PSIM SIMULATION OF VARIABLE DUTY CYCLE CONTROL DCM BOOST PFC CONVERTER TO ACHIEVE HIGH INPUT POWER FACTOR

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Abstract - *Power Factor Correction (PFC) converters have been widely used in ac–dc power conversions to achieve high power factor (PF) and low harmonic distortion. The methods of achieving PFC can be classified into active and passive types. Compared with a passive PFC converter, an active PFC converter can achieve a high PF and a small size. There are different topologies for implementing active PFC techniques, among which the boost converter is the representing topology because it exhibits many advantages such as small input– current ripple due to the series connection of the inductor at the input side, high PF over the whole input–voltage range, small size in the output capacitor due to its high voltage, and simple circuit.   When a boost PFC converter operates in CCM, the inductor current ripple is very small, leading to low root-mean-square (RMS) currents on the inductor and switch and to low electromagnetic interference (EMI). However, the switch always operates at hard switching, and the diode suffers from reverse recovery. A discontinuous-current-mode (DCM) boost power factor correction (PFC) converter features zero-current turn-on for the switch, no reverse recovery in diode, and constant– frequency operation. However, the input power factor (PF) is relatively low when the duty cycle is constant in a half line cycle. This thesis derives the expressions of the input current and PF of the DCM boost PFC converter, and based on that, variable-duty-cycle control is proposed so as to improve the PF to nearly unity in the whole input– voltage range. A method of fitting the duty cycle is further proposed for simplifying the circuit implementation. Other than a higher PF, the proposed variable-duty-cycle control achieves a lower output–voltage ripple and a higher efficiency over constant-duty-cycle control*

Key Words: Discontinuous current mode (DCM), power factor correction (PFC), variable-duty-cycle control.

INTRODUCTION

Most applications requiring ac-dc power converters need the output dc voltage to be well regulated with good steady-state and transient performance. The circuit typically favored until recently (diode rectifier-capacitor filter) for the utility interface is cost effective, but it severely deteriorates the quality of the utility supply thereby affecting the performance of other loads connected to it besides causing other well known problems. In order to maintain the quality of the utility supply, several national and international agencies have started imposing standards and recommendations for electronic instrument connected to the utility. Since the mid-1980's power electronics engineers have been developing new approaches for better utility interface, to meet these standards. These new circuits have been collectively called Power factor correction (PFC) circuits.

With the increase of consumer electronics the power quality becomes poor. The reactive power drawn from the supply is increasing. This is because of the use of rectification of the AC input and the use of a bulk capacitor directly after the diode bridge rectifier. Reducing the input current harmonics to meet the agency standards implies improvement of power factor as well. For this reason the publications reported in this area have used "Power factor correction methods" and "Harmonic elimination/reduction methods" almost inter changeably. Several techniques for PFC and harmonic reduction have been reported and a few of them have gained greater acceptance over the others.

This chapter discusses the i) Nonlinear loads and their effect on the electricity distribution network, ii) Standard IEC and IEEE regulation for harmonics, iii) Power factor correction and its benefits, iv) application of PFC both for linear and non-linear loads, v) research background, vi) aim of the dissertation.

I. NONLINEAR LOADS AND THEIR EFFECT ON THE ELECTRICITY DISTRIBUTION NETWORK:

 The instrument connected to an electricity distribution network usually needs some kind of power conditioning, typically rectification, which produces a non-sinusoidal line current due to the non-linear input characteristic. Line-frequency diode rectifiers convert AC input voltage into DC output voltage in an uncontrolled manner. Single-phase diode rectifiers are needed in relatively low power instrument that needs some kind of power conditioning, such as electronic instrument and household appliances. For higher power, three-phase diode rectifiers are used. In both single and three-phase rectifiers, a large filtering capacitor is connected across the rectifier output to obtain DC output voltage with low ripple. As a consequence, the line current is non sinusoidal. In most of these cases, the amplitude of odd harmonics of the line current is considerable with respect to the fundamental. While the effect of a single low power

nonlinear load on the network can be considered negligible, the cumulative effect of several nonlinear loads is important. Line current harmonics have a number of undesirable effects on both the distribution network and consumers.

These effects include:

1. Losses and overheating in transformers shunt capacitors, power cables, AC machines and Switchgear, leading to premature aging and failure.

2. Excessive current in the neutral conductor of three-phase four-wire systems, caused by odd Triple current harmonics (triple-n: 3rd, 9th, 15th, etc.).

3. Reduced power factor, hence less active power available from a wall outlet having a certain apparent power rating.

4. Electrical resonances in the power system, leading to excessive peak voltages and RMS currents, and causing premature aging and failure of capacitors and insulation.

