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Investigation And Design Of An Integrated Buck-Buck-Boost Converter For Power Factor Correction

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Abstract:
This paper presents the detailed analysis of an integrated buck-buck-boost (IBuBuBo) converter used for power factor correction. It is a one-stage one-switch AC/DC converter which steps down the voltage without a transformer. It combines a buck type PFC cell with a buck-boost type DC/DC cell. Two capacitors are sharing the voltage. Part of the input power is directly coupled to the output. With the above features it is able to achieve a high power factor, efficient power conversion and low output voltage without a transformer. This reduces the cost and size. The main switch handles the peak inductor current of DC/DC cell rather than the superposition of both inductor currents.

Key words*: Direct power transfer (DPT), integrated buck-buck-boost converter (IBuBuBo), power factor correction (PFC), single stage(SS), transformerless.*

1.Introduction

Because of the compact size, simple control and low cost, Single Stage converters are gaining importance. The average current of C_B (15) and critical inductance L_1(40) in [1] have been corrected. Most of them used boost PFC followed by a dc/dc cell for output voltage regulation [3],[4]. Because of boost type PFC cell, the intermediate bus voltage is higher than the line voltage [5]. A small step-down dc/dc cell (buck or buck-boost) has very poor efficiency. So a transformer is used which causes high spike on switch in addition to the leakage inductance. A snubber circuit is therefore needed to control the spike [2]. In [6], buck-boost PFC is used which gives negative polarity at the output terminal. The power is processed twice which reduces the efficiency.

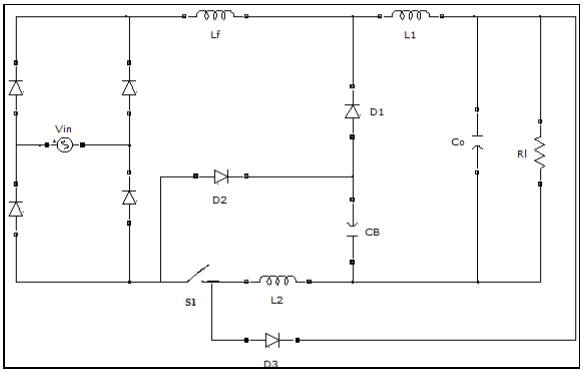

Figure 1: Ibububo AC/DC Converter

The proposed integrated buck-buck-boost converter keeps the intermediate bus voltage less than that of the line voltage. The transformer is not required. The polarity of the voltage at the output terminal is positive. The input power is processed only once.

2.Principle Of Operation

The IBuBuBo converter integrates a buck PFC cell with a buck-boost DC/DC cell. The PFC cell constitutes $C_{B,}$ $C_{O,}$ L_1, D_1 and S_1. The DC/DC cell constitutes $C_{B,}$ $C_{O,}$ L_2, $D_{2,}$ D_3 and $S_{1.}$ The initial current of both the inductors are zero as they operate in discontinuous conduction mode (DCM). There are two modes of operation.

Mode 1(V_{in} (θ) $\leq V_B+V_O$): In this mode the buck PFC cell becomes inactive as the rectifier bridge is reverse biased because the sum of the intermediate bus voltage and the output voltage is greater than the input voltage. Only the buck-boost cell sustains power to the load. No input current is drawn. It can be divided into three periods.

- Period 1: S_1 is turned ON; the bus voltage V_B charges the inductor $L_{2.}$ The load is supplied by the output capacitor $C_{O.}$
- Period 2: S_1 is turned OFF; L_2 is discharged through D_3 and supplied to C_o and load.

