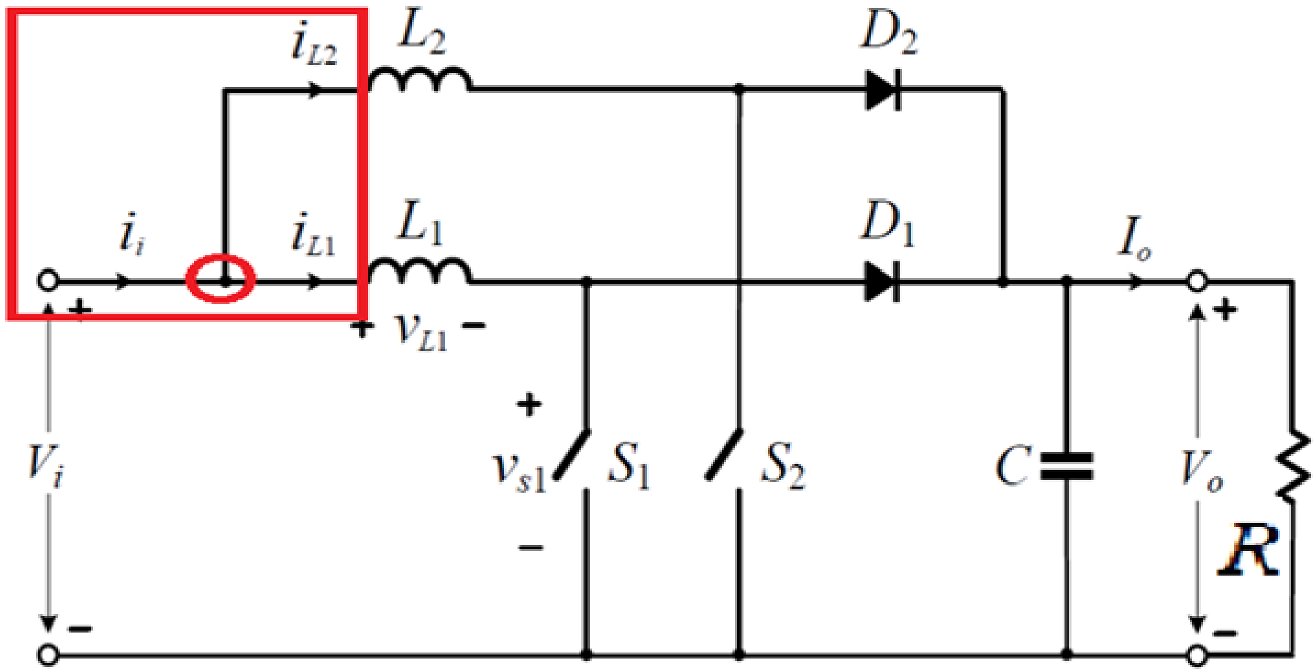


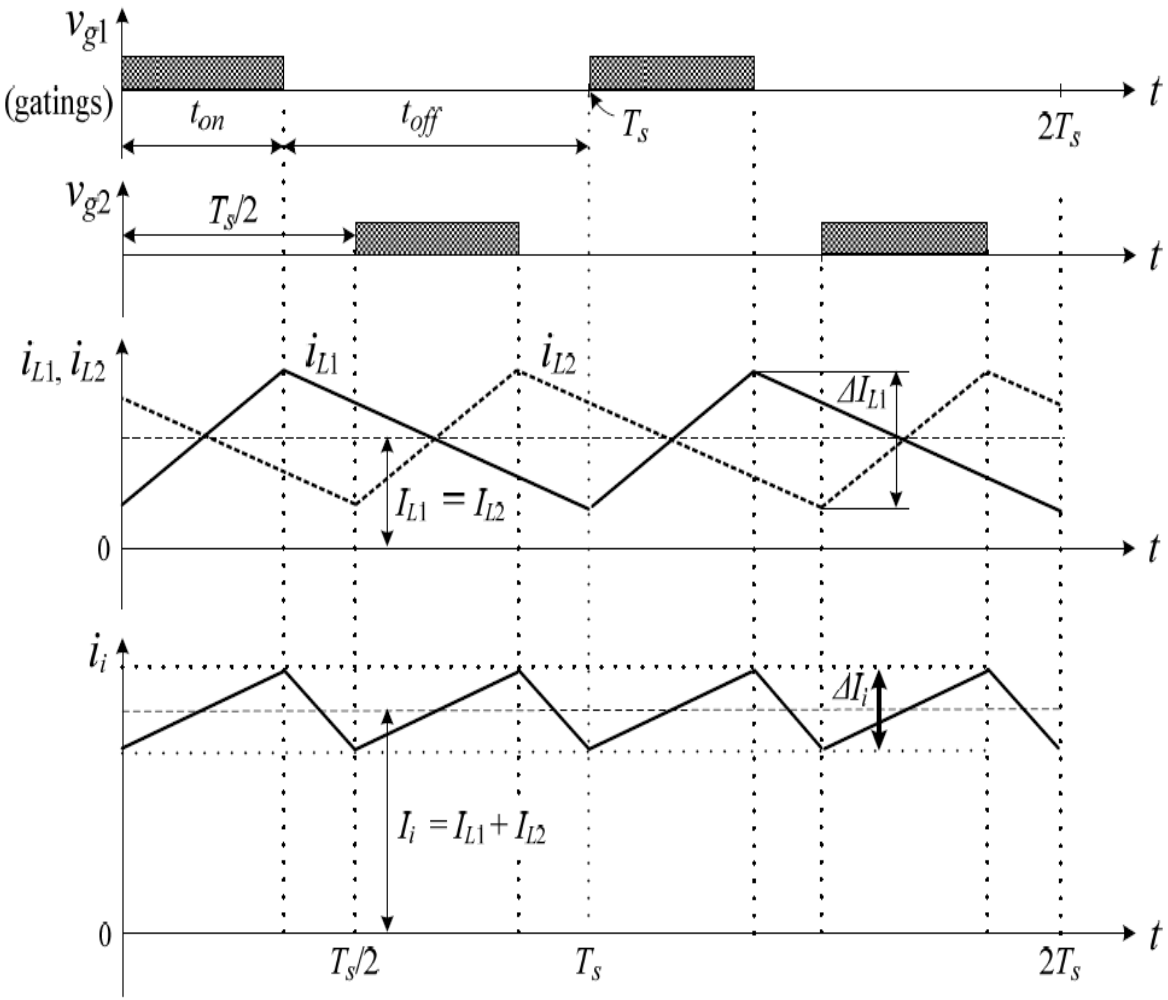
Operation & waveforms of individual converter channels

- Operation & waveforms of individual converter channels are same as those for single-channel converter

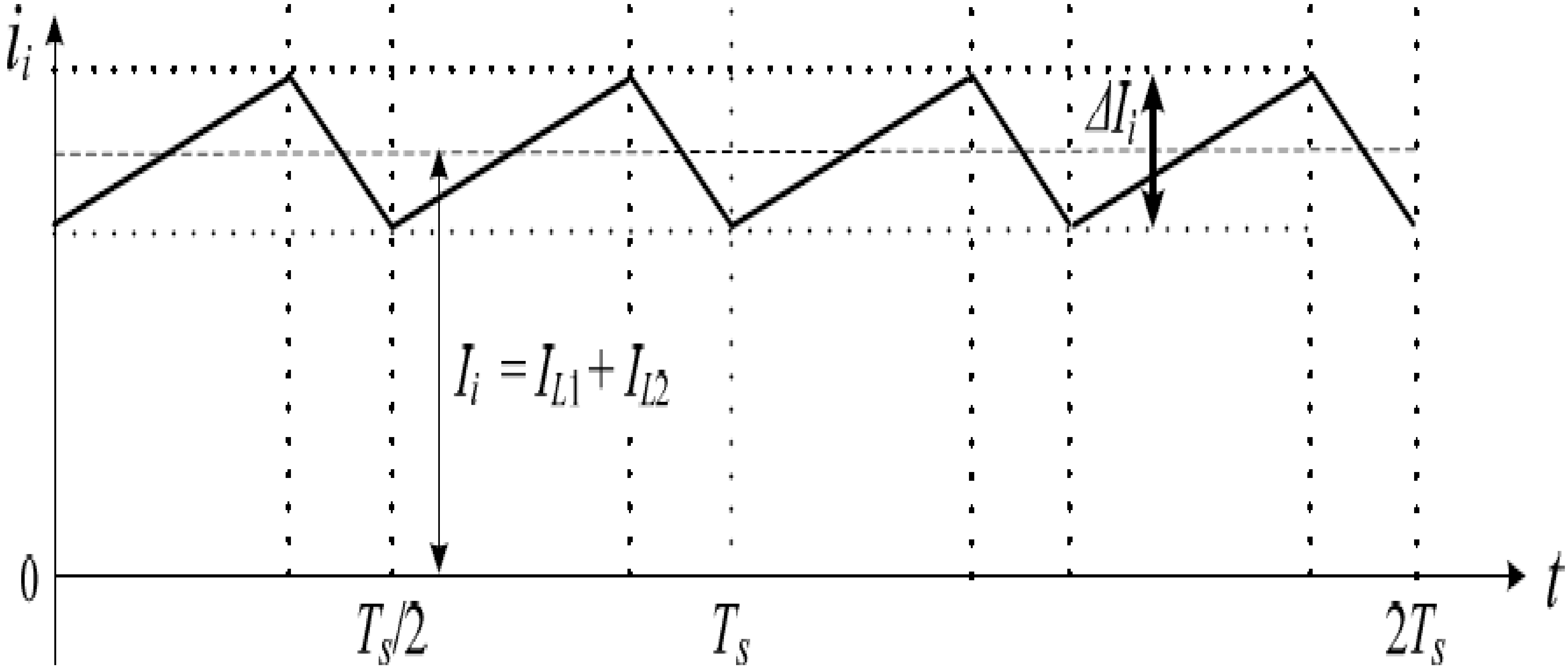
Inductor current waveforms of converter

- By KCL total input current i_i is sum of 2 inductor currents i_{L1} & i_{L2} i.e $i_i = i_{L1+} i_{L2}$

