01 Jan 2004

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Recommended Citation

Z. Nie et al., "Boost Integrated Push-Pull Rectifier with Power Factor Correction and Output Voltage Regulation using a New Digital Control Technique," *Proceedings of the 26th Annual International Telecommunications Energy Conference (2004, Chicago, IL)*, pp. 59-64, Institute of Electrical and Electronics Engineers (IEEE), Jan 2004.
The definitive version is available at https://doi.org/10.1109/INTLEC.2004.1401445

Boost Integrated Push-Pull Rectifier with Power Factor Correction and Output Voltage Regulation Using a New Digital Control Technique

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Abstract - **An integrated converter is a synthesized converter based on the overall system integration, which is simplified by the system objective and can implement the system functions similar to the discrete converters. An integrated converter consists of converter sets; each converter set has a special function defined by the designer. A family of DC/DC Boost based integrated rectifiers with two active switches can be derived by the integration concept. In this paper, Boost + Push-Pull integrated converter is introduced and derived.**

To regulate the output voltage and shape the input current, a new simple digital control method is applied. In contrast to the conventional analog control methods, the principal idea of this new digital control algorithm is to use real-time analysis and estimate the required on time of the switches based on the value of the output voltage, input inductor current, and input voltage. The high capacitor voltage stress caused by the compatibility of the integration can be reduced by two methods. Pulse regulation control method is used to control this converter. Simulation results are presented.

I. INTRODUCTION TO INTEGRATED CONVERTERS

Integrated converter means synthesized converter based on the system integration, which is simplified by the system objective and can implement the system functions similar to the discrete converter without integration. In Fig. 1, the simplified model for the integrated converter is given. The detailed model for integrated converter is presented in Fig. 2. This detailed model presents the difference between the basic converter and the integrated converter. For integrated converter, it consists of converter sets. Each converter set has a specific function required by designer. The integrated converter has at least two converter sets. In most applications of power electronic converter, the general model in Fig. 3 for integrated converters can be used.

From the above definition of the integrated converter, we know that an integrated converter not only has all discrete functions of every converter set, but also has simplicity based on the system integration. Care must be taken that each converter set can be a sub-integrated converter or a basic converter.

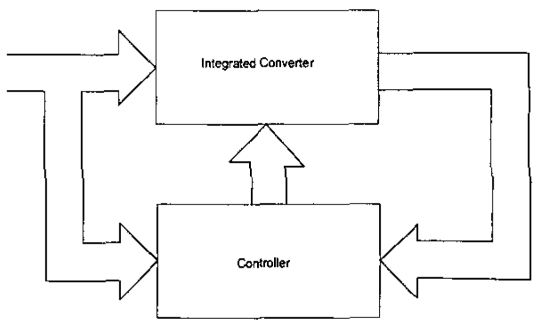

Fig. 1. Simplified model for an integrated converter.

By analyzing the function relationship in Fig. 3, a family of Boost based integrated rectifiers with two active switches can be derived by the integration concept. For example, if converter set 1 is configured to be the diode bridge rectifier, converter set 2 is the Boost converter and converter set 3 is the half-bridge converter. After combing converter set 2 and converter set 3 and then combining them with converter set 1, the Boost half-bridge rectifier circuit introduced by I. Takahashi is achieved. In this paper, Boost + Push-Pull integrated converter is introduced and derived by this method.

In Fig. 4, Boost + interleave Buck converter is shown. Fig. 5 is the Boost + interleave Forward converter, which is the isolated interleave Buck converter.

Boost + Push-Pull converter can be derived by saving switch Q_3 of Boost + Forward converter in Fig. 5. Based on dither signal principle [2], in the Boost + Push-Pull topology, the dither signal is generated by the capacitor C_1. In this

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paper, we take the Boost + Push-Pull converter as an example to illustrate the characteristics and control method of this kind of converters.