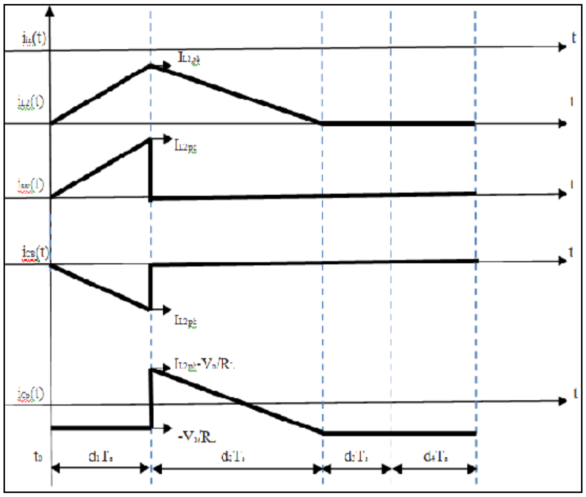

Figure 2

1) Period 3: L_2 is completely discharged. The load is supplied by the output capacitor $C_{O.}$

Mode 2(V_{in} (θ) $>V_B+V_O$): the input voltage is greater than the sum of the intermediate bus voltage and the output voltage.

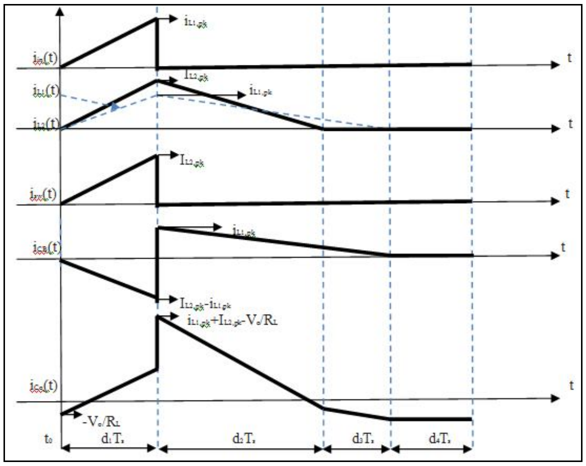

Figure 3

- Period 1: S_1 is turned ON; L_1 and L_2 are charged by the difference of voltage across them.
- Period 2: S_1 is turned OFF; the energy of L_2 is released to C_o and current is supplied to the load through D_3. Part of the input power is supplied to the load directly. L_1 is discharging to charge C_O and $C_{B.}$ this period lasts as long as L_2 has current.
- Period 3: This period lasts as long as L_1 has current and it supplies to C_o and load.
- Period 4: Only C_o delivers power to the load.

3.Converter Design

Following assumptions are made to do the analysis:

- all components are ideal;
- line input source is pure sinusoidal;
- the capacitors can be treated as constant DC voltage sources due to high capacitances;
- the input voltage is constant within a switching period.

A. Circuit characteristics

$$V_T = V_O + V_B \qquad (1)$$

The phase angles of dead-time α and β are given as

$$\alpha = \sin^{-1}\left(\frac{V_T}{V_{pk}}\right) \qquad (2)$$

$$\beta = \pi - \alpha = \pi - \sin^{-1}\left(\frac{V_T}{V_{pk}}\right) \qquad (3)$$

The conduction angle of the converter is

$$\gamma = \beta - \alpha = \pi - 2\sin^{-1}\left(\frac{V_T}{V_{pk}}\right) \qquad (4)$$

Peak currents of the inductors

$$i_{L1-pk} = \begin{cases} \begin{pmatrix} \dfrac{V_{in}(\theta) - V_T}{L_1} \\ d_1 T_S \end{pmatrix} & \alpha \le \theta \le \beta \\ 0 & \end{cases} \qquad (5)$$

$$i_{L2-pk} = \frac{V_B}{L_2} d_1 T_S \qquad (6)$$

Where $T_S\,(\frac{1}{f_s})$ is the switching period of the converter

By considering the volt-second balance of the L_1 and L_2 ,the duty relations can be expressed as

$$(\mathrm{d}_2 + d_3)V_T = d_1(V_{in}(\theta) - V_T)$$

$$\mathrm{d}_2 + d_3 = \begin{cases} \begin{pmatrix} \dfrac{V_{in}(\theta) - V_T}{V_T} \\ d_1 \end{pmatrix} & \alpha \le \theta \le \beta \\ 0 & \end{cases} \qquad (7)$$