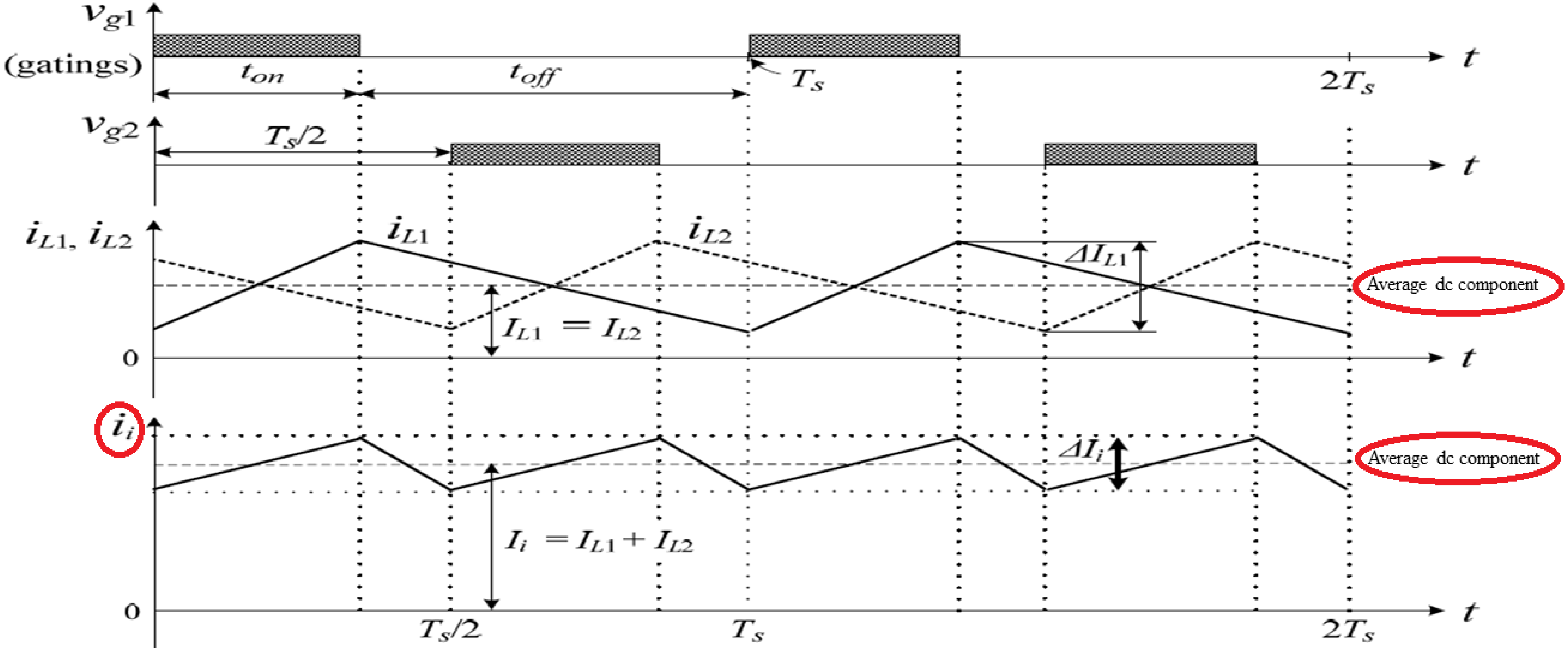




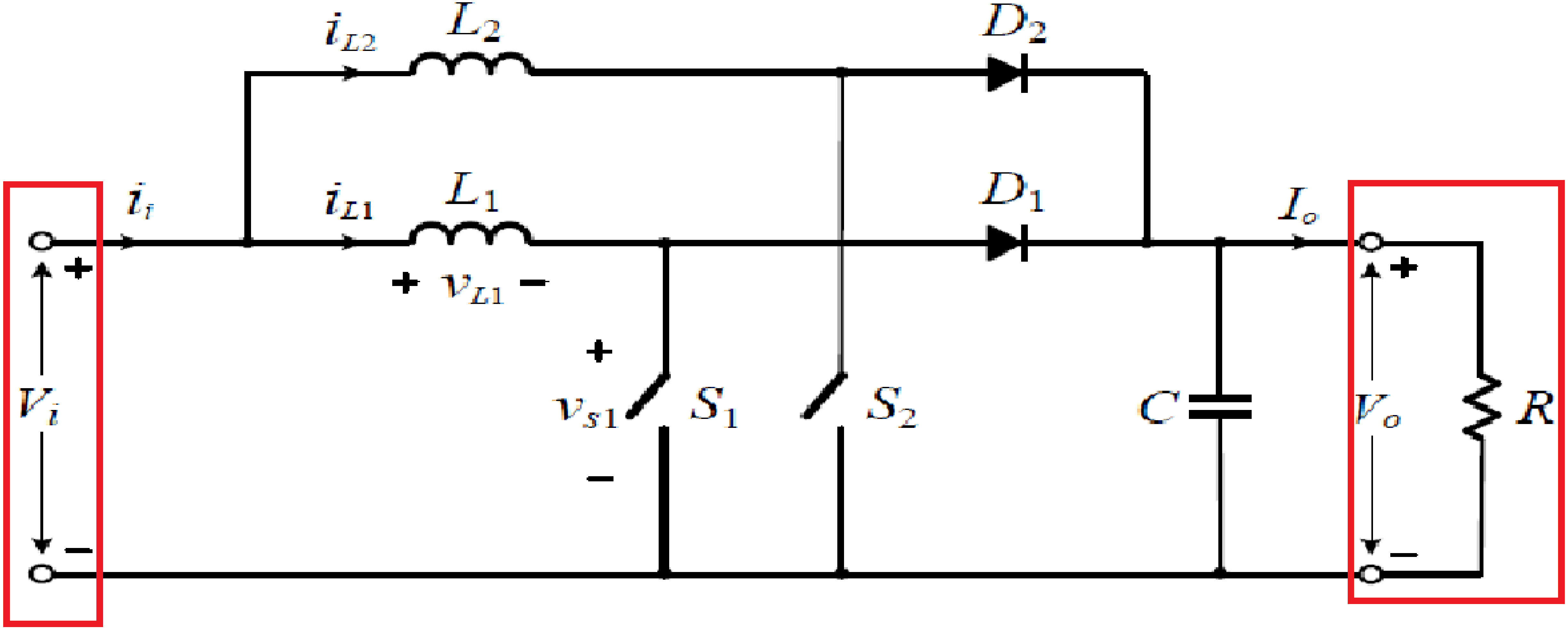
Characteristics of Input current i_i



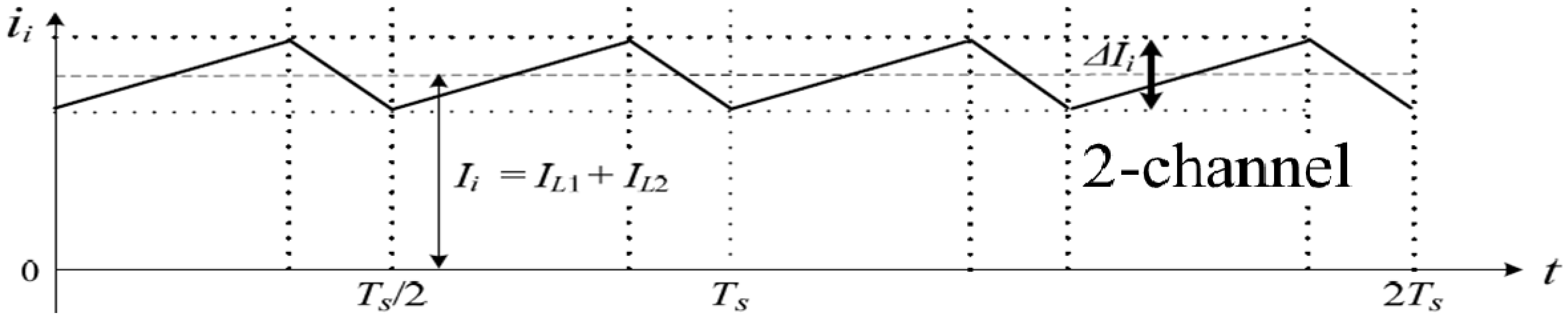
1.Average dc component of input current (Ii) is twice that of individual inductor current ($I_i = I_{L1} + I_{L2}$).

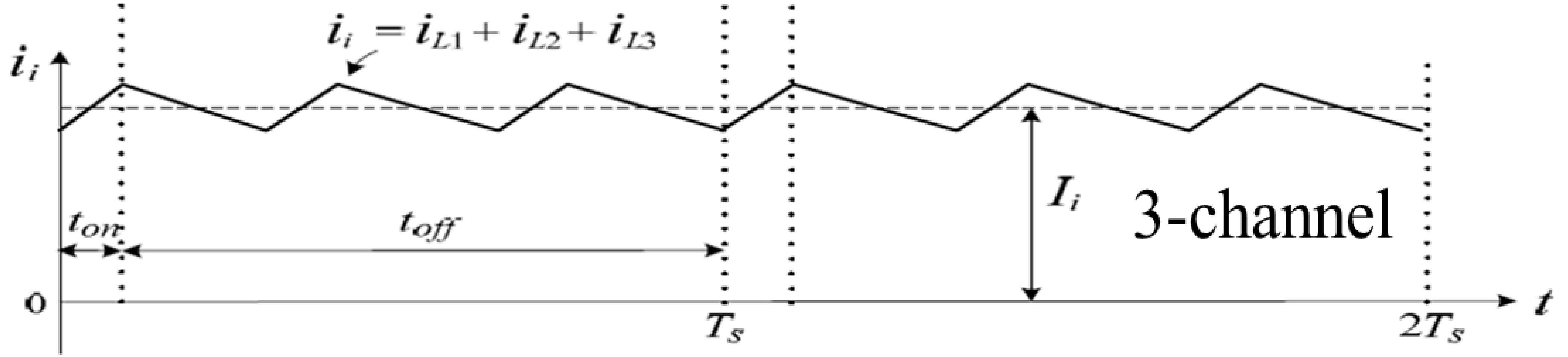


Since input & output voltages for parallel converters are same so each channel handles only ½ of total power to load

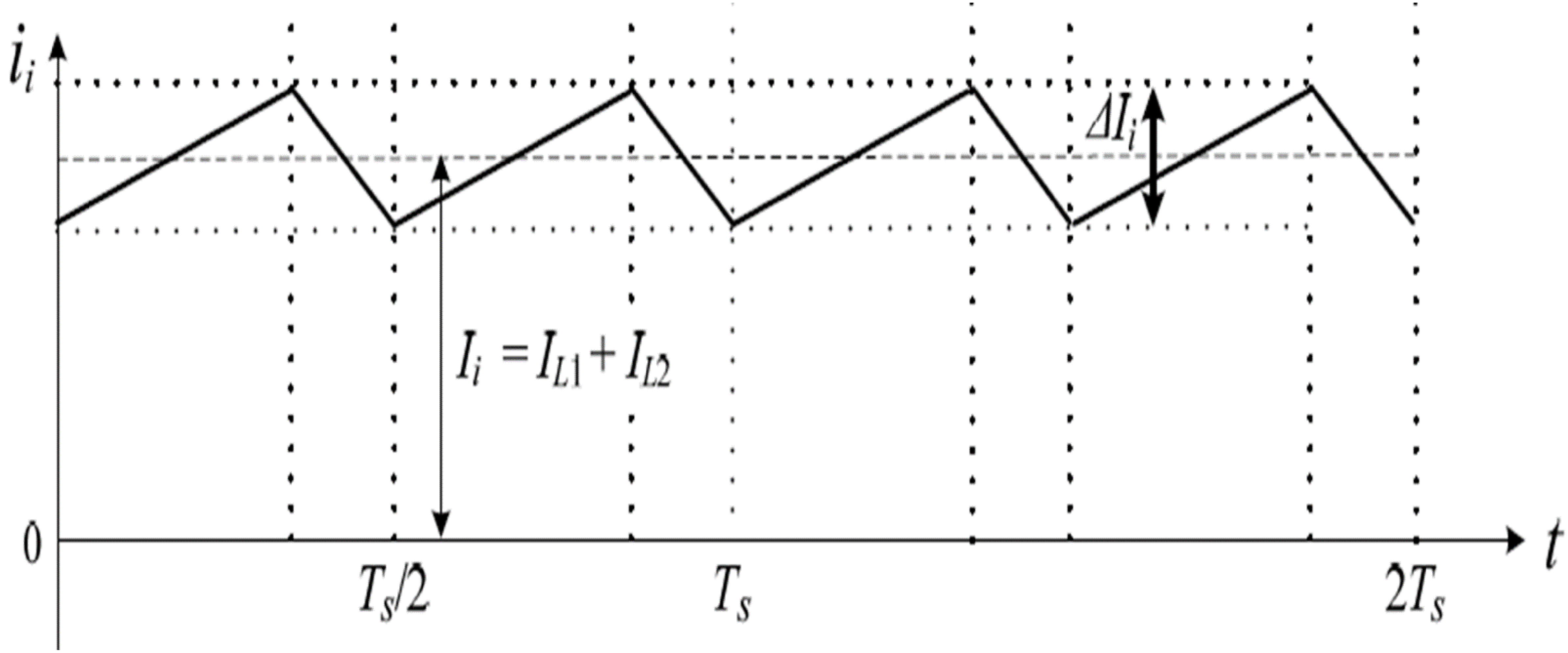


2.Peak-to-peak input current ripple ΔI_i is smaller than that in individual channels due to use of interleaved technique.



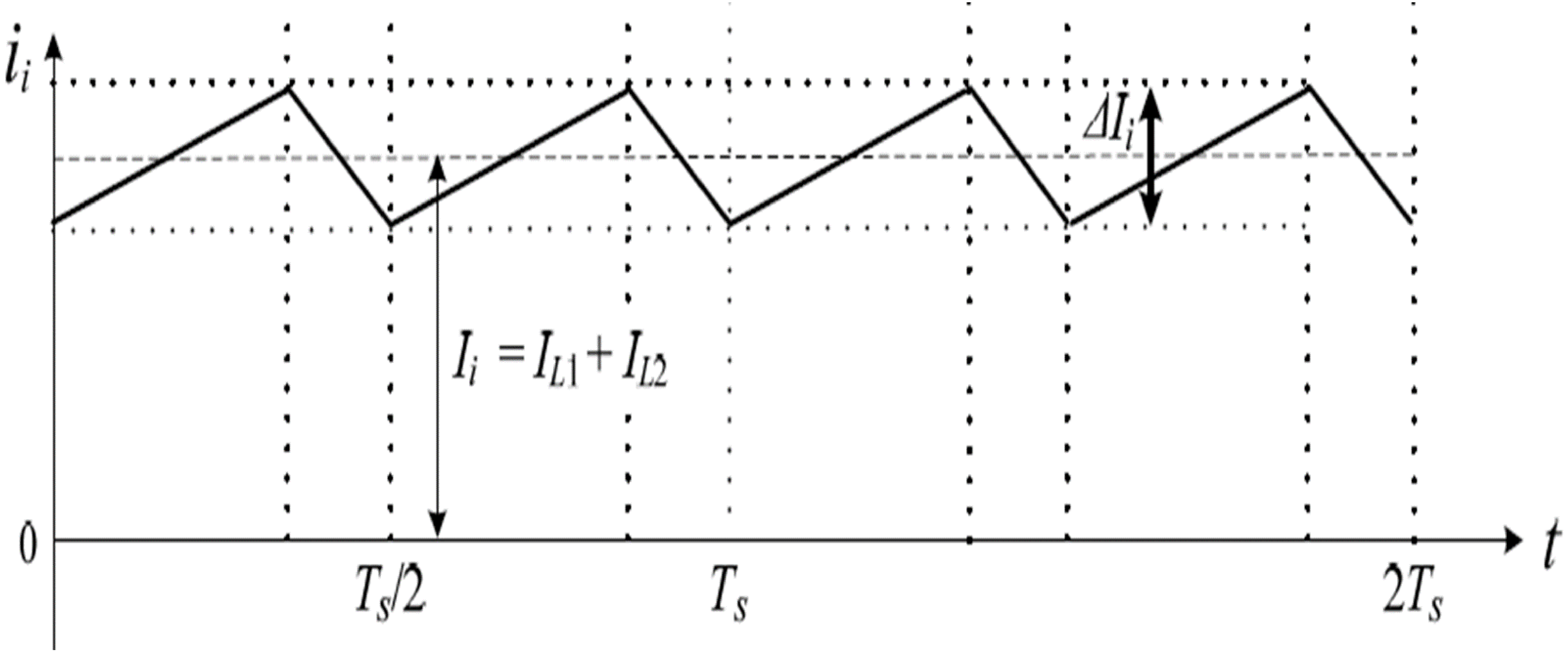


Frequency of input ripple current is twice that of individual channels or equivalent switching frequency of interleaved converter is twice of that of each channel.