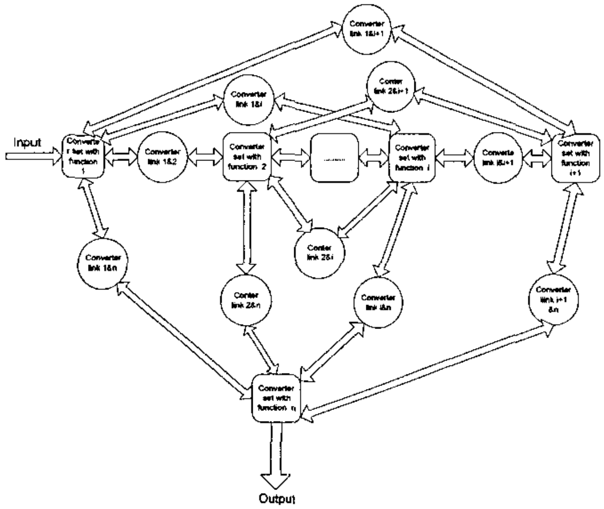

Fig. 2. Detailed model for integrated converters.

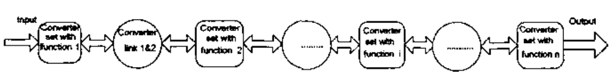

Fig. 3. General model for an integrated converter.

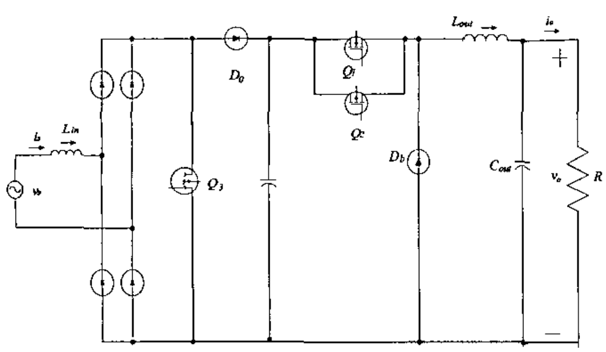

Fig. 4. Boost + interleave buck converter.

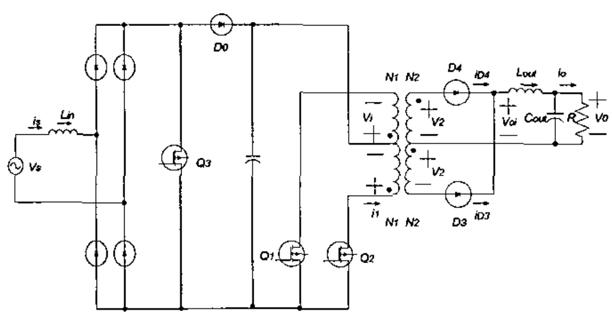

Fig. 5. Boost + interleave forward converter.

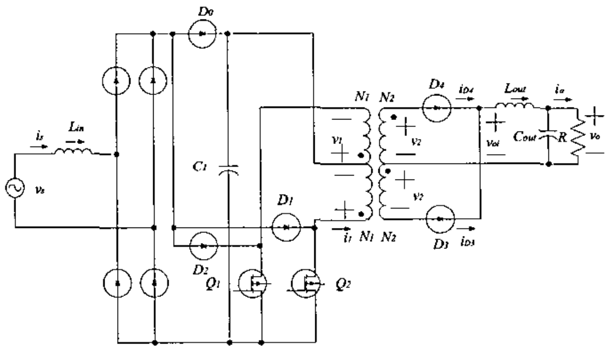

Fig. 6. Boost + Push-Pull integrated converter.

II. Operating Modes

This Boost + Push-Pull converter working in DCM-CCM operation is discussed first. There are four operational modes. For mode I shown in Fig. 7a, Q_1 is on, D_4 is on, Q_2 is off, and D_3 is off. Input inductor stores energy and capacitor C_1 transfers energy to the output. For mode II shown in Fig. 7b, Q_1 is off, D_4 is on, Q_2 is off, and D_3 is on. Inductor transfers energy to the capacitor. For mode III shown in Fig. 7c, Q_1 is off, D_4 is off, Q_2 is on, and D_3 is on. Input inductor stores energy and capacitor C_1 transfers energy to the output. For the forth mode in the Fig. 6, the circuit has the same working states as the mode II.