$$\mathrm{d}_2 V_0 = d_1 V_B$$

$$\mathrm{d}_2 = \frac{V_B}{V_0} d_1 \qquad (8)$$

By applying charge balance of C_B over a half-line period, the bus voltage can be determined

$$\left\langle i_{CB} \right\rangle_{sw} = \frac{1}{2}\left[\begin{array}{l} \left(i_{L1-pk} - i_{L2-pk}\right) d_1 + \\ d_2 i_{L1-pk} + d_3 i_{L1-pk} \end{array}\right] \qquad (9)$$

$$\left\langle i_{CB} \right\rangle_{sw} = \frac{1}{2}\left[\begin{array}{l} i_{L1-pk}\left(d_1 + d_2 + d_3\right) \\ -i_{L2-pk}\, d_1 \end{array}\right] \qquad (10)$$

$$\left\langle i_{CB} \right\rangle_{sw} = \frac{1}{2}\left[\begin{array}{l} \dfrac{V_{in}(\theta) - V_T}{L_1} d_1 T_S (d_1 + d_2 + d_3) \\ -\dfrac{V_B}{L_2} d_1 T_S d_1 \end{array}\right]$$

$$\left\langle i_{CB} \right\rangle_{sw} = \frac{1}{2}\left[\begin{array}{l} \dfrac{V_{in}(\theta) - V_T}{L_1} d_1{}^2 T_S + \dfrac{V_{in}(\theta) - V_T}{L_1} \\ d_1 T_S \left(\dfrac{V_{in}(\theta) - V_T}{V_T} d_1\right) - \dfrac{V_B}{L_2} d_1{}^2 T_S \end{array}\right]$$

$$\left\langle i_{CB} \right\rangle_{sw} = \frac{d_1{}^2 T_S}{2}\left[\begin{array}{l} \dfrac{V_{in}(\theta) - V_T}{L_1} \\ \left(1 + \dfrac{V_{in}(\theta) - V_T}{V_T}\right) - \dfrac{V_B}{L_2} \end{array}\right]$$

$$\left\langle i_{CB} \right\rangle_{sw} = \frac{d_1{}^2 T_S}{2}\left[\begin{array}{l} \dfrac{V_{in}(\theta) - V_T}{L_1 V_T} V_{in}(\theta) \\ -\dfrac{V_B}{L_2} \end{array}\right] \qquad (11)$$

and

$$\left\langle i_{CB} \right\rangle_{\pi} = \frac{1}{\pi}\int_0^{\pi} \left\langle i_{CB} \right\rangle_{sw} d\theta \qquad (12)$$

From (11)

$$\left\langle i_{CB}\right\rangle_{\pi} = \frac{1}{\pi}\int_{0}^{\pi}\frac{d_1{}^2T_S}{2}\left[\frac{V_{in}(\theta)-V_T}{L_1V_T}V_{in}(\theta)-\frac{V_B}{L_2}\right]$$

$$\left\langle i_{CB}\right\rangle_{\pi} = \frac{d_1{}^2T_S}{2}\int_{0}^{\pi}\begin{pmatrix}\dfrac{V_{in}{}^2(\theta)}{L_1V_T}-\dfrac{V_{in}(\theta)}{L_1} \\ -\dfrac{V_B}{L_2}\end{pmatrix}d\theta \tag{13}$$

$$\left\langle i_{CB}\right\rangle_{\pi} = \frac{d_1{}^2T_S}{2}\int_{0}^{\pi}\begin{pmatrix}\dfrac{V_{pk}{}^2(\sin^2\theta)}{L_1V_T}- \\ \dfrac{V_{pk}\sin\left(\theta\right)}{L_1}-\dfrac{V_B}{L_2}\end{pmatrix}d\theta$$