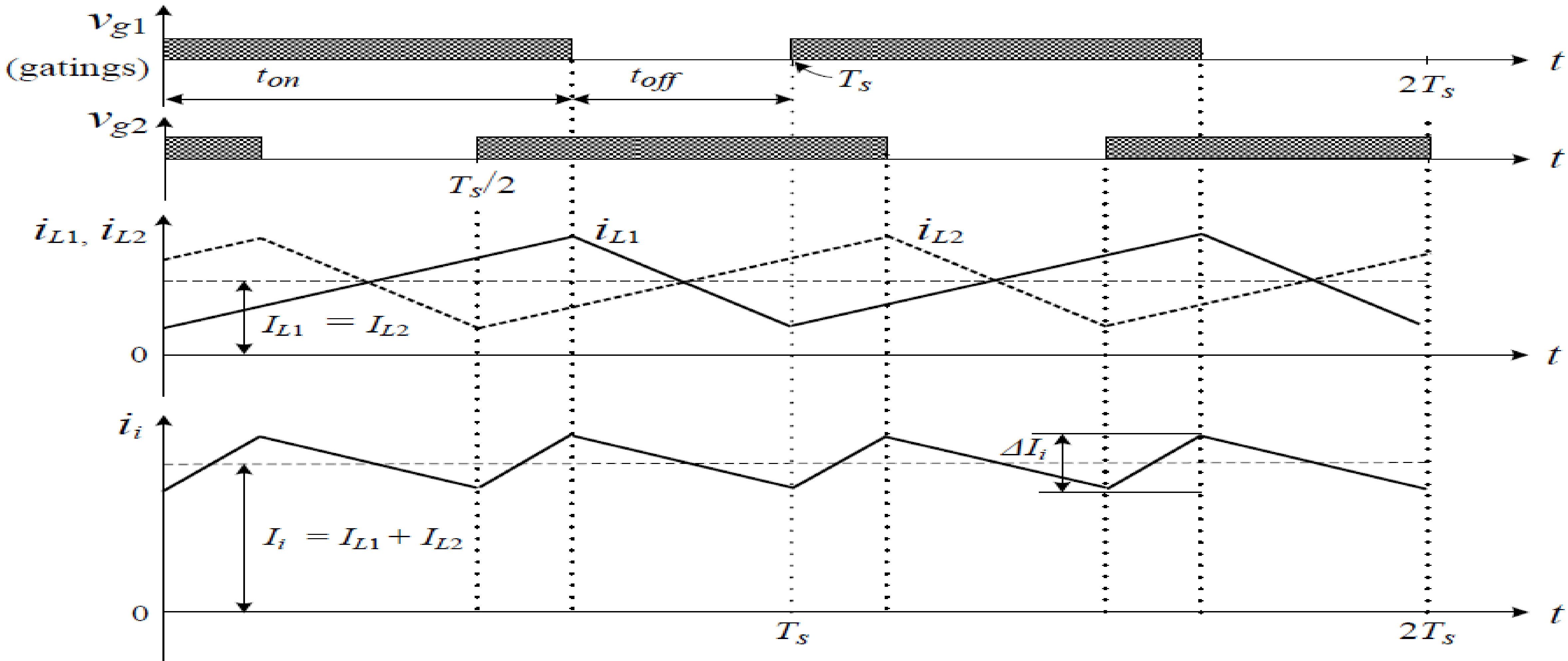


a) Input Current Ripple

Q. When $\Delta I_i = 0$?



When duty cycle D increases from about 0.35-0.5, ripple in 2 inductor currents i_{L1} & i_{L2} cancels each other & does not appear in i_i, i.e, $\Delta I_i = 0$.

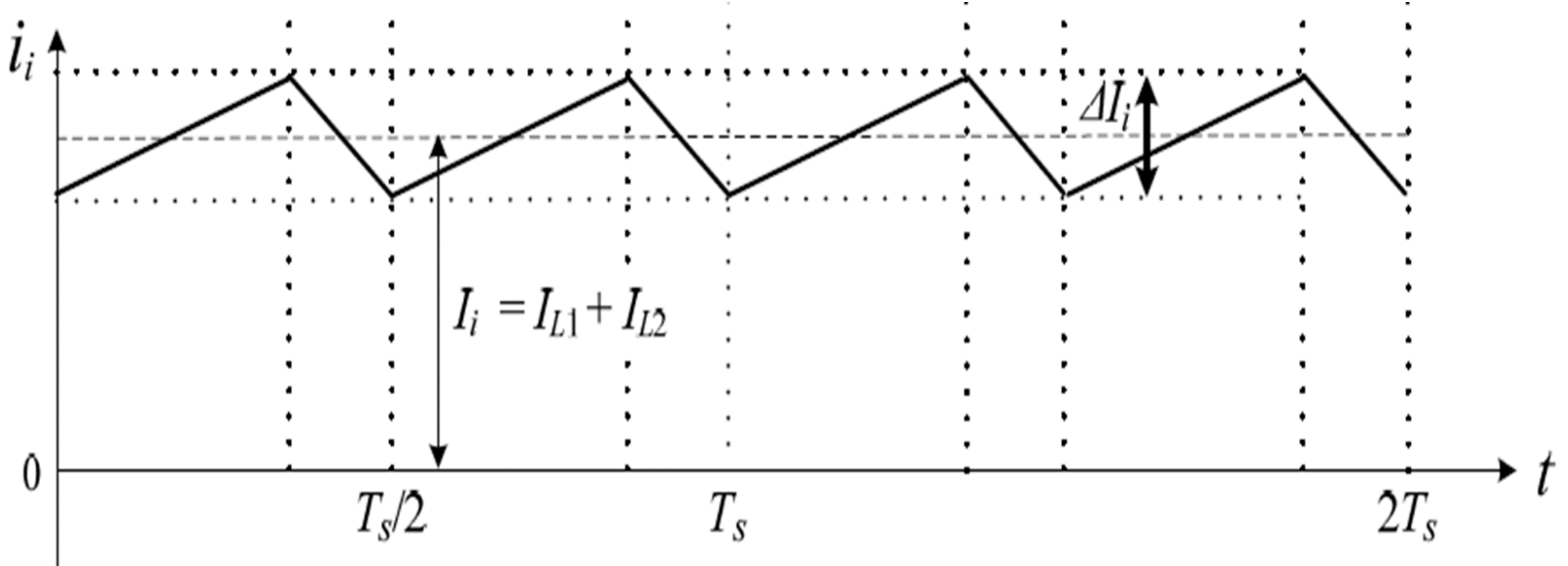


Ripple current starts to increase when $D > 0.5$

- So analysis for input current ripple can be carried out for 2 cases.

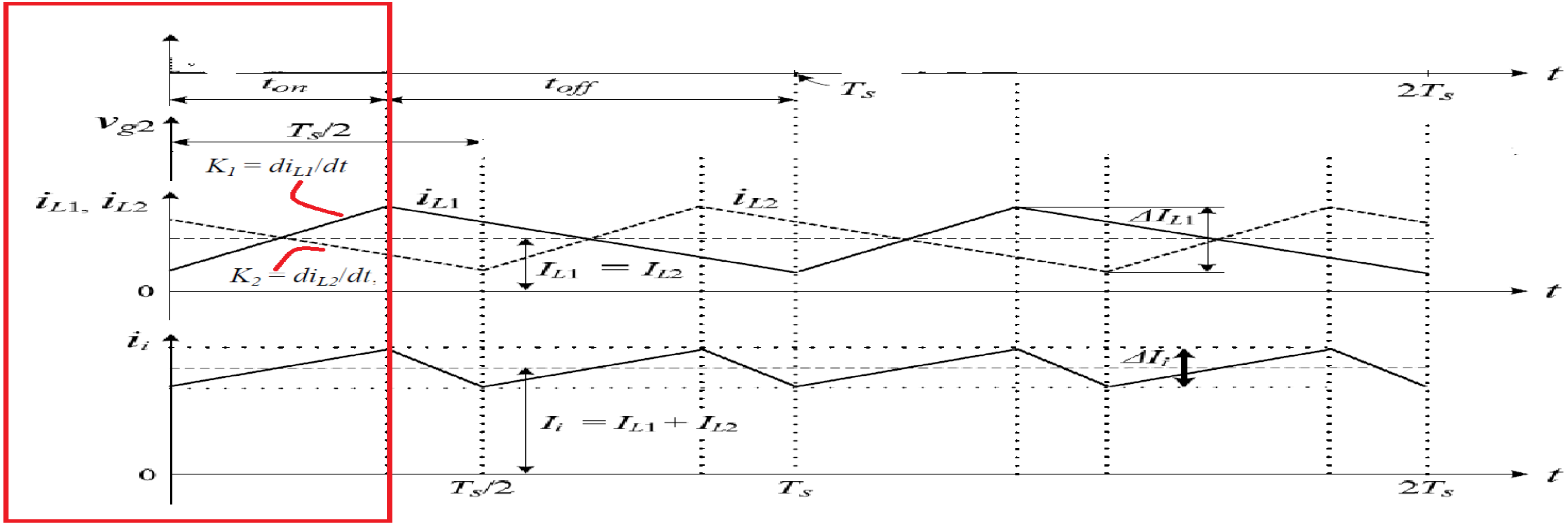
Case 1: $\mathbf{0 < \mathit{D} \leq 0.5}$

Case 2: $\mathbf{0.5 < \mathit{D} < 1}$

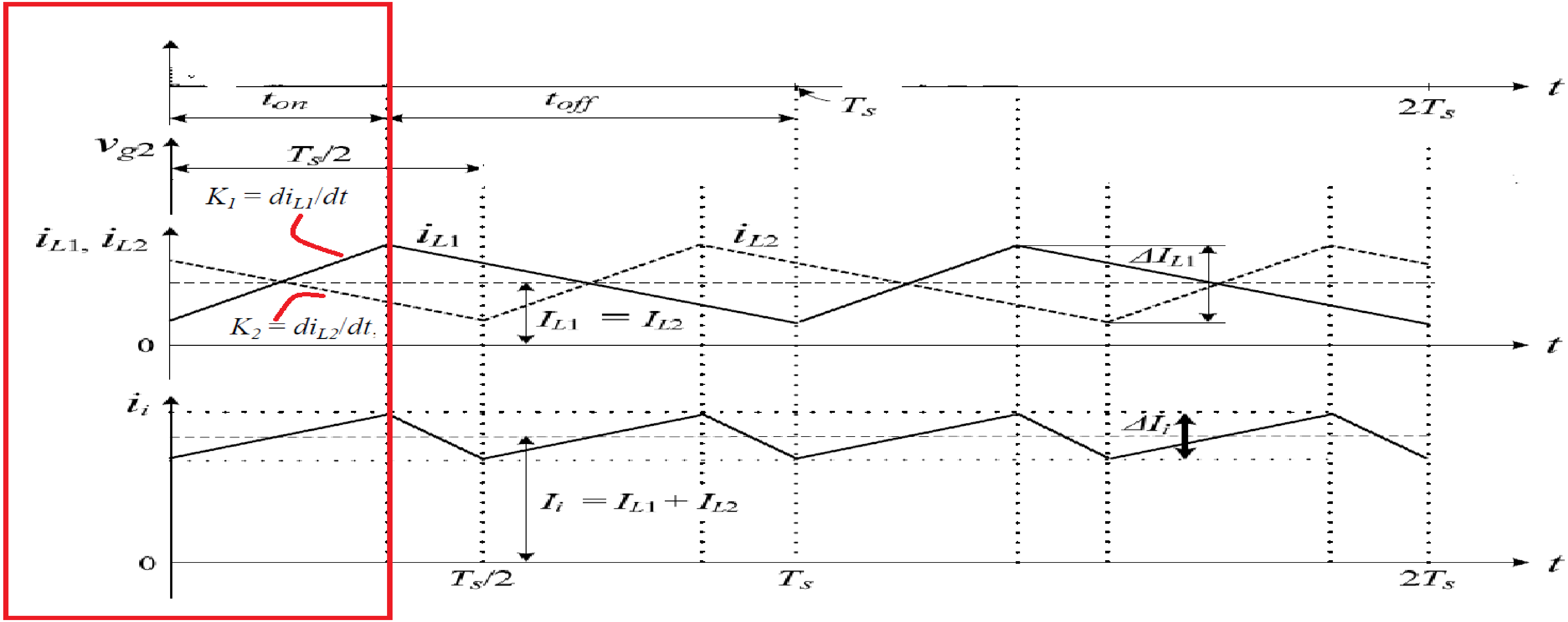


Analyse of input current ripple ΔIi in 2-channel converter. (Case 1: $0 < D \leq 0.5$)

- It is more convenient to perform analysis for t_{on} period, during which total input current i_i increases.