The formulations are derived for this operational mode. For DCM Boost converter, current of the input inductor I_{Lin} begins the switching period at zero, and increase during model I with a constant slope, given by the applied input voltage divided by the inductance. The peak inductor current $I_{Lin,\max}$ is equal to the constant slope, multiplied by the length (d_1T) of the model I:

$$I_{Lin,\max} = \frac{d_1 T V_{in}}{L_{in}}. \tag{1}$$

Likewise, for the descending current of the input inductor in mode 2, one obtains:

$$I_{Lin,\max} = \frac{d_2 T\left(V_{C_1} - V_{in}\right)}{L_{in}}. \tag{2}$$

Then average current for input inductor is:

$$I_{Lin,avg} = \frac{d_1^2 T V_{C_1} V_{in}}{L_{in}\left(V_{C_1} - V_{in}\right)}. \tag{3}$$

Assuming the power factor to be unity, the input power is:

$$P_{in} = \frac{V_{in} I_{Lin,avg}}{2} = \frac{d_1^2 T V_{C_1} V_{in}^2}{2L_{in}\left(V_{C_1} - V_{in}\right)}. \tag{4}$$

For CCM push-pull converter, the circuit just looks like isolated buck converter in CCM condition. So the output power is:

$$P_{out} = \frac{V_o^2}{R} = \frac{4d_1^2 V_{C1}^2}{n^2 R}. \quad (5)$$

In the ideal situation, input power equal to the output power. So we obtain:

$$V_{C1} = \frac{1+\sqrt{1+\frac{n^2 RT}{2L_{in}}}}{2} V_{in}. \quad (6)$$

From the above equation, we know that when R increases, V_{C1} will increase. Therefore, Boost + Push-Pull converter in DCM-CCM mode is not suitable for wide load ranges.

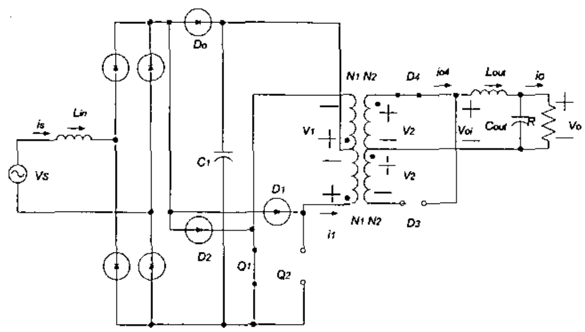

Fig. 7a. Mode I (Q_1: on, Q_2: off, D_3: on, D_4: off).

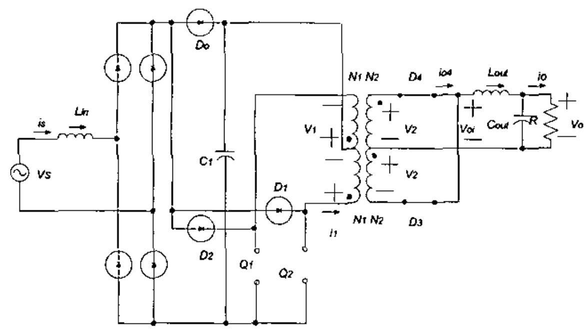

Fig. 7b. Mode II (Q_1: off, Q_2: off, D_3: on, D_4: on).

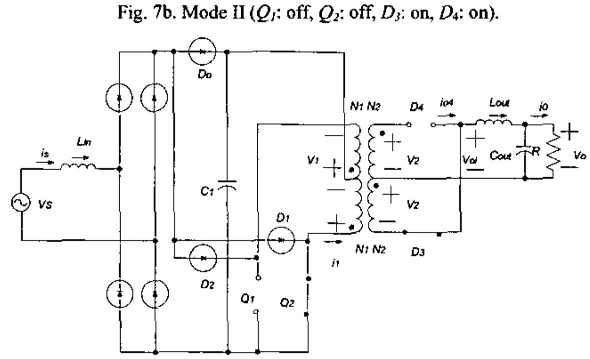

Fig. 7c. Mode III (Q_1: off, Q_2: on, D_3: on, D_4: off).

There are five operating modes for Boost + Push-Pull converter working in DCM-DCM. In the first half period, circuit works in modes I (Fig. 7a), V (Fig. 9), and VI (Fig. 10). In the second half period, circuit works in modes III (Fig. 7c), IV (Fig. 8), and VI (Fig. 10).