$$\left\langle i_{CB}\right\rangle_{\pi} = \frac{d_1{}^2T_S}{2}\begin{pmatrix}\displaystyle\int_{\alpha}^{\beta}\frac{V_{pk}}{L_1}\left(\frac{V_{pk}(\sin^2\theta)}{V_T}-\sin\left(\theta\right)\right) \\ d\theta-\dfrac{d_1{}^2T_S}{2}\displaystyle\int_{0}^{\pi}\frac{V_B}{L_2}d\theta\end{pmatrix}$$

$$\left\langle i_{CB}\right\rangle_{\pi} = \frac{d_1{}^2T_S}{2}\begin{bmatrix}\dfrac{V_{pk}}{L_1}\left(\displaystyle\int_{\alpha}^{\beta}\frac{V_{pk}}{V_T}\left(\frac{1-\cos 2\theta}{2}\right)-\sin\left(\theta\right)\right) \\ d\theta-\displaystyle\int_{0}^{\pi}\frac{V_B}{L_2}d\theta\end{bmatrix} \tag{14}$$

$$\left\langle i_{CB}\right\rangle_{\pi} = \frac{d_1{}^2T_S}{2}\begin{bmatrix}\dfrac{V_{pk}}{L_1}\left(\dfrac{V_{pk}}{V_T}\left(\dfrac{\gamma}{2}+\dfrac{A}{4}\right)-B\right) \\ -\dfrac{\pi V_B}{L_2}\end{bmatrix} \tag{15}$$

Where the constants A and B are

$$A = \sin 2\alpha - \sin 2\beta$$
$$\mathrm{B} = \cos\alpha - \cos\beta$$

Equating to zero

$$\frac{\pi V_B}{L_2} = \frac{V_{pk}}{L_1}\left(\frac{V_{pk}}{V_T}\left(\frac{\gamma}{2}+\frac{A}{4}\right)-B\right) \tag{16}$$

$$V_B = \frac{V_{pk}}{\pi}\frac{L_2}{L_1}\frac{V_{pk}}{V_T}\left(\left(\frac{\gamma}{2}+\frac{A}{4}\right)-\frac{BV_T}{V_{pk}}\right)$$

$$V_B = \frac{V_{pk}{}^2}{2\pi}\frac{M}{V_T}\left[\gamma + \frac{A}{2} - \frac{2BV_T}{V_{pk}}\right] \qquad (17)$$

Where $\frac{L_2}{L_1} = M$

$$\frac{A}{2} = \frac{\sin 2\alpha - \sin 2\beta}{2}$$

$$\frac{A}{2} = \sin\alpha\cos\alpha - \sin\beta\cos\beta$$

From equation (2)

$$\sin\alpha = \left(\frac{V_T}{V_{pk}}\right) \qquad (18)$$

and

$$\cos\alpha = \frac{\sqrt{V_{pk}{}^2 - V_T{}^2}}{V_{pk}} \qquad (19)$$

From equation (3)

$$\sin\beta = \sin\pi - \frac{V_T}{V_{pk}}$$

$$\sin\beta = -\frac{V_T}{V_{pk}} \qquad (20)$$

And

$$\cos\beta = \frac{\sqrt{V_{pk}{}^2 - V_T{}^2}}{V_{pk}} \qquad (21)$$

$$\frac{A}{2} = \left(\frac{V_T}{V_{pk}}\frac{\sqrt{V_{pk}{}^2 - V_T{}^2}}{V_{pk}}\right) - \left(-\frac{V_T}{V_{pk}}\frac{\sqrt{V_{pk}{}^2 - V_T{}^2}}{V_{pk}}\right) \quad \frac{A}{2} = \frac{2V_T}{V_{pk}{}^2}\sqrt{V_{pk}{}^2 - V_T{}^2} \qquad (22)$$

$$\frac{2BV_T}{V_{pk}} = \frac{2V_T}{V_{pk}}\cos\alpha - \cos\beta \quad \frac{2BV_T}{V_{pk}} = \frac{2V_T}{V_{pk}}\left(\frac{\sqrt{V_{pk}{}^2 - V_T{}^2}}{V_{pk}} - \frac{\sqrt{V_{pk}{}^2 - V_T{}^2}}{V_{pk}}\right) = 0 \qquad (23)$$

$$V_B = \frac{V_{pk}{}^2}{2\pi}\frac{M}{V_T}\left[\begin{array}{l} \pi - 2\sin^{-1}\left(\frac{V_B+V_O}{V_{pk}}\right) - \frac{2\left(V_B+V_O\right)}{V_{pk}{}^2} \\ \sqrt{\left(V_{pk}+V_B+V_O\right)\left(V_{pk}-V_B-V_O\right)} \end{array}\right] \tag{24}$$