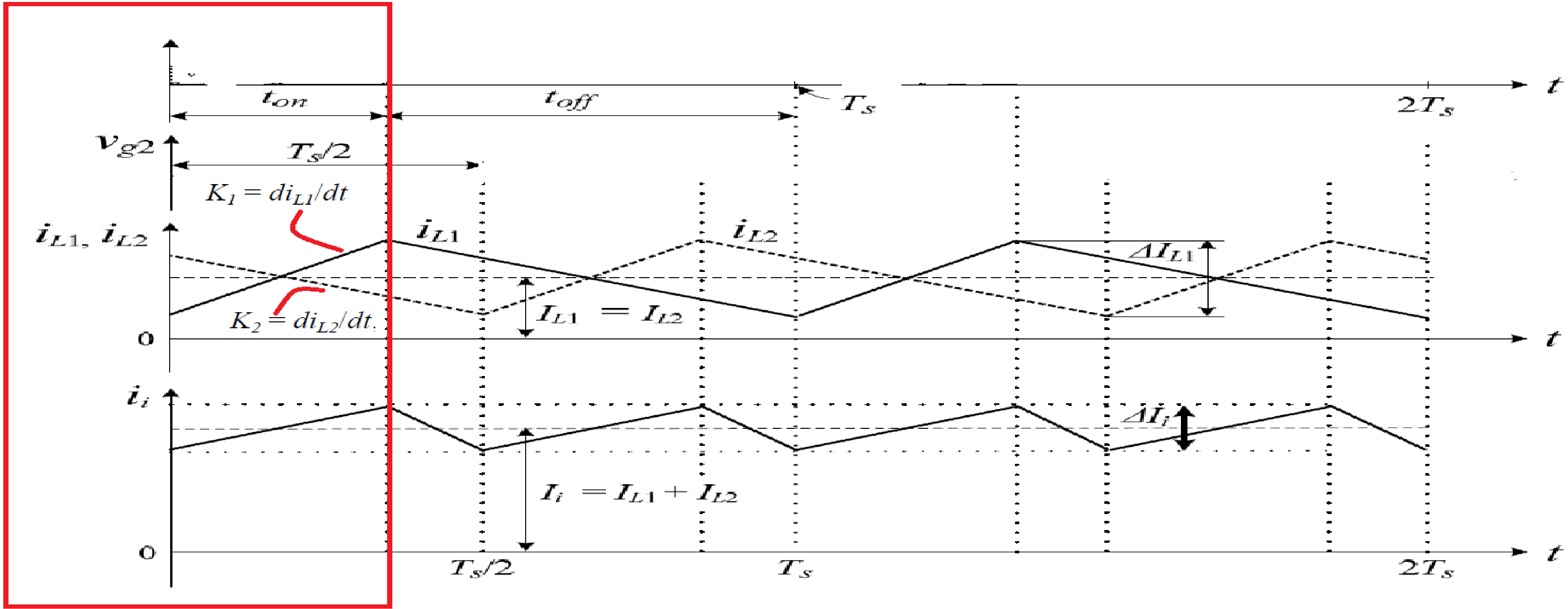


$K_1 = di_{L1}/dt$ & $K_2 = di_{L2}/dt$ are slopes of inductor currents i_{L1} & i_{L2} during charging & discharging process, respectively.



Input current ripple of converter

$$\Delta I_i = (K_1 - K_2)t_{on} = (K_1 - K_2)DT_s$$



$$\Delta I_i = (K_1 - K_2) D T_s$$

$K_1 = di_{L1}/dt$ & $K_2 = di_{L2}/dt$

$V_{Li} = L\, di_{Li}/dt$ & $K_1 = di_{Li}/dt$

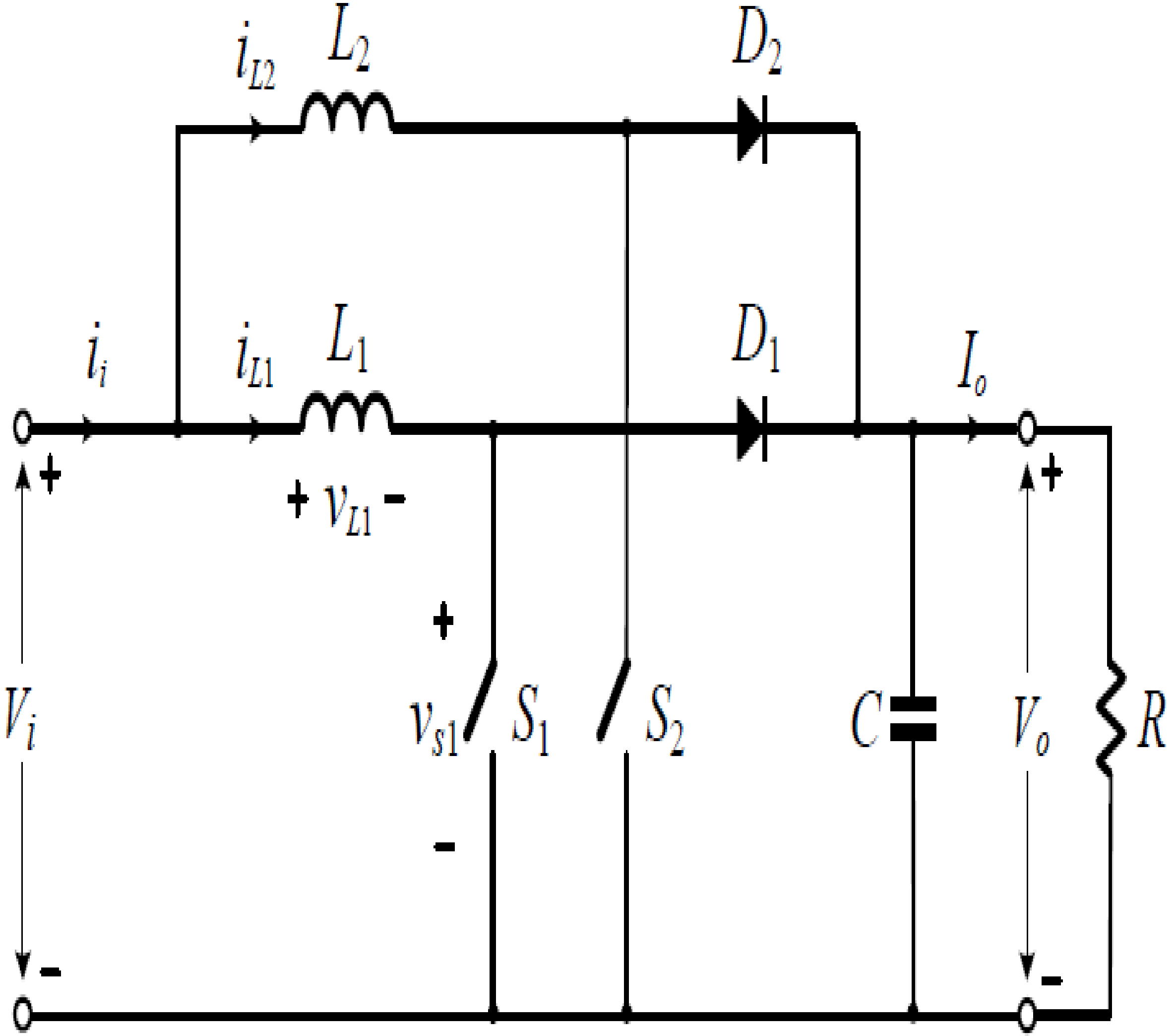
so $V_{Li} = L \times K_1$

Similarly $K_2 = (V_o - V_i)/L$

We know that

$$\frac{V_o}{V_i} = \frac{1}{1-D} \qquad DV_o = (V_o - V_i)$$

$$\Delta I_i = \left(\frac{V_i}{L} - \frac{V_o - V_i}{L}\right)\left(1 - \frac{V_i}{V_o}\right) T_s$$



Maximum input current ripple $\Delta Ii,_{\max}$ can be determined by differentiating the equation with respect to *Vi[**partial derivative**]*

$$\Delta I_i = \left(\frac{V_i}{L} - \frac{V_o - V_i}{L} \right)\left(1 - \frac{V_i}{V_o} \right) T_s$$

$$\frac{\partial \Delta I_i}{\partial V_i} = \left(\frac{2V_i - V_o}{L} \right)\left(1 - \frac{V_i}{V_o} \right) T_s = 0$$

Find Vi and D from

$$\frac{\partial \Delta I_i}{\partial V_i} = \left(\frac{2V_i - V_o}{L} \right) \left(1 - \frac{V_i}{V_o} \right) T_s = 0$$

Vi & D from

$$\frac{\partial \Delta I_i}{\partial V_i} = \left(\frac{2V_i - V_o}{L}\right)\left(1 - \frac{V_i}{V_o}\right)T_s = 0$$

$$V_i = \frac{3}{4}V_o \text{ and } D = 0.25 \quad \text{for } \Delta I_i = \Delta I_{i,\max}$$

Maximum current ripple $\Delta I_{i,\max}$ can be found by substituting

$$V_i = \frac{3}{4}V_o \text{ and } D = 0.25$$

$$\Delta I_i = \left(\frac{V_i}{L} - \frac{V_o - V_i}{L}\right)\left(1 - \frac{V_i}{V_o}\right)T_s$$

$$\Delta I_{i,\max} = \frac{V_o T_s}{8L}$$

Maximum current ripple $\Delta I i,_{\max}$ in 2-channel boost converter=½ of single-channel converter for $D \leq 0.5$.

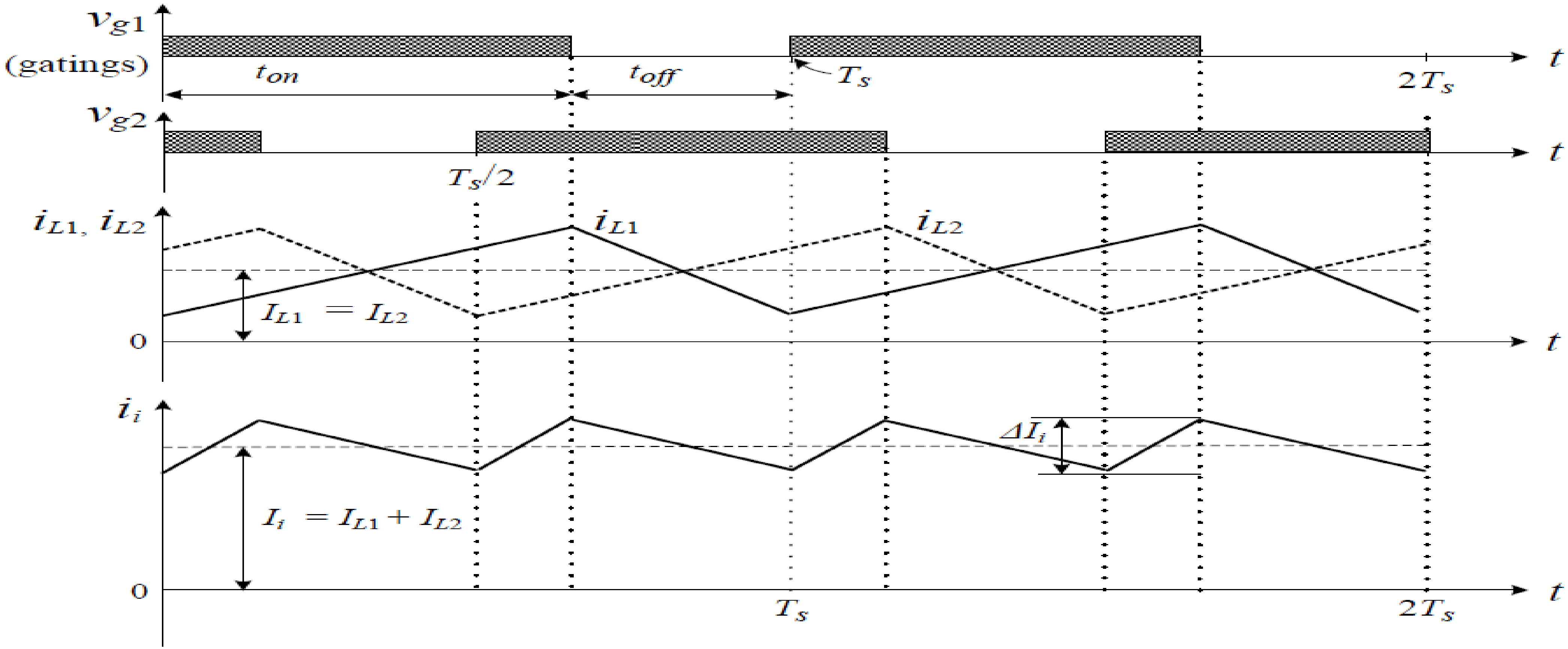
Compared both equation:

$$\Delta I_{i,\max} = \frac{V_o T_s}{8L}$$

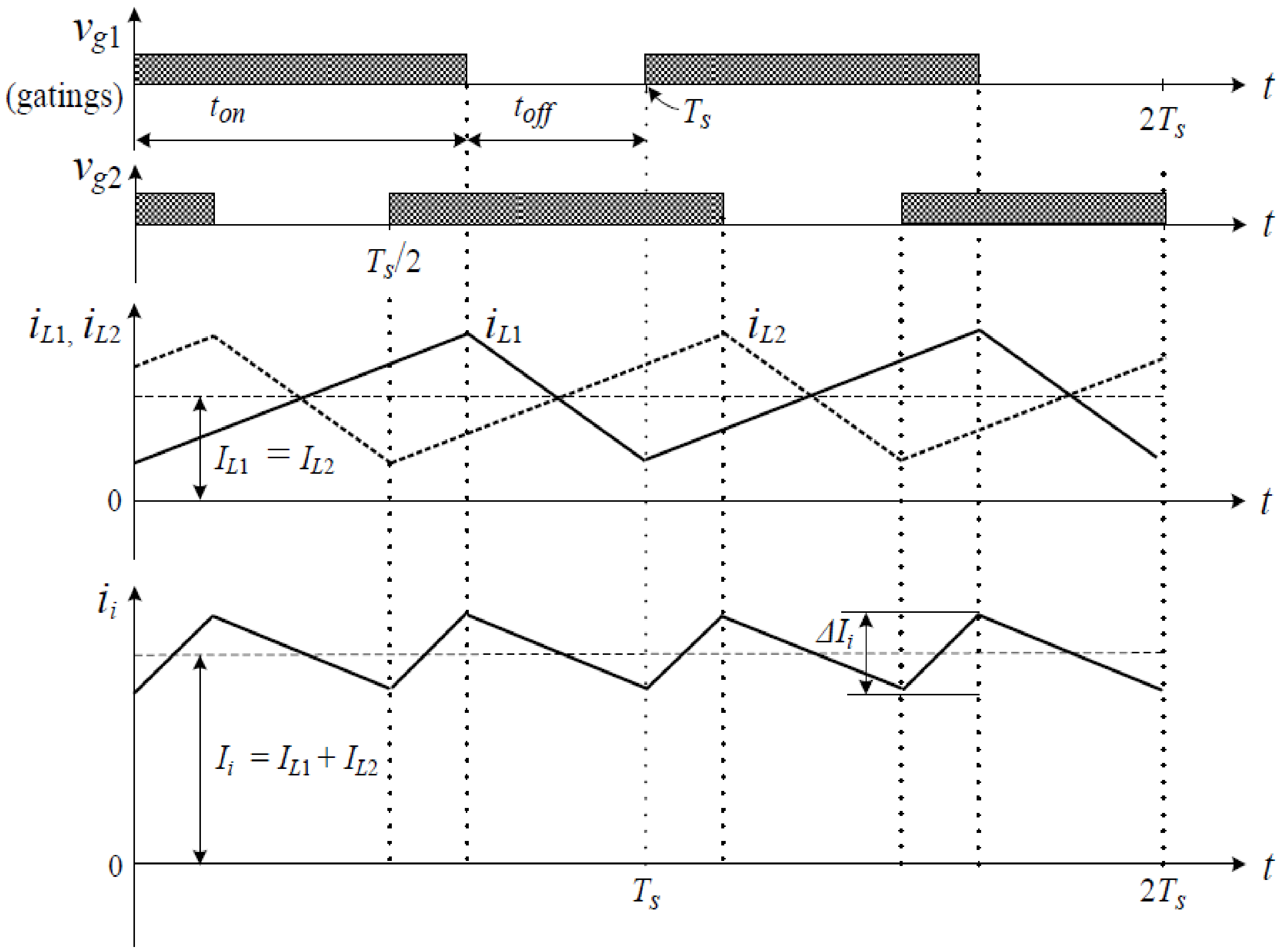
$$\Delta I_{L1,\max} = \frac{V_o T_s}{4L}$$

Case 2: $0.5 < D < 1$

Waveforms for analysis of input ripple current in 2-channel interleaved converter ($D > 0.5$).