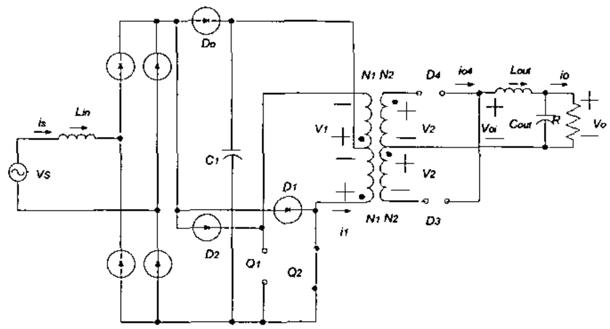

Fig. 8. Mode IV (Q_1: off, Q_2: on, D_3: off, D_4: off).

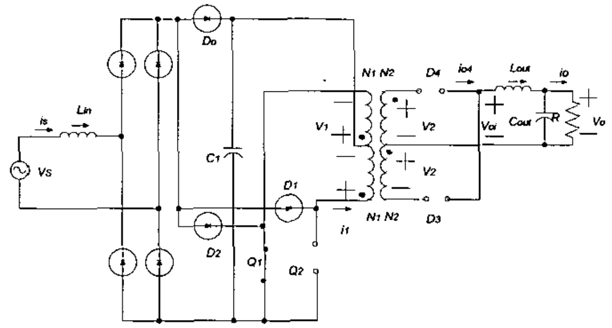

Fig. 9. Mode V (Q_1: on, Q_2: off, D_3: off, D_4: off).

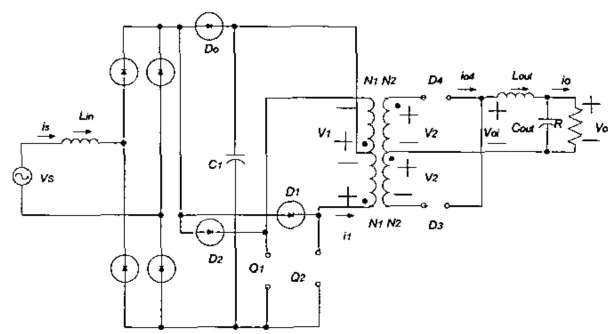

Fig. 10. Mode VI (Q_1: off, Q_2: off, D_3: off, D_4: off).

For DCM Push-Pull converter, the following constraint exists.

$$\frac{2L_{out}}{RT} \le 1 - d_1. \quad (7)$$

The output power is:

$$P_{out} = \frac{V_o^2}{R} = \frac{(MV_{C1})^2}{R}. \quad (8)$$

Where M is the voltage ratio between output voltage and input voltage for DCM Push-Pull converter.

$$M = \frac{V_o}{V_{C1}} = \frac{4}{n\left(1+\sqrt{1+8L_{out}/RTd_1^2}\right)}. \quad (9)$$

From equation (4), (8), and (9), we obtain:

$$V_{C1}=\frac{1+\sqrt{1+\frac{n^2RT}{2L_{in}}\cdot\frac{d_1^{\,2}\left(1+\sqrt{1+\frac{8L_{out}}{RTd_1^{\,2}}}\right)^2}{4}}}{2}V_{in}\,. \tag{10}$$

From equation (7) and (10), we have:

$$\frac{d_1^{\,2}\left(1+\sqrt{1+\frac{8L_{out}}{RTd_1^{\,2}}}\right)^2}{4}\le\frac{d_1^{\,2}\left(1+\sqrt{1+\frac{4(1-d_1)}{d_1^{\,2}}}\right)^2}{4}=1\,. \tag{11}$$

From equation (6), (10) and (11), we can know that boost + push-pull converter in DCM-DCM situation has smaller capacitor voltage than that in the DCM- CCM situation.

The second method to reduce the bulk capacitor voltage is introduced below. In this method, inductor L_b is added in the circuit. There are five operational modes for this topology. Mode I is shown in the Fig. 9. In this mode, Q_1 and Q_2 are both on at the same time. The primary side of the transformer is shorted for the reason of flux cancellation. The input inductor L_{in} is charged by the input voltage source. The inductor L_b is also charged by the capacitor C_1. In the first half period, the circuit works in modes I, II, III, and IV. In the second half period, the circuit works in modes I, V, VI, and IV.