5. The distorted line voltage may affect other consumers connected to the electricity distribution network.

6. Telephone interference.

7. Errors in metering instrument.

8. Increased audio noise.

9. Cogging or crawling in induction motors, mechanical oscillation in a turbine-generator combination or in a motor-load system

II. POWER FACTOR CORRECTION:

Reduction of line current harmonics is needed in order to comply with the standard. This is commonly referred to as the Power Factor Correction - PFC, which may be misleading. When an electric load has a PF lower than 1, the apparent power delivered to the load is greater than the real power that the load consumes. Only the real power is capable of doing work, but the apparent power determines the amount of current that flows into the load, for a given load voltage.

Power factor correction (PFC) is a technique of counteracting the undesirable effects of electric loads that create a power factor PF that is less than 1.

The power factor is defined as the ratio of the active power P to the apparent power S:

$$PF = P/S \qquad (2.1)$$

For purely sinusoidal voltage and current, the classical definition is obtained:

$$pf = \cos\phi \qquad (2.2)$$

Where $\cos\Phi$ is the displacement factor of the voltage and current. In classical sense, PFC means compensation of the "displacement factor".

The line current is non-sinusoidal when the load is nonlinear. For sinusoidal voltage and non-sinusoidal current the PF can be expressed as.

$$PF = \frac{V_{rms}I_{1rms}}{V_{rms}I_{rms}}\cos\phi = \frac{I_{1rms}}{I_{rms}}\cos\phi = K_p\cos\phi \qquad (2.3)$$

$$K_p = \frac{I_{1rms}}{I_{rms}}, K_p \in [0,1] \qquad (2.4)$$

Kp describes the harmonic content of the current with respect to the fundamental. Hence, the power factor depends on both harmonic content and displacement factor. Kp is referred to as purity factor or distortion factor.

The total harmonic distortion factor THDi is defined as

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n,rms}^2}}{I_{1rms}} \qquad (2.5)$$

Hence the relation between Kp and THDi

$$K_p = \frac{1}{\sqrt{1+THD^2}} \qquad (2.6)$$

Standard IEC 1000-3-2 sets limits on the harmonic content of the current but does not specifically regulate the purity factor Kp or the total harmonic distortion of the line current THDi. The values of Kp and THDi for which compliance with IEC 1000-3-2 is achieved depend on the power level. For low power level, even a relatively distorted line current may comply with the standard. In addition to this, it can be seen from (1.6) that the distortion factor Kp of a waveform with a moderate THDi is close to unity (e.g. Kp=0.989 for THDi=15%). Considering (2.3) as well, the following statements can be made:

1. Power factor PF is not significantly degraded by harmonics, unless their amplitude is quite large (low Kp, very large THDi).

2. Low harmonic content does not guarantee high power factor (Kp close to unity, but low cosΦ).

Benefits of Power Factor:

1. Voltage distortion is reduced.

2. All the power is active.

3. Smaller RMS current.

4. Higher number of loads can be fed.

Most of the research on PFC for nonlinear loads is actually related to the reduction of the harmonic content of the line current. There are several solutions to achieve PFC. The shape of the input current can be further improved by using a combination of low pass input and output filters Depending on whether active switches (controllable by an

external control input) are used or not, PFC solutions can be categorized as "Passive" or "Active".

In passive PFC, only passive elements are used in addition to the diode bridge rectifier, to improve the shape of the line current. Obviously, the output voltage is not controllable. For active PFC, active switches are used in conjunction with reactive elements in order to increase the effectiveness of the line current shaping and to obtain controllable output voltage. The switching frequency further differentiates the active PFC solutions into two classes. In low frequency active PFC, switching takes place at low-order harmonics of the line-frequency and it is synchronized with the line voltage. In high-frequency active PFC, the switching frequency is much higher than the line frequency.

III. OPERATION IN DISCONTINUOUS CURRENT MODE - DCM:

These converters operating in CCM reduces the line current harmonics, it also has Drawbacks, such as:

1) It increases the EMI, due to the high-frequency content of the input current.

2) It introduces additional losses, thus reducing the overall efficiency and

3) It increases the complexity of the circuit, with negative effects on the reliability of the instrument, as well as on its size, weight and cost.

The high frequency EMI can be eliminated by introducing an EMI filter between AC supply and diode bridge rectifier. The additional losses will be reduced by using soft switching techniques such as 'ZVS', 'ZCS' and 'ZVT'. Some of the basic EMI filter requirements and a novel Zero Voltage Transition - ZVT technique, which can be applied to boost converter used in the PFC

In this chapter, basic types of dc-dc converter topologies are studied to investigate their self-PFC capabilities. Basic types of dc-dc converters, when operating in discontinuous inductor current mode, have self power factor correction (PFC) property, that is, if these converters are connected to the rectified ac line, they have the capability to give higher power factor by the nature of their topologies. Input current feedback is unnecessary when these converters are employed to improve power factor. This property of DCM input circuit can be called "self power factor correction" because no control loop is required from its input side. This is also the main advantage over a CCM power factor correction circuit, in which multi-loop control strategy is essential. The peak of the inductor current is sampling the line voltage automatically.