It is more convenient to perform analysis for t_{off} period, during which the input current i_i decreases. Input current ripple can be determined by:



$$\Delta I_i = (K_2 - K_1)t_{off} = (K_2 - K_1)(1-D)T_s$$

$$= \left(\frac{V_0 - V_i}{L} - \frac{V_i}{L}\right)\left(\frac{V_i}{V_0}\right)T_s = (2D-1)(1-D)\frac{V_0 T_s}{L}$$

Following same procedure, maximum input current ripple $\Delta Ii,_{\max}$ can be determined for t_{off} period.

$$\Delta I_{i,\max} = \frac{V_o T_s}{8L}$$

Based on these equations, input current ripple *ΔIi* for single-channel (*N* = 1) & 2-channel (*N* = 2) converter versus duty cycle *D* is given in Fig.

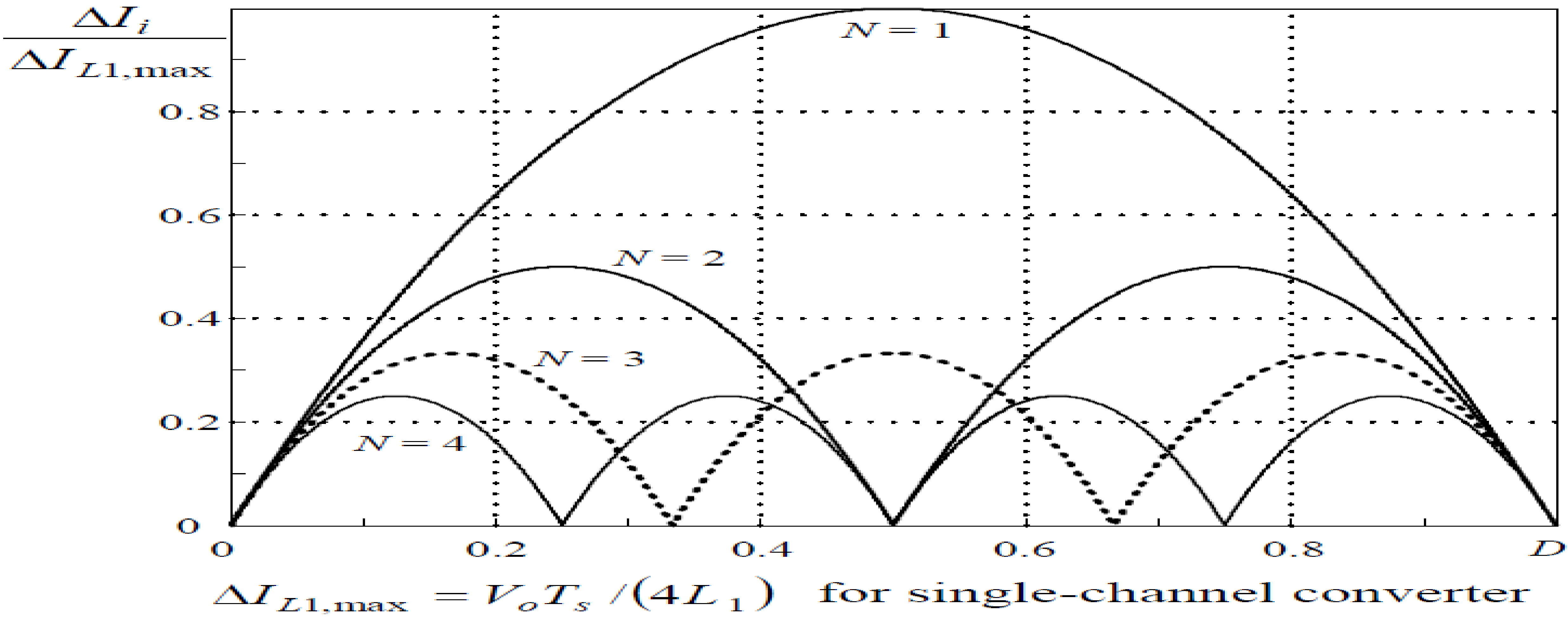
$$\frac{I_o}{I_i} = 1 - D \qquad \text{for} \quad 0 \le D < 1$$

$$\Delta I_i = \left(\frac{V_i}{L} - \frac{V_o - V_i}{L}\right)\left(1 - \frac{V_i}{V_o}\right)T_s = (1 - 2D)D\frac{V_o T_s}{L}$$

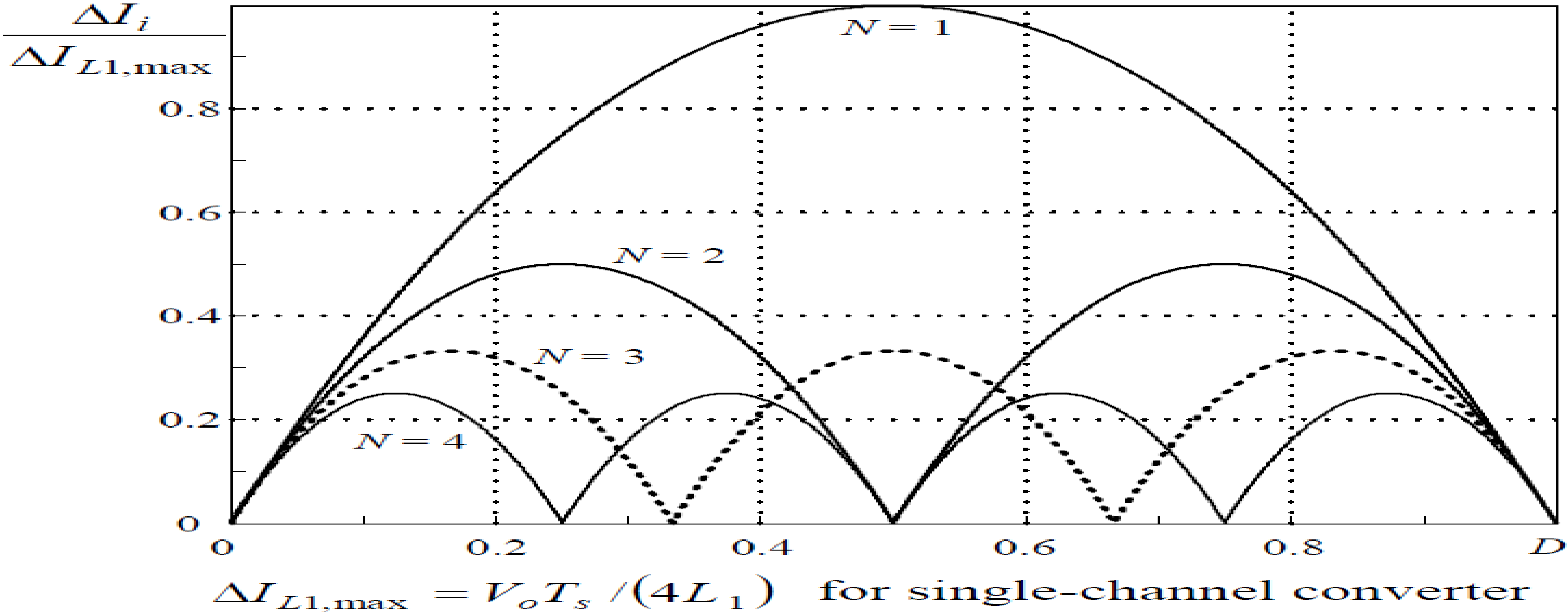
$$\Delta I_i = (K_2 - K_1)t_{off} = (K_2 - K_1)(1 - D)T_s$$

$$= \left(\frac{V_o - V_i}{L} - \frac{V_i}{L}\right)\left(\frac{V_i}{V_o}\right)T_s = (2D - 1)(1 - D)\frac{V_o T_s}{L}$$

It is shown that magnitude of input ripple current for 2-channel converter is much lower than that in single-channel converter.



In particular, ripple current for 2-channel converter becomes 0 at D = 0.5 whereas it reaches its maximum value for single-channel converter.

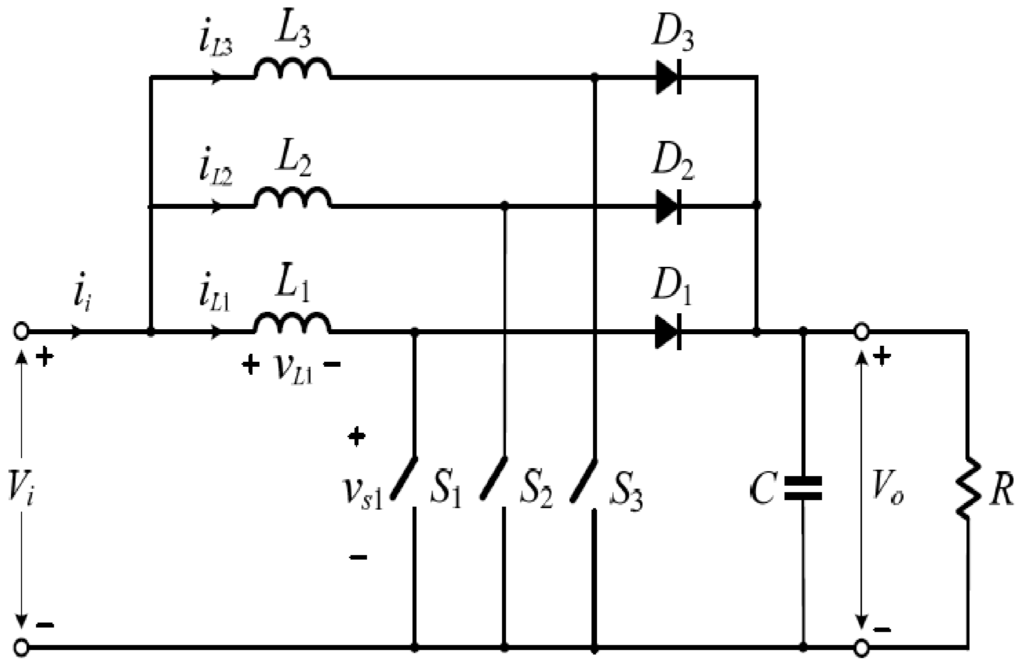


b) Output Voltage Ripple

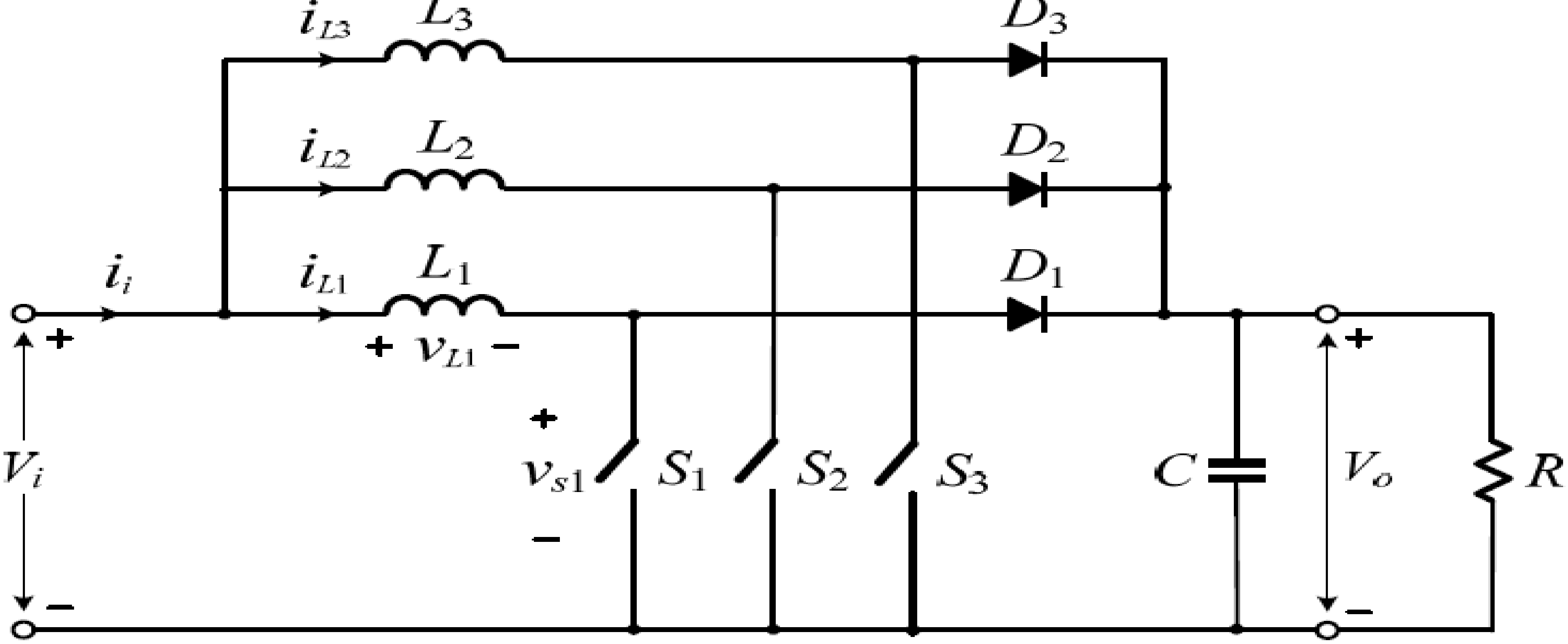
- As mentioned earlier, one of the benefits for interleaved converters is reduction of output ripple.
- In 2-channel converter, 2 parallel converters share same output capacitor *C*, which makes analysis a little tedious.
- Computer simulation techniques can be used to determine output voltage ripples.