In this method, input inductor L_{in} works in DCM mode. L_b works in DCM as well. The duty on time for input inductor L_{in} is d_1T. The duty on time for inductor L_b is d_2T. T is the switching period.

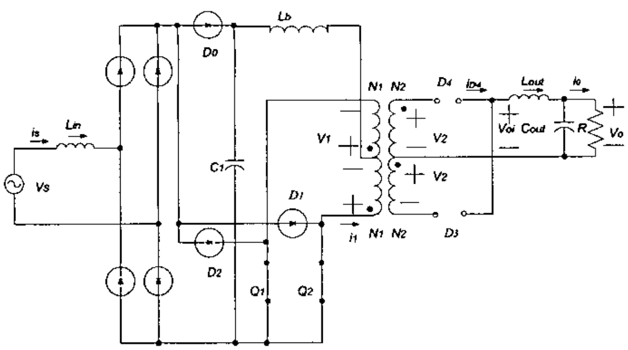

Fig. 11. Mode I (Q_1: on, Q_2: on, D_3: off, D_4: off).

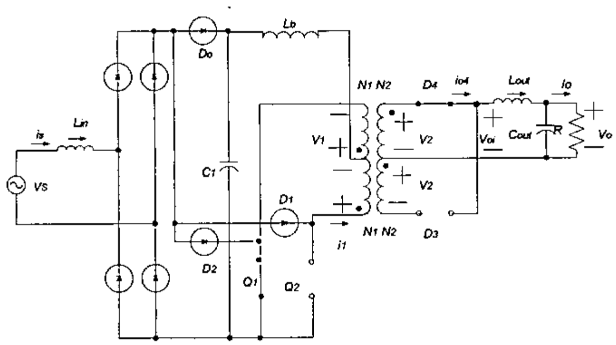

Fig. 12. Mode II (Q_1: on, Q_2: off, D_3: on, D_4: off).

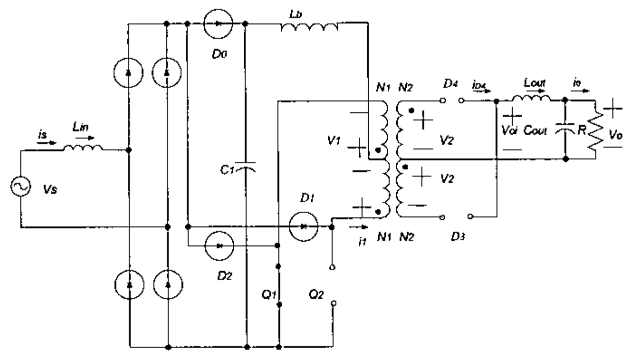

Fig. 13. Mode III (Q_1: on, Q_2: off, D_3: off, D_4: off).

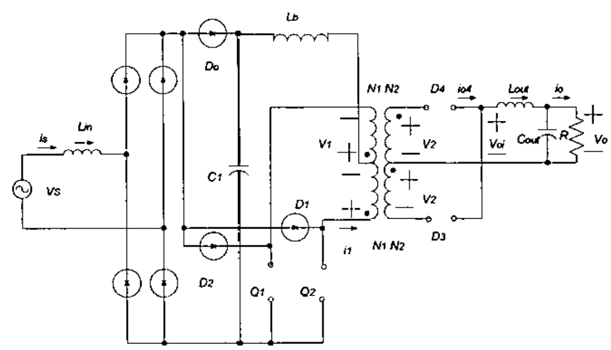

Fig. 14. Mode IV (Q_1: off, Q_2: off, D_3: off, D_4: off).