However, the input inductor operating in DCM cannot hold the excessive input energy because it must release all its stored energy before the end of each switching cycle. As a result, a bulky capacitor is used to balance the instantaneous

power between the input and output. In addition, if discontinuous inductor current mode is applied, the input current is normally a train of triangle pulse with nearly constant duty ratio. In this case, an input filter is necessary for smoothing the pulsating input current into a continuous one. Obviously, to ensure high power factor, the average current of the pulsating current should follow the input voltage in both shape and phase. In this operating mode, the inductor current varies from zero to a maximum and returns back to zero before the beginning of the next switching cycle.

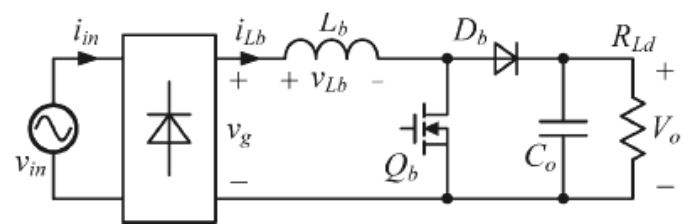IV.DCM BOOST PFC CONVERTER WITH CONSTANT-DUTY-CYCLE CONTROL


Fig. 4.1 boost PFC converter

Fig. 4.1 shows the main circuit of a boost PFC converter. For simplicity, the following assumptions are made: 1) All the devices and components are ideal; 2) the ripple of the output voltage is too small to be neglected; and 3) the switching frequency is much higher than the line frequency.

Supposing that the input voltage is purely sine waveform and it has no distortion, the input voltage is defined as

$$v_{in}(t) = V_m \sin \omega t \quad \text{...............} \quad (4.1)$$

Where V_m is the amplitude of the input voltage and ω is the angular frequency of the input voltage.

Then, the rectified voltage is
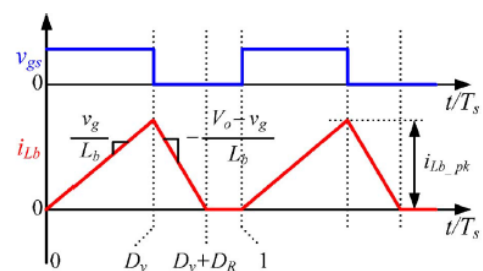
$$v_g = V_m |\sin \omega t| \quad \text{...........} \quad (4.2)$$

Fig. Inductor current waveform in a switching cycle

Fig. 4.2 shows the inductor current waveform in a switching cycle when the converter operates in DCM. In a switching cycle, the inductor peak current i_{Lb_pk} is

$$i_{Lb\_pk}(t) = \frac{v_g}{L_b}D_y T_s = \frac{V_m|\sin \omega t|}{L_b}D_y T_s \quad \ldots \quad (4.3)$$

Where D_y is the duty cycle and T_s is the switching cycle.

In each switching cycle, the inductor has a volt-second balance, i.e.,

$$v_g D_y T_s = (V_o - v_g)D_R T_s \quad \ldots\ldots\ldots\ldots \quad (4.4)$$

Where V_o is the output voltage and D_R is the duty cycle corresponding to the reset time of the inductor current.. Equation (4) can be rewritten as

$$D_R = \frac{v_g}{V_o - v_g}D_y = \frac{V_m|\sin \omega t|}{V_o - V_m|\sin \omega t|}D_y \quad (4.5)$$

From eq.(4.3) and (4.5), the average inductor current in a switching cycle can be derived as

$$i_{Lb\_av}(t) = \frac{1}{2}i_{Lb\_pk}(t)(D_y + D_R) = \frac{V_m D_y^2}{2L_b f_s}\frac{|\sin \omega t|}{1 - \frac{V_m}{V_o}|\sin \omega t|}D_y$$

$$\ldots \quad (4.6)$$

Where $f_s = 1/T_s$ is the switching frequency.   Thus, the

$$i_{in}(t) = \frac{V_m D_y^2}{2L_b f_s}\frac{\sin \omega t}{1 - \frac{V_m}{V_o}|\sin \omega t|}$$

input current is $\ldots\ldots$ (4.7)