The instantaneous input current is given by

$$\left\langle i_{in}\right\rangle_{sw} = \frac{i_{L1-pk}}{2}d_1$$

$$\left\langle i_{in}\right\rangle_{sw} = \begin{cases} \left(\begin{array}{c} \frac{V_{in}(\theta)-V_T}{L_1} \\ d_1{}^2 T_S \end{array}\right) & \alpha \le \theta \le \beta \\ 0 & \end{cases} \tag{25}$$

The average input current is given by

$$I_{in} = \frac{1}{\pi}\int_{\alpha}^{\beta}\left\langle i_{in}\right\rangle_{sw} d\theta$$

From (25)

$$I_{in} = \frac{1}{\pi}\frac{d_1{}^2 T_S}{2L_1}\int_{\alpha}^{\beta}\left(V_{pk}\sin\left(\theta\right)-V_T\right)d\theta$$

$$I_{in} = \frac{1}{\pi}\frac{d_1{}^2 T_S}{2L_1}\left(\begin{array}{l} V_{pk}\left(\cos\alpha-\cos\beta\right) \\ -V_T\left(\beta-\alpha\right) \end{array}\right)$$

$$I_{in} = \frac{1}{\pi}\frac{d_1{}^2 T_S}{2L_1}\left(V_{pk}B - V_T\gamma\right) \tag{27}$$

The rms value of input current is given by

$$I_{in\_rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\beta}\left\langle i_{in}\right\rangle^2{}_{sw} d\theta} \tag{28}$$

$$I_{in\_rms} = \frac{1}{\sqrt{\pi}}\frac{d_1{}^2 T_S}{2L_1}\int_{\alpha}^{\beta}\left(V_{pk}\sin\left(\theta\right)-V_T\right)^2 d\theta$$

$$I_{in\_rms} = \frac{1}{\sqrt{\pi}}\frac{d_1{}^2 T_S}{2L_1}\int_{\alpha}^{\beta}\left(\begin{array}{l} V_{pk}{}^2(\sin^2\theta)+V_T{}^2 \\ -2V_{pk}\sin\left(\theta\right)V_T \end{array}\right)d\theta$$

From (13) and (15)

$$I_{in\_rms} = \frac{d_1^{\,2}T_S}{2L_1\sqrt{\pi}}\begin{bmatrix} V_{pk}^{\,2}\left(\frac{\gamma}{2}+\frac{A}{4}\right)+V_T^{\,2}\left(\beta-\alpha\right) \\ -2V_{pk}\left(\cos\alpha-\cos\beta\right)V_T \end{bmatrix} \quad I_{in\_rms} = \frac{1}{\sqrt{\pi}}\frac{d_1^{\,2}T_S}{2L_1}\begin{bmatrix} V_{pk}^{\,2}\left(\frac{\gamma}{2}+\frac{A}{4}\right)+ \\ V_T^{\,2}\gamma-2BV_{pk}V_T \end{bmatrix} \quad (29)$$

The average input power is given by

$$P_{in} = \frac{1}{\pi}\int_{\alpha}^{\beta}\left(V_{in}(\theta)\left\langle i_{in}\right\rangle_{sw}\right)d\theta \quad (30)$$

$$P_{in} = \frac{1}{\pi}\int_{\alpha}^{\beta}\left(V_{in}(\theta)\frac{V_{in}(\theta)-V_T}{2L_1}d_1^{\,2}T_S\right)d\theta$$

$$P_{in} = \frac{1}{\pi}\frac{d_1^{\,2}T_S}{2L_1}\int_{\alpha}^{\beta}\left(V_{in}^{\,2}(\theta)-V_{in}(\theta)V_T\right)d\theta$$

$$P_{in} = \frac{1}{\pi}\frac{d_1^{\,2}T_S}{2L_1}\int_{\alpha}^{\beta}\begin{pmatrix} V_{pk}^{\,2}(\sin^2\theta)- \\ V_{pk}\sin(\theta)V_T \end{pmatrix}d\theta$$