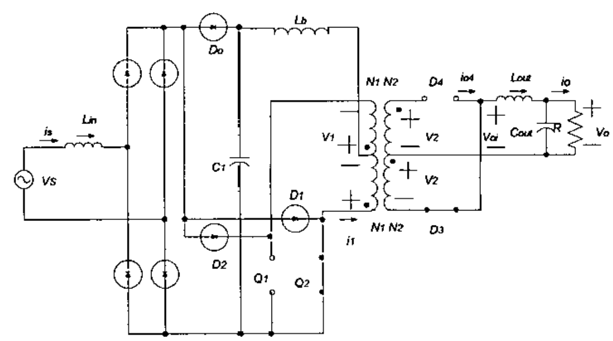

Fig. 15. Mode V (Q_1: off, Q_2: on, D_3: off, D_4: on).

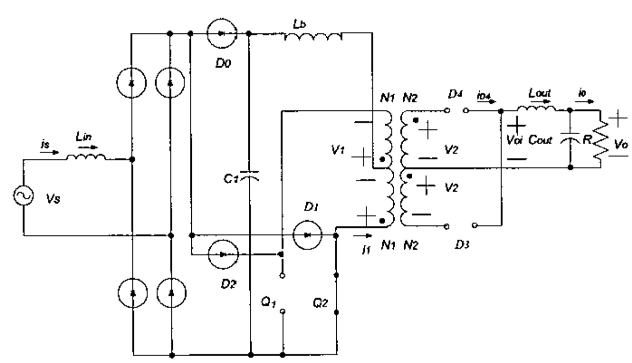

Fig. 16. Mode VI (Q_1: off, Q_2: on, D_3: off, D_4: off).

In the second method, for DCM Boost converter, the following constraint exists.

$$\frac{2L_b}{R`T} \le d_2(1-d_2)^2. \tag{12}$$

where R` is the equivalent resistor. The output power is:

$$P_{out} = \frac{V`_o{}^2}{R`} = \frac{(M`V_{C1})^2}{R`}. \tag{13}$$

where M` is the voltage ratio between the output voltage and input voltage for DCM Boost converter.

$$M` = \frac{V_o`}{V_{C1}} = \frac{1+\sqrt{1+\frac{4d_2{}^2 R`T}{2L_b}}}{4}. \tag{14}$$

From equations (4), (13), and (14), we obtain:

$$V_{C1} = \frac{1+\sqrt{1+\frac{n^2RT}{2L_{in}}\cdot\frac{4d_1{}^2}{M`^2}}}{2}V_{in}. \tag{15}$$

As introduced above, in this control method, we have:

$$0 \le d_2 < d_1 < 0.5. \tag{16}$$

From equations (12), (15) and (16), we have:

$$\frac{4d_1{}^2}{M`^2} \le \frac{4d_1{}^2}{\left(\frac{1+\sqrt{4d_2/(1-d_2)^2}}{2}\right)^2} = (2d_1(1-d_2))^2 < 1. \tag{17}$$

From equations (6), (15) and (17), the new Boost + Push-Pull converter in DCM-DCM mode has smaller capacitor voltage than that in the DCM- CCM mode.

III. Control Method for Boost Integrated Converter

In the DCM-CCM mode, the voltage on the bulk capacitor is dependent on the load. Variable frequency control was employed to reduce the bulk capacitor voltage. However, this way will increase the difficulty for inductor and transformer design and circuit filter.

In the DCM-DCM mode, the front-end Boost converter has the inherent PFC function. The voltage on the bulk capacitor is independent on the load. We only need to use the voltage control method to regulate the output voltage.

As it was shown, the introduced integrated power converter enjoys features such as wide range of output voltage regulation, small size, low implementation cost. However, the dynamic of the converter is more complicated than the conventional single stage power converters. It is not almost a doable task to derive the small signal model of the proposed topology. Hence, the new control method of Pulse Regulation is proposed to achieve line and load regulation [9]. This method is simple and does not require a detailed model of the converter.

Pulse Regulation control algorithm achieves output voltage regulation based on generating high and low power pulses. If the output voltage is lower than the desired level, the controller chooses D_H to be the duty ratio and therefore, high-power pulses are generated sequentially until the desired voltage level is reached. On the other hand, if the output voltage is higher than the desired level, instead of generating the high-power pulses, the controller chooses D_L ($D_L < D_H$) to be the duty ratio and hence, low-power pulses are generated to descend the level of the output voltage. Fig. 17 depicts the block diagram of the Pulse Regulation control technique. Due to the longer on time of the switch during a high-power pulse, compared to a low-power pulse, more power will be delivered to the load. The switching frequency is constant and D_H is chosen in a way that the converter operates in DCM but as close as possible to the critical conduction mode. Critical conduction mode occurs when the input voltage is at its maximum level. *K*, the ratio between duty cycle of the switch in a high-power cycle D_H and duty cycle of the switch in a low-power cycle D_L, is chosen by making a compromise between the output voltage ripple and the power regulation range from full load to low load.