4.3.3 Multi-channel Interleaved Boost Converters

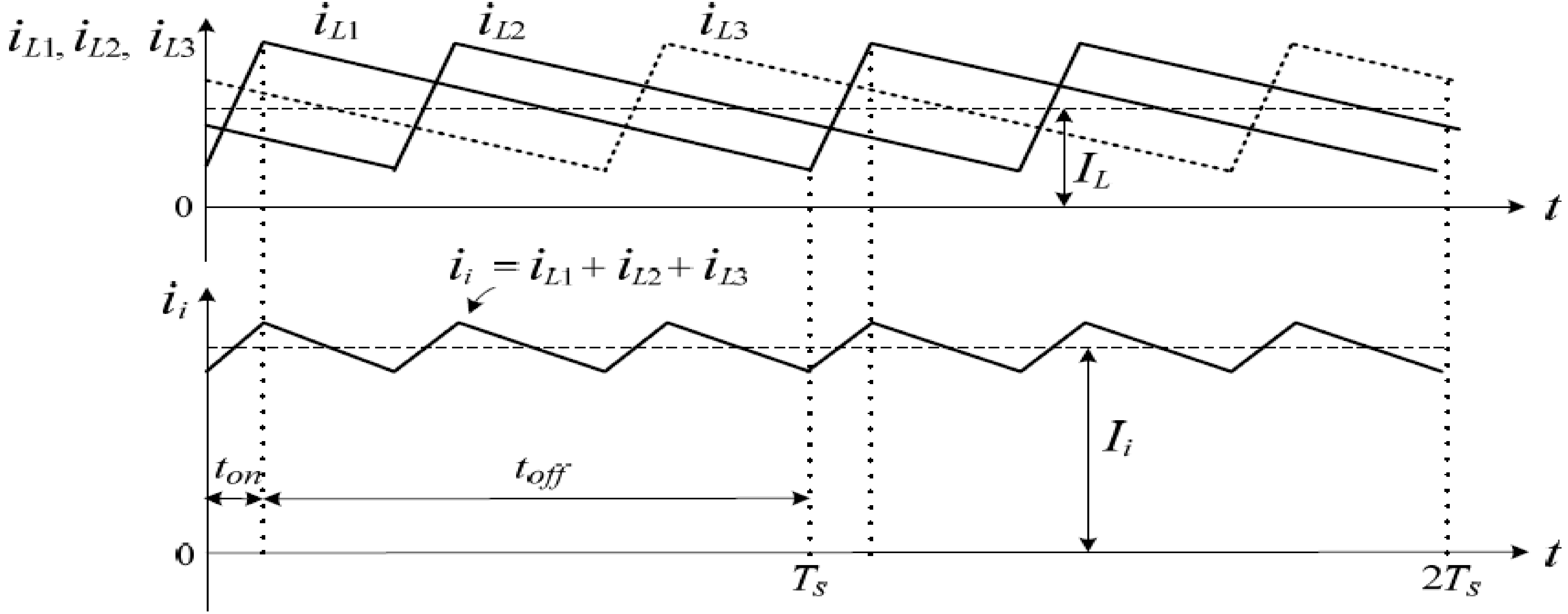
- Fig. shows converter topology for a 3-channel boost converter interleaved by 360°/N = 120°.
- It is essentially composed of 3 single-channel converters connected in parallel and operating in the interleaving manner.



Gate signals for converters are identical except a time delay of *Ts*/3 among converters.



It can be observed that frequency of converter input current *ii* is 3 times that of individual converters.

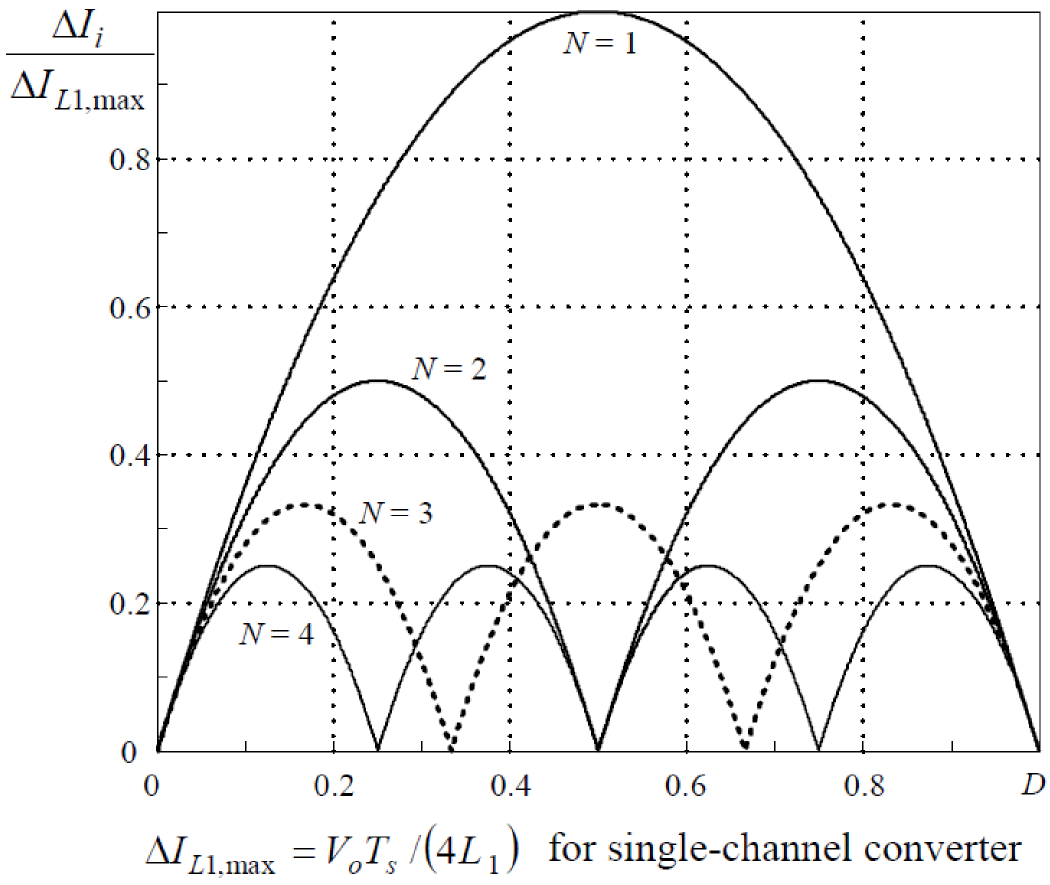


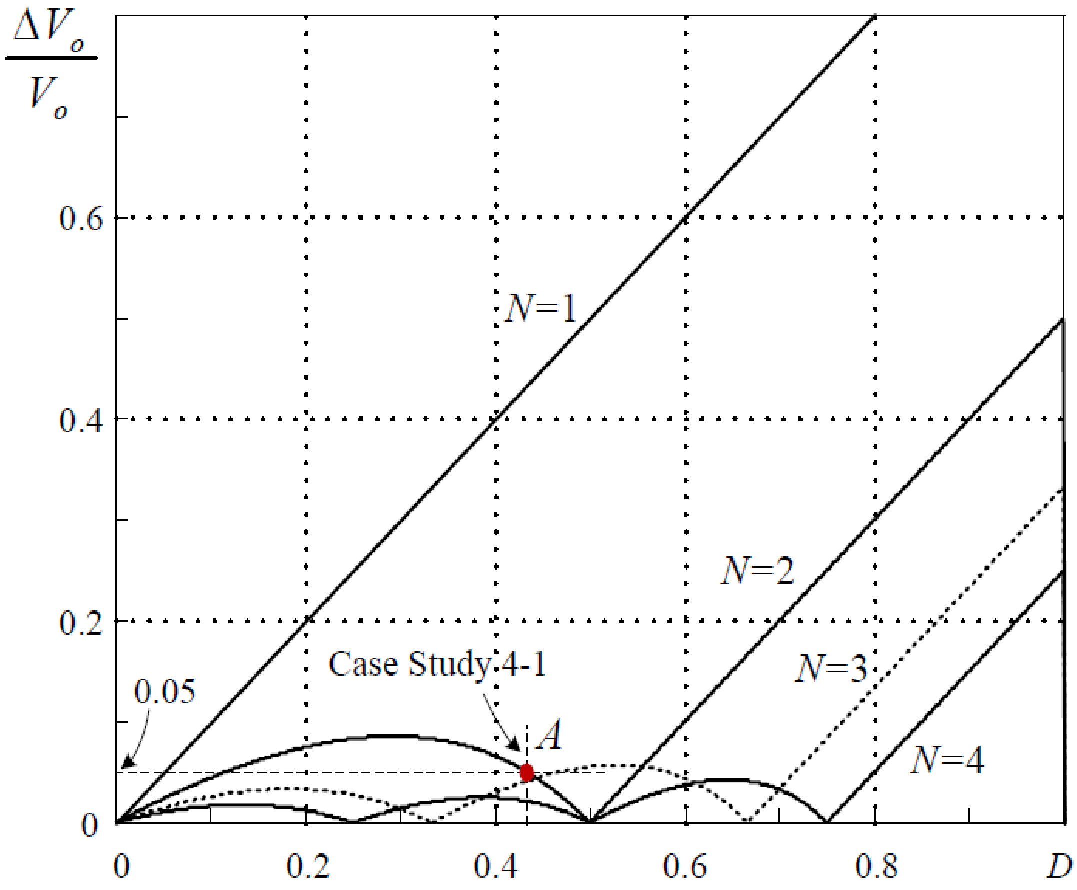
Following same procedure presented for 2-channel converters, input current ripple in 3-channel converter can be derived & given by

$$\Delta I_i = \begin{cases} (1-3D)D\dfrac{V_o T_s}{L} & \text{for } 0 \le D < \dfrac{1}{3} \\ \left(3D(1-D)-\dfrac{2}{3}\right)\dfrac{V_o T_s}{L} & \text{for } \dfrac{1}{3} \le D < \dfrac{2}{3} \\ (3D-2)(1-D)\dfrac{V_o T_s}{L} & \text{for } \dfrac{2}{3} \le D < 1 \end{cases}$$

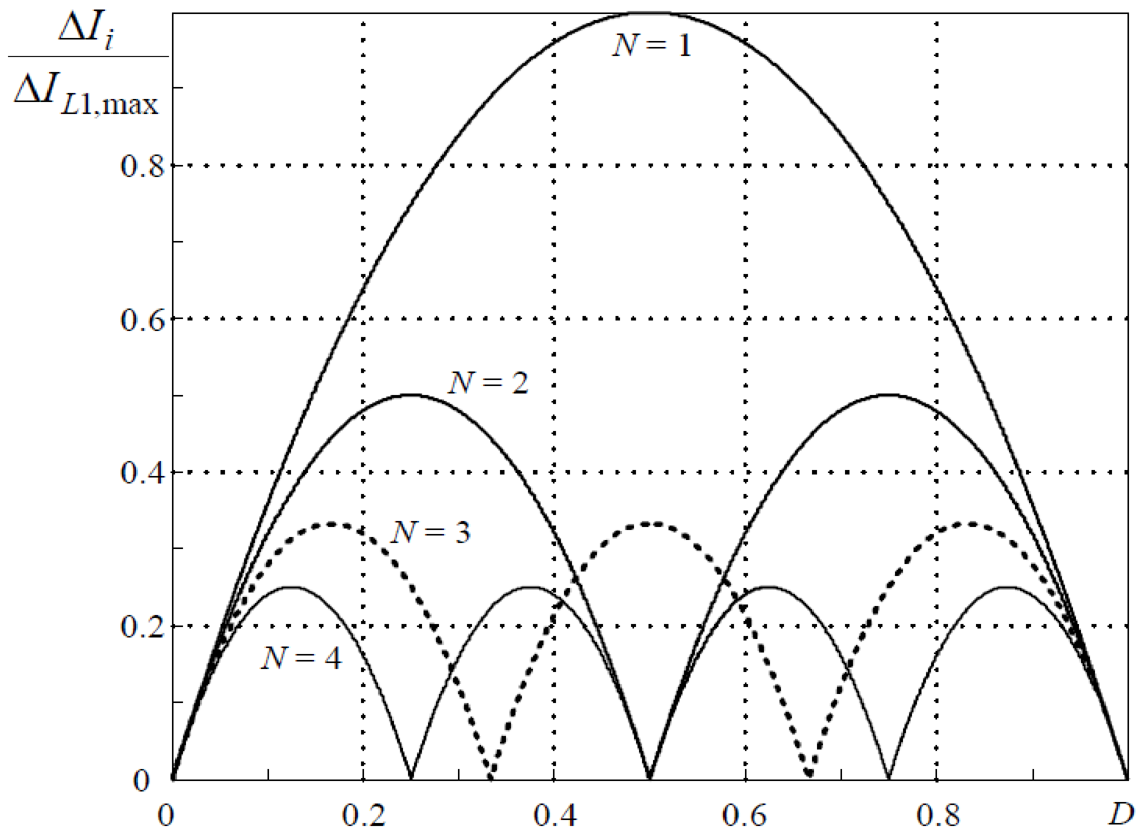
where L is inductance of each converter channel, that is, $L = L1 = L2 = L3$.