From (13) and (15)

$$P_{in} = \frac{1}{\pi}\frac{d_1^{\,2}T_S}{2L_1}V_{pk}\left[V_{pk}\left(\frac{\gamma}{2}+\frac{A}{4}\right)-BV_T\right] \quad (31)$$

The power factor is given by

$$PF = \frac{\frac{1}{\pi}\int_{\alpha}^{\beta}\left(V_{in}(\theta)\left\langle i_{in}\right\rangle_{sw}\right)d\theta}{\frac{V_{pk}}{\sqrt{2}}I_{in\_rms}} \quad (32)$$

$$PF = \frac{\frac{1}{\pi}\frac{d_1^{\,2}T_S}{2L_1}V_{pk}\left[V_{pk}\left(\frac{\gamma}{2}+\frac{A}{4}\right)-BV_T\right]}{\frac{V_{pk}}{\sqrt{2}}\frac{1}{\sqrt{\pi}}\frac{d_1^{\,2}T_S}{2L_1}\begin{bmatrix} V_{pk}^{\,2}\left(\frac{\gamma}{2}+\frac{A}{4}\right)+ \\ V_T^{\,2}\gamma-2BV_{pk}V_T \end{bmatrix}}$$

From (29) and (31)

$$PF = \sqrt{\frac{2}{\pi}}\,\frac{\left[V_{pk}\left(\frac{\gamma}{2}+\frac{A}{4}\right)-BV_T\right]}{\left[V_{pk}{}^2\left(\frac{\gamma}{2}+\frac{A}{4}\right)+V_T{}^2\gamma-2BV_{pk}V_T\right]} \tag{33}$$

B. Condition for DCM

For the cells to work in DCM the critical inductance must be determined. To allow L_1 working in discontinuous mode

Inequalities:

$$d_{1\_\mathrm{PFC}} + d_2 + d_3 \le 1$$

$$d_2 + d_3 \le 1 - d_{1\_\mathrm{PFC}} \tag{34}$$

$$d_{1\_\mathrm{PFC}} \le \begin{cases} \frac{V_T}{V_{in}}(\theta) & \alpha \le \theta \le \beta \\ 0 \end{cases} \tag{35}$$

Where d_{1_PFC} is the maximum d_1 of PFC cell

For DC/DC cell to work in DCM, the following inequality must be held

$$d_{1\_\mathrm{DC/DC}} + d_2 \le 1$$

$$d_2 \le 1 - d_{1\_\mathrm{DC/DC}} \tag{36}$$

$$\frac{V_B}{V_0} d_{1\_\mathrm{DC/DC}} \le 1 - d_{1\_\mathrm{DC/DC}} \tag{37}$$

$$d_{1\_\mathrm{DC/DC}} \le \frac{V_0}{V_O + V_B} = \frac{V_0}{V_T}$$

As the switch is shared in both cells of the converter, the maximum duty cycle $d_{1\_\max}$ is given by

$$d_{1\_\max} = \begin{cases} \min\begin{pmatrix} d_{1\_\mathrm{PFC}}, \\ d_{1\_\mathrm{DC/DC}} \end{pmatrix} & \alpha \le \theta \le \beta \\ d_{1\_\mathrm{DC/DC}} \end{cases} \tag{38}$$