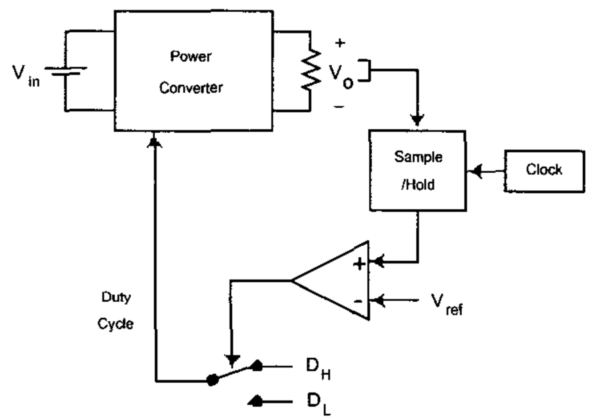

Fig. 17. Block diagram of Pulse Regulation control scheme.

Fig. 18 depicts the current waveform of the input after Pulse Regulation is being applied. At the beginning of each switching cycle, output voltage is being sampled and based on the difference of the output voltage with the desired voltage level, Pulse Regulation controller decides whether a high-power or a low-power cycle needs to be generated. Since the input current ramps linearly with the on-time of the switch, the amount of energy that is drawn from the input power source in a high-power cycle is equal to

$$\Delta E_{in,HP} = \frac{(V_{in}T)^2}{2L_m} D_H{}^2. \tag{18}$$

While the amount of energy that is drawn from the input power source in a low-power cycle is equal to:

$$\Delta E_{in,Lp} = \frac{(V_{in}T)^2}{2L_m} D_L{}^2 = \frac{\Delta E_{in,HP}}{k^2}. \tag{19}$$

Therefore a low-power pulse transfers just $1/k^2$ time as much energy as a high-power pulse. Output voltage sampler and the driver of the switch of the converter are synchronized, therefore the switching frequency is constant and the output voltage is being sampled only once during each switching period.

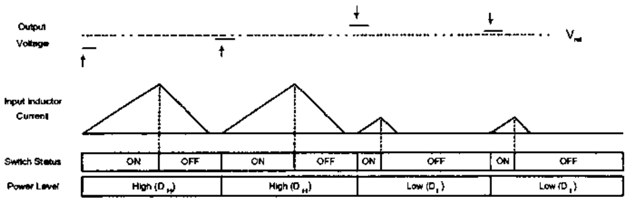

Fig. 18. High and low-power pulse cycles.

IV. Simulation Results

Input voltage is 110V AC, switching frequency is 25 kHz, P=100W, n=5, V_O=24V. The input voltage and current for the DCM Boost converter is in shown in Fig. 19. CCM and DCM current waveforms for push pull converter are drawn in Figs. 20 and 21. Current waveform of Lb in the second method is shown in Fig. 22. Both methods to reduce the capacitor voltage are tested. The bulk capacitor voltage is 20% lower than that in CCM.

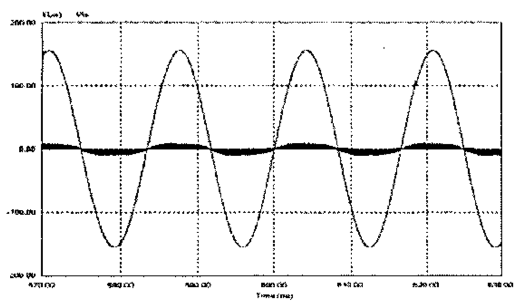

Fig. 19. Input current and voltage waveform for the Boost converter.