Input current ripple ΔIi & output voltage ripple ΔVo for 3 & 4 channel interleaved converters are illustrated in Figs.

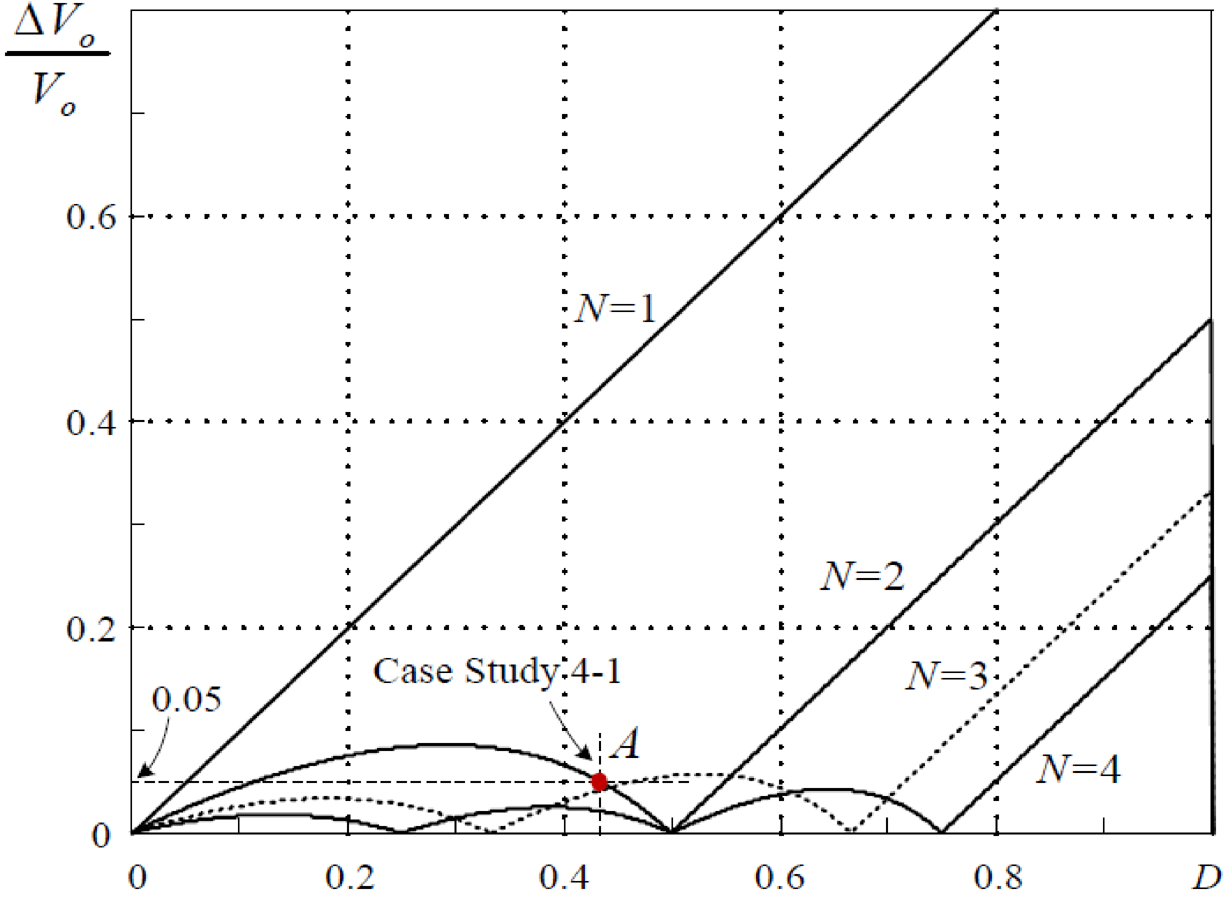




These current & voltage ripples are further reduced in comparison to those in 1- & 2-channel converters. As a result, size and cost of input & output filters can be further reduced.



$\Delta I_{L1,\max} = V_o T_s / (4L_1)$ for single-channel converter

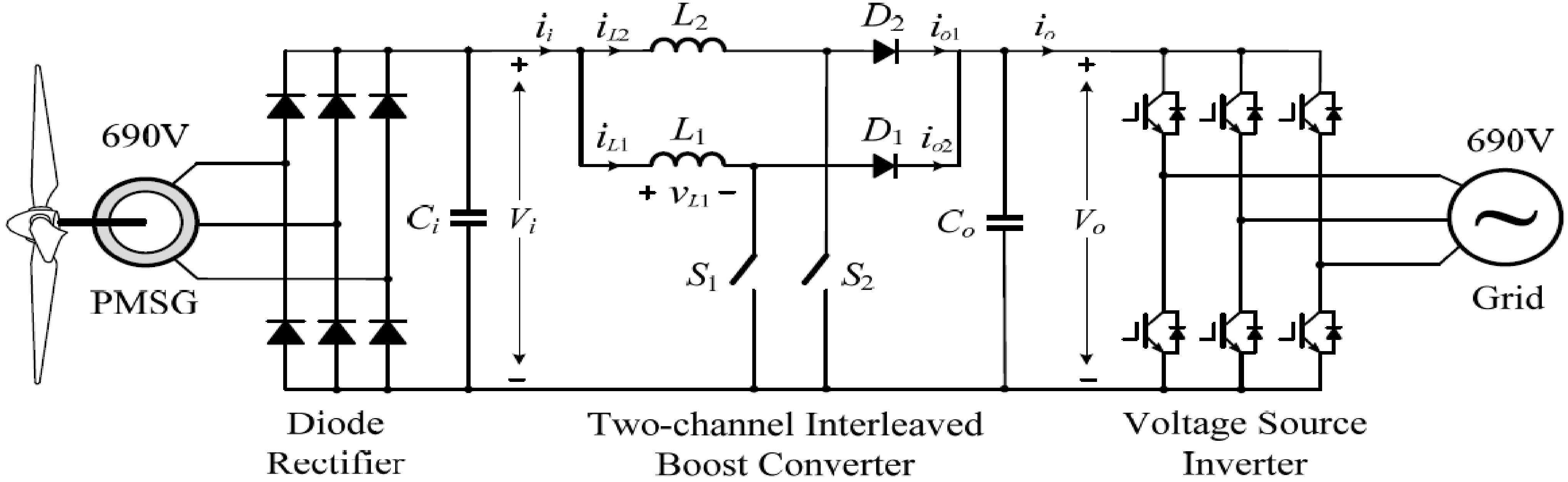


Practical wind energy conversion systems

- In practical wind energy conversion systems, maximum power rating for each converter channel is around 500kW to 600kW.
- For a 1.5MW WECS, 3 interleaved converters are required.

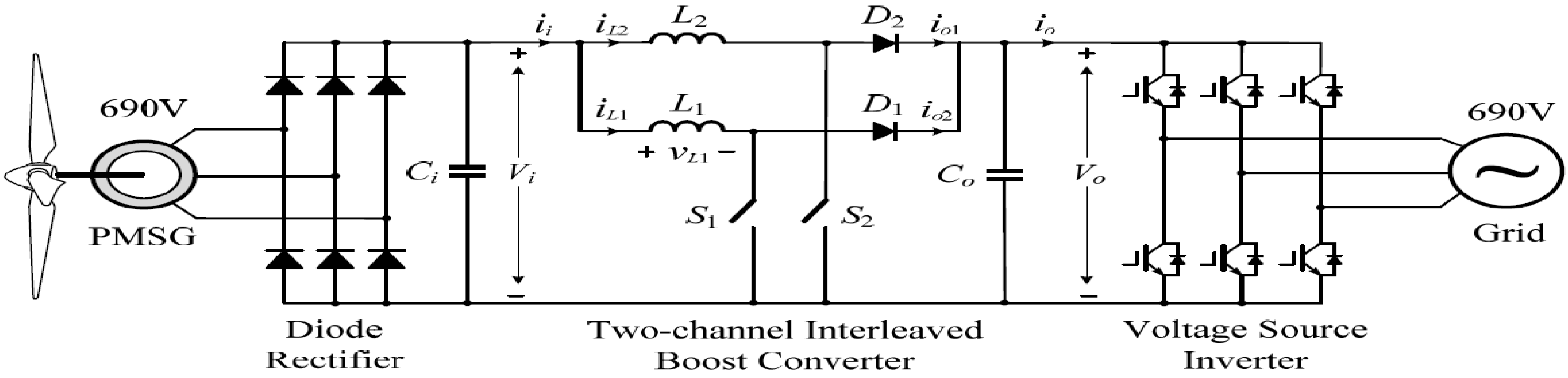
Case Study 4-1 PMSG Wind Energy System with a 2-channel Interleaved Boost Converter

- 1.2MW/690V permanent magnetic synchronous generator (PMSG) based wind energy conversion system is shown in Fig. , where 2-channel interleaved boost converter & a PWM voltage source inverter is employed.

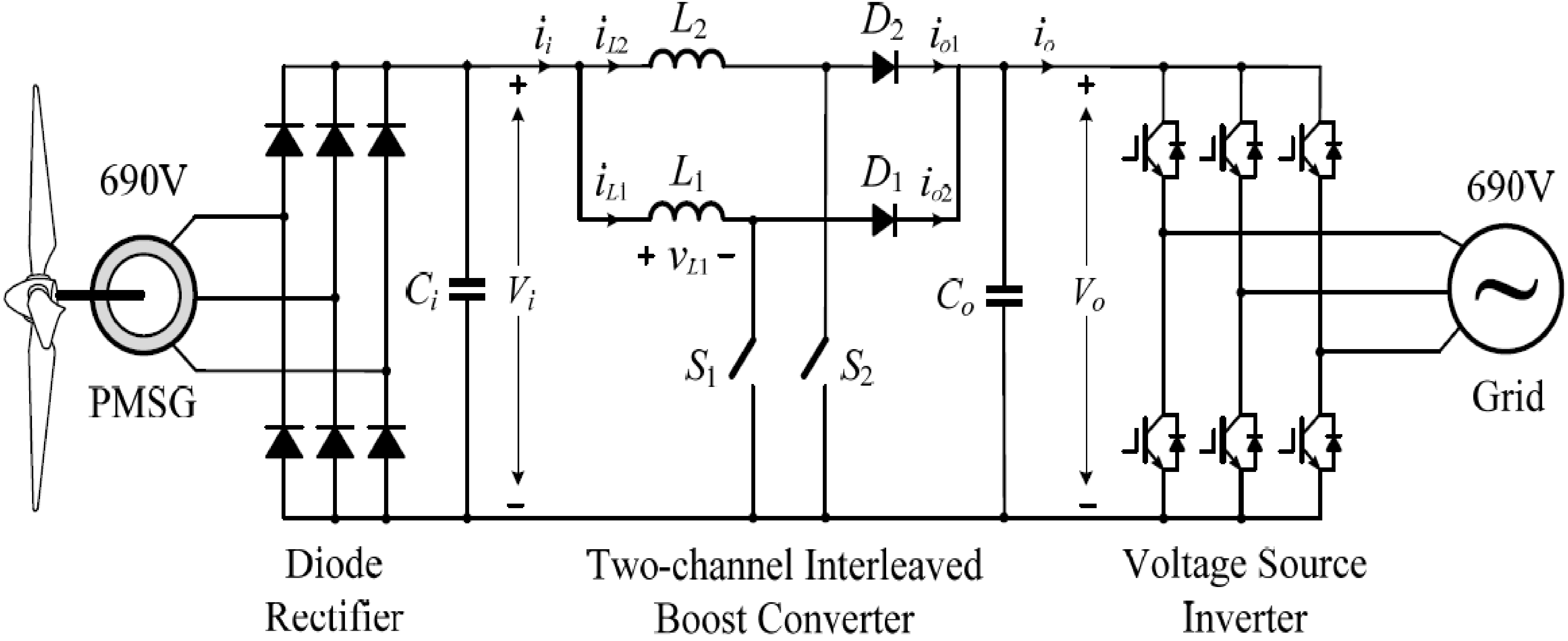


Boost converter provides 02 main functions:

1) Boost its input dc voltage *Vi* to a higher dc voltage *Vo* at its output, and
2) Perform maximum power point tracking (MPPT) such that system can deliver its maximum possible power captured by turbine to grid at any wind speeds.



Main function of inverter is to keep its input dc voltage, which is output of boost converter, at a fixed value & also to control reactive power to grid.



At a given wind speed, generator operates at a speed=0.7pu & delivers 412kW (0.73pu) power to grid. Input voltage of boost converter *Vi*=680V.

- Output voltage of boost converter *Vo* is kept at a constant value of 1200V by inverter, which is a voltage required to deliver power to grid of 690V (refer to Section 4.7 for details).
- Inductance of 2-channel converter is $L = L1 = L2 = 270\mu H$, & capacitance of output filter capacitor *Co* is 300µF, respectively. Boost converter operates at a switching frequency of 2KHz.
- Assuming that all converters are ideal without power losses, investigate input current ripple & output voltage ripple of boost converter.