The output power is given by

$$P_{out} = \frac{V_0{}^2}{R_{L\_\min}} \tag{39}$$

By applying input-output power balance

From (31) and (39)

$$\frac{V_0^{\ 2}}{R_{L\_\min}} = \frac{1}{\pi}\frac{d_{1\_\max}{}^{2}T_S}{2L_{1\_crit}}V_{pk}\left[\begin{matrix} V_{pk}\left(\frac{\gamma}{2}+\frac{A}{4}\right) \\ -BV_T \end{matrix}\right]$$

$$L_{1\_crit} = \frac{R_{L\_\min}}{\pi}\left(\begin{matrix} \frac{d_{1\_\max}{}^{2}T_S}{2V_0^{\ 2}}V_{pk} \\ \left[V_{pk}\left(\frac{\gamma}{2}+\frac{A}{4}\right)-BV_T\right] \end{matrix}\right) \quad (40)$$

WhereR_{L_min} is the minimum load resistance

And L_{1_crit} is the critical value of the inductance

The critical inductanceL_{2_crit} is calculated from the input power to the DC/DC cell and is given by

$$P_{in\_DC/DC} = \frac{V_B}{\pi}\int_0^{\pi}\left\langle i_{DC/DC}\right\rangle_{sw} d\theta \qquad (41)$$

$$\left\langle i_{DC/DC}\right\rangle_{sw} = \frac{i_{L2-pk}}{2}d_1$$

From (6)

$$\left\langle i_{DC/DC}\right\rangle_{sw} = \frac{V_B}{2L_2}d_1^{\ 2}T_S \qquad (42)$$

$$P_{in\_DC/DC} = \frac{V_B}{\pi}\int_0^{\pi}\left(\frac{V_B}{2L_2}d_1^{\ 2}T_S\right)d\theta \qquad (43)$$

$$P_{in\_DC/DC} = \frac{V_B}{\pi}\frac{V_B\pi}{2L_2}d_1^{\ 2}T_S$$

$$P_{in\_DC/DC} = \frac{V_B^{\ 2}}{2L_2}d_1^{\ 2}T_S \qquad (44)$$

From (39) and (44)

$$\frac{V_0^{\ 2}}{R_{L\_\min}} = \frac{V_B^{\ 2}}{2L_{2\_crit}}d_{1\_\max}{}^{2}T_S$$

$$L_{2\_crit} = \frac{R_{L\_\min}V_B^{\ 2}}{2V_0^{\ 2}}d_{1\_\max}{}^{2}T_S \qquad (45)$$

C.Capacitors optimization

$$E = \frac{1}{2} C V^2 \tag{46}$$

$$E = P * \mathrm{t} \tag{47}$$

From (46) and (47)

$$C_B = \frac{2Pt}{V^2}$$

$$C_B = \frac{2 P_O t_{hold\_up}}{\left(V_B @ 90 V_{rms} \right)^2}$$

Where t_{hold_up} is the hold-up time

D. Distribution of Direct Power Transfer

$$p_o(\theta) = p_{o\_PFC}(\theta) + p_{o\_DC/DC}(\theta) \tag{48}$$

$$p_{o\_PFC}(\theta) = V_O \left\langle i_{L1}(\theta) \right\rangle_{sw} \tag{49}$$

$$\left\langle i_{L1}(\theta) \right\rangle_{sw} = \frac{1}{2} \left[i_{L1-pk} \left(d_1 + d_2 + d_3 \right) \right]$$

From (9) and (11)

$$\left\langle i_{L1}(\theta) \right\rangle_{sw} = \frac{d_1{}^2 T_S}{2} \left(\frac{V_{in}(\theta) - V_T}{L_1 V_T} V_{in}(\theta) \right) \quad p_{o\_\mathrm{PFC}}(\theta) = \begin{cases} \dfrac{d_1{}^2 T_S}{2} \begin{pmatrix} \dfrac{V_{in}(\theta) - V_T}{L_1 V_T} \\ V_{in}(\theta) \end{pmatrix} & \alpha \le \theta \le \beta \\ 0 & \end{cases}$$

$$p_{o\_DC/DC}(\theta) = p_{\mathrm{in}\_DC/DC}(\theta)$$

$$p_{o\_DC/DC}(\theta) = V_B \left\langle i_{DC/DC} \right\rangle_{sw} \tag{50}$$

$$\left\langle i_{DC/DC} \right\rangle_{sw} = \frac{1}{2} \left\langle i_{L2-pk} \right\rangle d_1$$