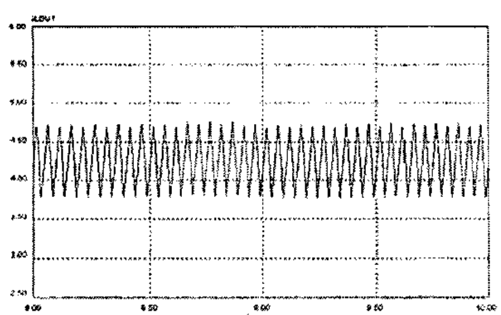

Fig. 20. Output current waveform for Push-Pull converter in CCM.

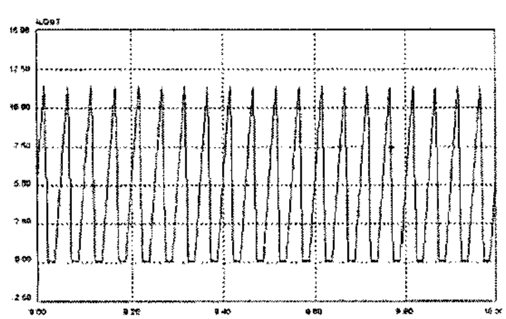

Fig. 21. Output current waveform for Push-Pull converter in DCM.

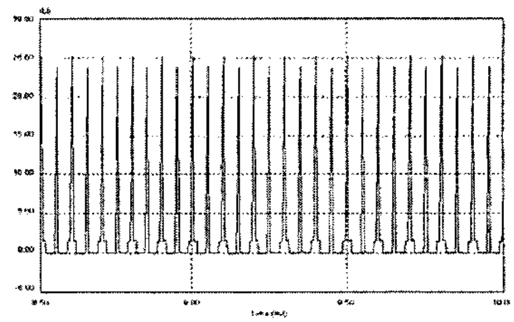

Fig. 22. Current waveform of Lb in the second method.

V. Conclusion

This paper discusses Boost + Push-Pull integrated converter. Formulation and operation mode for DCM-CCM and DCM-DCM are given. One additional DCM-DCM operation mode is explained. Pulse regulation control method is used to control this converter. Simulation results are presented.

VI. Refreences

[1] M. J. Willers, M. G. Egan, J. M. D. Murphy, and S. Daly, "A BIFRED converter with a wide load range," in *Proc. IEEE 20th International Conference on Industrial Electronics, Control and Instrumentation,* 1994.

[2] V. S. Murali and C. K. Tse, "Comparison of small-signal dynamics of BIFRED and single-stage cascaded boost-and-fly back PFC converters," in *Proc. IEEE 29th Power Electronics Specialists Conference,* 1998.

[3] J. Chen and C. Chang, "Analysis and design of SEPIC converter in boundary conduction mode for universal-line power factor correction applications," in *Proc. 32nd IEEE Power Electronics Specialists Conference,* 2001.

[4] M. J. Willers, M.G. Egan, J. M. D. Murphy, and S. Daly, "Analysis and design of a practical discontinuous-conduction-mode BIFRED converter," *IEEE Transactions on Industrial Electronics,* vol. 46, No. 4, Aug. 1994.

[5] M. T. Madigan, R. W. Erichson, and E. H. Ismail, " Integrated high-quality rectifier-regulators," *IEEE Transactions on Industrial Electronics,* vol. 46, No. 4, Aug. 1999.

[6] D. S. L. Simonetti, J. Sebastian, and J. Uceda, "The discontinuous conduction mode SEPIC and Cuk power factor preregulators: analysis and design," *IEEE Transactions on Industrial Electronics,* vol. 44, no. 5, Oct. 1997.

[7] Z. Nie, A. Emadi, J. Mahdavi, and M. Telefus, "SEPIC and BIFRED converters for switch-mode power supplies: a comparative study," in *Proc. IEEE 24th International Telecommunications Energy Conference,* 2002, pp. 444-450.

[8] M. Ferdowsi and A. Emadi, "Estimative current mode control technique for DC-DC converters operating in discontinuous conduction mode," *IEEE Power Electronics Letters,* vol. 2, no. 1, pp. 20-23, March 2004.

[9] M. Ferdowsi and A. Emadi, "Pulse regulation control technique for flyback converter," in *Proc. 19th Annual IEEE Applied Power Electronics Conference,* Anaheim, CA, Feb. 2004.