Assuming the boost converter operates in the continuous current mode, the duty cycle of the each converter channel is

$$D = D_1 = D_2 = 1 - \frac{V_i}{V_o} = 1 - \frac{680}{1200} = 0.4333$$

The ripple current in the two inductors can be calculated by

$$\Delta I_L = \Delta I_{L1} = \Delta I_{L2} = D(1-D)\frac{V_o T_s}{L} = 545.6\ A$$

The boundary inductor current relates the inductor ripple current by

$$I_{LB} = I_{LB1} = I_{LB2} = \Delta I_L / 2 = 272.8\ A$$

The boundary output current for each channel

$$I_{oB} = I_{oB1} = I_{oB2} = (1 - D)I_{LB} = 154.6\ A$$

The total average output current of the interleaved converter is

$$I_o = P_o / V_o = 343.3\ A$$

from which the average output current of each channel is

$$I_{o1} = I_{o2} = I_o / 2 = 171.7A$$

Since $I_{o1} = I_{o2} > I_{oB}$

- Converter operates in continuous current mode. Total input current of the boost converter is given by

$$I_i = \begin{cases} P_i / V_i = P_o / V_i = 412 \times 10^3 / 680 = 605.8\ A \\ I_o /(1 - D) = 343.4 /(1 - 0.4333) = 605.8 A \end{cases}$$

The percentage inductor ripple current in each channel can be found from

$$\frac{\Delta I_{L1}}{I_{L1}} = \frac{\Delta I_{L2}}{I_{L2}} = \frac{\Delta I_L}{I_i / 2} = \frac{545.6}{605.8 / 2} = 180.1\%$$

The total input current ripple

$$\Delta I_i = (1 - 2D) D \frac{V_o T_s}{L} = 128.4\ A$$

The total input current ripple can be found from

$$\frac{\Delta I_i}{I_i} = \frac{128.4}{606} = 21.2\%$$

which is much lower than the inductor ripple current of 180.1% in each of the channels.

The ratio of the total input ripple current ΔIi to the inductor ripple current ΔIL of each channel is

$$\frac{\Delta I_i}{\Delta I_L} = \frac{128.4}{545.6} = 23.5\%$$

which is verified by Point *A* in Fig. 4.3-8.

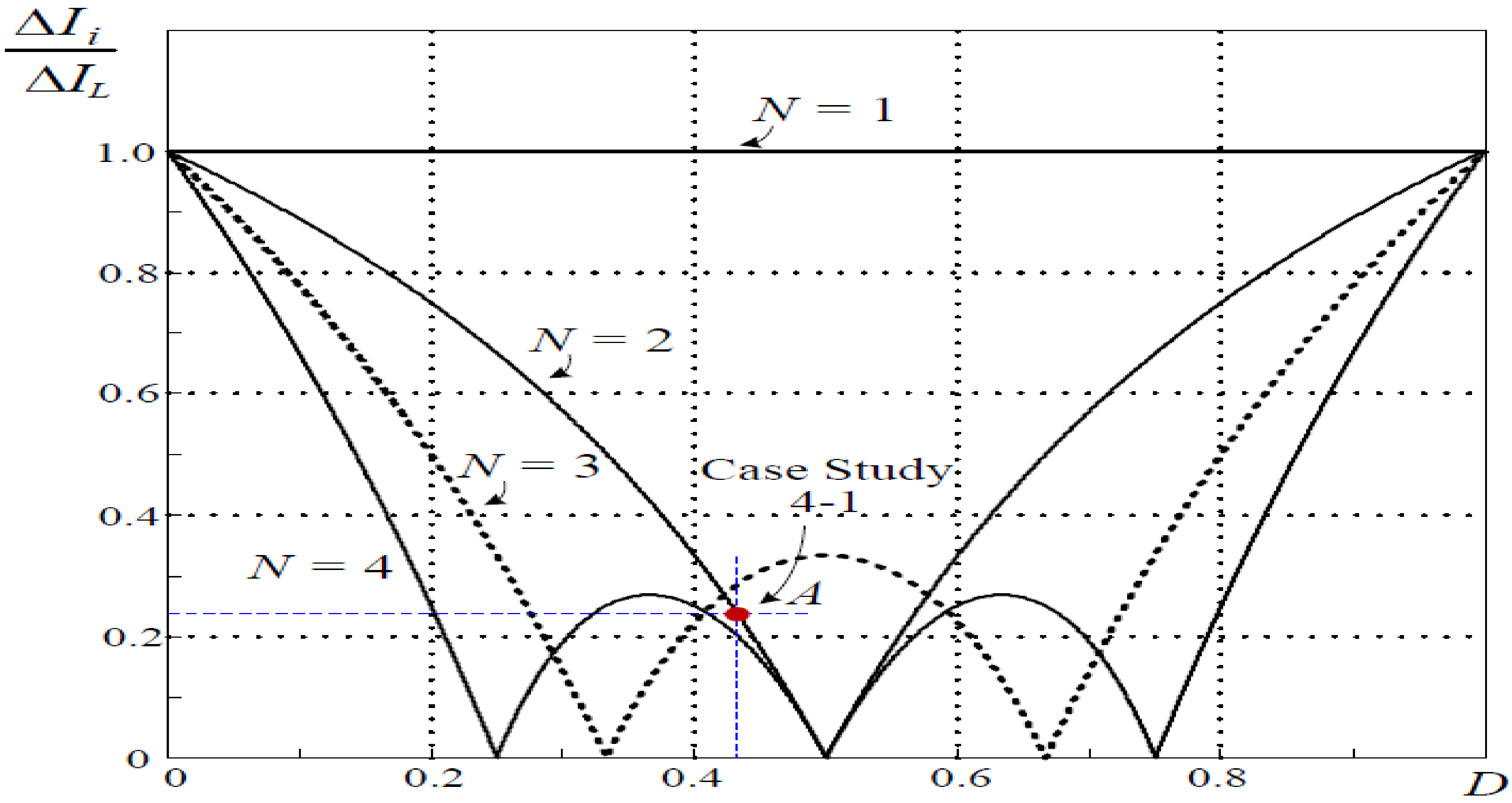
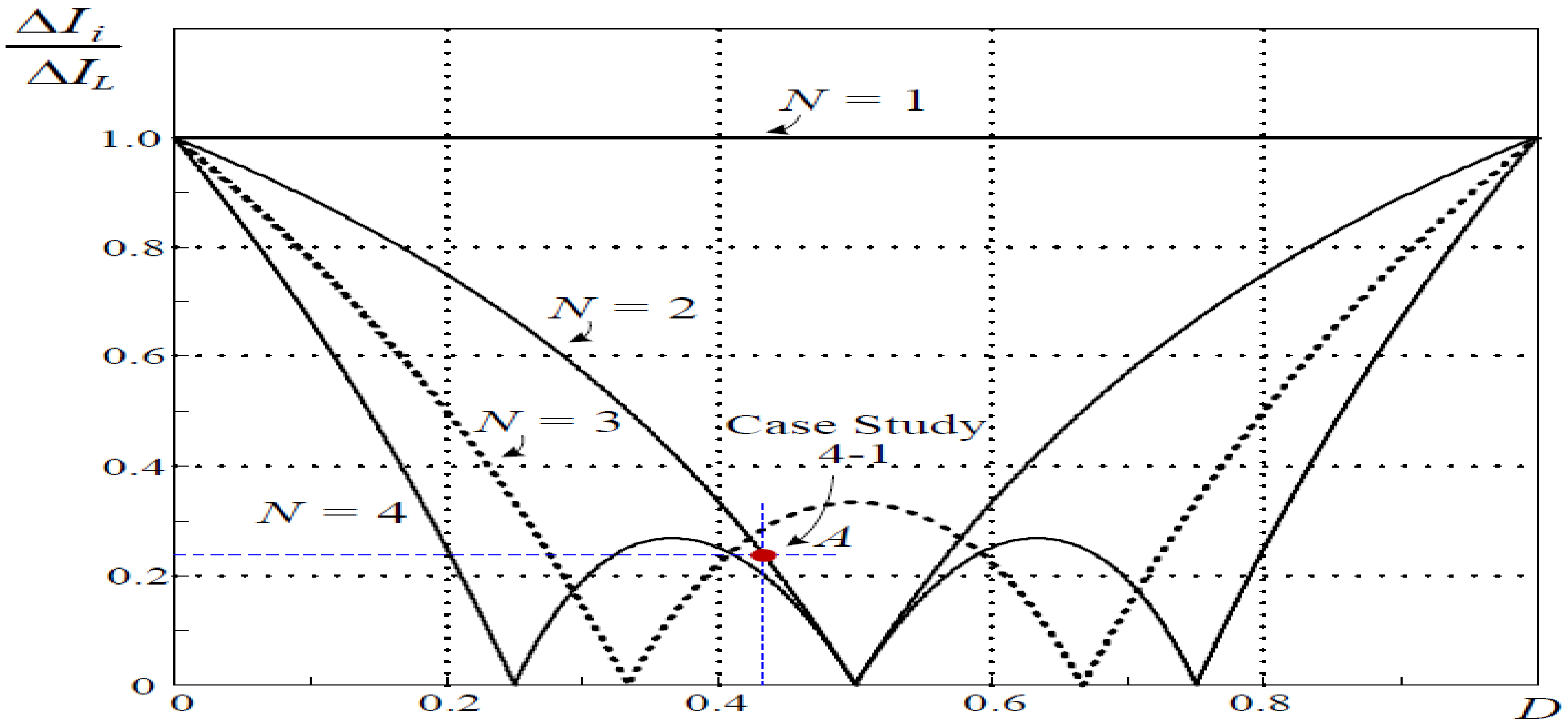


Fig. 4.3-8 Ratio of the input ripple current Δ*Ii* to the channel ripple current Δ*IL* versus duty cycle *D* for *N*-channel boost converters.



To determine output ripple voltage of interleaved boost converter, it is assumed that effect of inverter operation on dc voltage ripple is neglected.

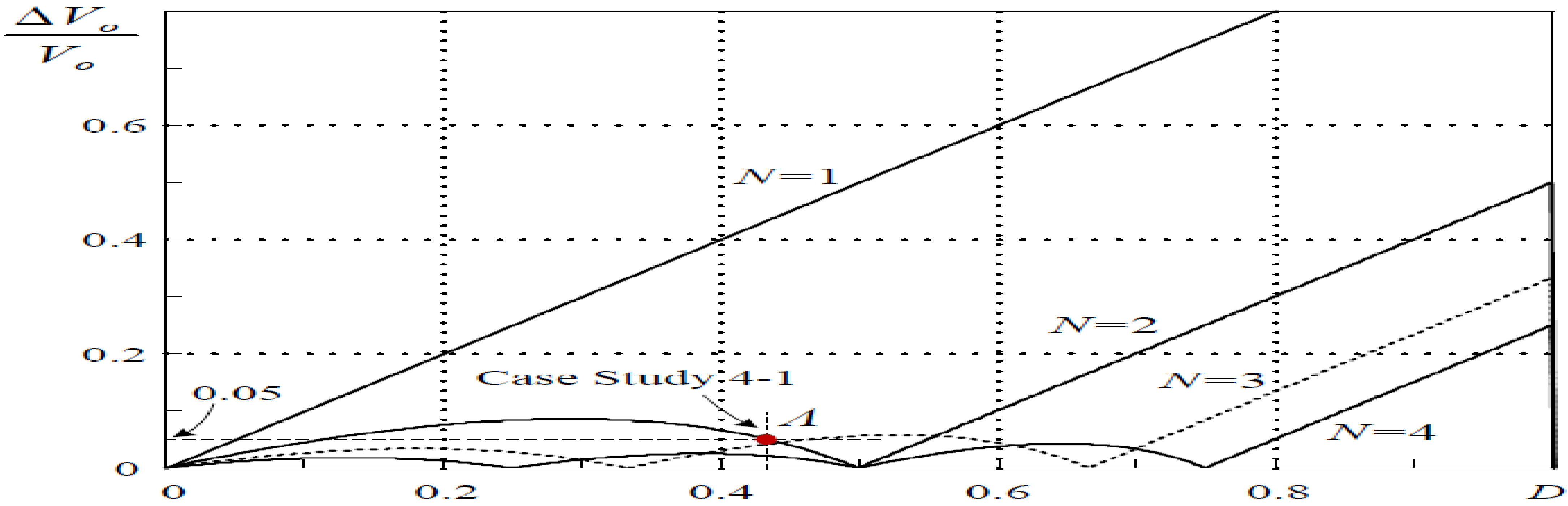
Load of boost converter, which is the inverter, can be modeled by an equivalent resistance given by:

$$R_{eq} = \frac{V_o}{I_o} = 3.495\,\Omega$$

Making use of Fig. 4.3-9, the percentage output ripple voltage can be obtained by

$$\frac{\Delta V_o}{V_o} = 0.05 \times \left(\frac{T_s}{R_{eq} C_o} \right) = 0.05 \times \frac{1/2000}{3.495 \times 300 \times 10^{-6}} = 2.38\%$$

Relative output ripple voltages (×*Ts* /(*RC*))versus duty cycle *D* for *N*-channel boost converters.



$$\frac{\Delta V_o}{V_o} = 0.05 \times \left(\frac{T_s}{R_{eq} C_o} \right) = 0.05 \times \frac{1/2000}{3.495 \times 300 \times 10^{-6}} = 2.38\%$$

If the operation of the two-channel converters were not interleaved, switches $S1$ and $S2$ would be turned on and off simultaneously. The output ripple voltage would then be

$$\frac{\Delta V_o}{V_o} = D\left(\frac{T_s}{R_{eq}C_o}\right) = 0.433 \times \frac{1/2000}{3.495 \times 300 \times 10^{-6}} = 20.6\%$$

which is around 8.6 times higher than that for the interleaved boost converter.

In summary, the multi-channel interleaved converter produces much lower input current ripple and output voltage ripple in comparison to the single-channel boost converter.