From (6)

$$\left\langle i_{DC/DC} \right\rangle_{sw} = \frac{1}{2} \frac{V_B}{L_2} d_1 T_S d_1$$

$$\left\langle i_{DC/DC} \right\rangle_{sw} = \frac{V_B}{2 L_2} d_1{}^2 T_S \tag{51}$$

$$p_{o\_DC/DC}\left(\theta\right)=V_B\left\langle i_{DC/DC}\right\rangle_{sw} \qquad (52)$$

From (42)

$$p_{o\_DC/DC}\left(\theta\right)=\frac{V_B T_S}{2L_2}d_1^{\,2}\left(\theta\right)$$

$$I_O=\begin{cases}\left(\begin{array}{l}\left\langle i_{L1}\left(\theta\right)\right\rangle_{sw}+\\ \left\langle i_{D3}\left(\theta\right)\right\rangle_{sw}\end{array}\right) & \alpha\le\theta\le\beta\\ \left\langle i_{D3}\left(\theta\right)\right\rangle_{sw} & \end{cases}$$

$$\left\langle i_{D3}\left(\theta\right)\right\rangle_{sw}=\frac{P_{in\_DC/DC}}{V_O}=\frac{V_B^{\;2}}{2L_2V_O}d_1^{\,2}T_S$$

$$I_O=\begin{cases}\left(\begin{array}{l}\dfrac{d_1^{\,2}T_S}{2}\left(\dfrac{V_{in}(\theta)-V_T}{L_1V_T}\right)\\ V_{in}(\theta)+\dfrac{V_B^{\;2}}{2L_2V_O}d_1^{\,2}T_S\end{array}\right) & \alpha\le\theta\le\beta\\ \dfrac{V_B^{\;2}}{2L_2V_O}d_1^{\,2}T_S & \end{cases}$$

$$I_O=\begin{cases}\left(\dfrac{d_1^{\,2}T_S}{2}\left[\begin{array}{l}\left(\dfrac{V_{in}(\theta)-V_T}{L_1V_T}\right)\\ V_{in}(\theta)+\dfrac{V_B^{\;2}}{L_2V_O}\end{array}\right]\right) & \alpha\le\theta\le\beta\\ \dfrac{V_B^{\;2}}{2L_2V_O}d_1^{\,2}T_S & \end{cases}$$

$$I_O=\frac{P_O}{V_O}$$

$$\frac{P_O}{V_O}=\begin{cases}\left(\dfrac{\left(d_1\left(\theta\right)\right)^2T_S}{2}\left[\begin{array}{l}\left(\dfrac{V_{in}(\theta)-V_T}{L_1V_T}\right)\\ V_{in}(\theta)+\dfrac{V_B^{\;2}}{L_2V_O}\end{array}\right]\right)\\ \dfrac{V_B^{\;2}\left(d_1\left(\theta\right)\right)^2}{2L_2V_O}T_S\end{cases}$$

$$d_1\left(\theta\right)=\begin{cases}\sqrt{\dfrac{2P_O}{V_O T_S\left[\left(\dfrac{V_{in}(\theta)-V_T}{L_1 V_T}V_{in}(\theta)\right)+\dfrac{V_B{}^2}{L_2 V_O}\right]}}\\ \sqrt{\dfrac{2L_2P_O}{V_B{}^2T_S}}\end{cases}$$

4.Conclusion

The proposed IBuBuBo converter, from (24), achieves a very low bus voltage. From (2) decrease of V_B extends the conduction angle giving better power factor. The power handled by both PFC cell and dc/dc cell is changed oppositely to maintain the load power under different input conditions. At low-line condition, there is more input power coupled directly to the output. At high-line condition, more power is delivered to the output by the dc/dc cell.

5.References

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