When D_y is constant, according to eq.(4.3) and eq.(4.6), Fig.4.3 shows the instantaneous waveform, the peak value envelope, and the ave rage value of the inductor current. It can be seen that the shape of the peak inductor current is sinusoidal; however, the shape of the average inductor current is not sinusoidal, and there is distortion in it.
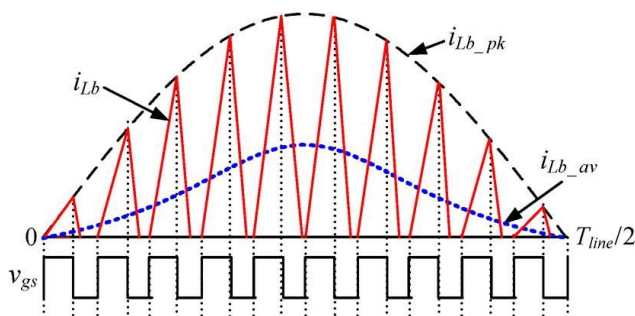

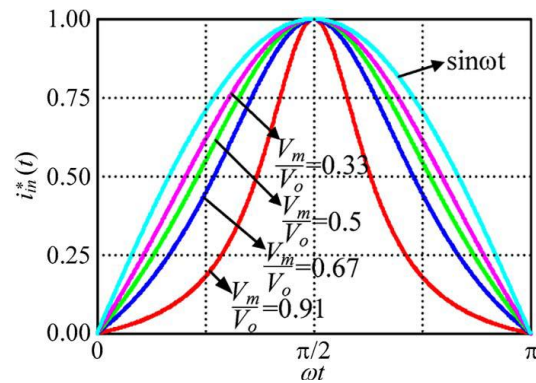Fig. 4.3. Inductor current waveform in a half line cycle.

Fig. 4.4. Normalized input-current waveform in a half line cycle. For analysis simplicity, the average inductor current is

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$$(V_m D_y^2 / 2L_b f_s)(1/(1 - V_m / V_o)) \text{, so eq.(4.7) is rewritten as}$$

$$i_{in}^* = \left(1 - \frac{V_m}{V_o}\right)\frac{\sin \omega t}{1 - \frac{V_m}{V_o}|\sin \omega t|}$$

$$\ldots\ldots\ldots \quad (4.8)$$

According to eq.(4.8), the normalized average inductor current is shown in Fig. 5.4, from which it can be seen that the shape of the average inductor current is only dependent on V_m/V_o, and the smaller the V_m/V_o is, the closer to sinusoidal the current shape is. This can be explained as follows. As the duty cycle is constant in a line cycle, the peak value of the inductor current is in the sinusoidal shape, and the average value of the inductor current in the rising period is sinusoidal. However, the falling time of the inductor current is dependent on the value of $(V_o - v_g)$, and it varies with v_g, so the average value of the inductor current in the falling period is not sinusoidal. Thus, the average value of the inductor current in a switching cycle is not sinusoidal. The smaller the V_m/V_o is, the shorter the falling time of the inductor current is and, thus, the closer to sinusoidal shape the average inductor current in a switching cycle is.

From eq.(4.1) and eq.(4.7), the average input power is derived as

$$P_{in} = \frac{1}{T_{line}/2}\int_0^{\frac{T_{line}}{2}} v_{in}(t)i_{in}(t)dt$$

$$= \frac{V_m^2 D_y^2}{2L_b f_s}\frac{1}{\pi}\int_0^\pi \frac{\sin^2 \omega t}{1 - \frac{V_m}{V_o}|\sin \omega t|}d\omega t$$

$$\ldots \quad (4.9)$$

Where T_{line} is the line cycle.

Assuming that the efficiency of the converter is 100%, i.e., $P_{in} = P_o$, the duty cycle is

$$D_y = \frac{1}{V_m}\sqrt{\frac{2L_b f_s \pi P_o}{\displaystyle\int_0^\pi \frac{\sin^2 \omega t}{1-\frac{V_m}{V_o}\left|\sin \omega t\right|} d\omega t}}$$

...... (4.10)

From eq.(4.7) and eq.(4.9), the input PF can be derived as

$$PF = \frac{P_{in}}{\frac{1}{\sqrt{2}}V_m I_{in\_rms}} = \frac{P_{in}}{\frac{1}{\sqrt{2}}V_m \sqrt{\frac{1}{\pi}\int_0^\pi \left(i_{in}(t)\right)^2 d\omega t}}$$

$$=\frac{\sqrt{\dfrac{2}{\pi}\displaystyle\int_0^\pi \dfrac{\sin^2 \omega t}{1-\dfrac{V_m}{V_0}\left|\sin \omega t\right|} d\omega t}}{\sqrt{\displaystyle\int_0^\pi \left(\dfrac{\sin \omega t}{1-\dfrac{V_m}{V_0}\left|\sin \omega t\right|}\right)^2 d\omega t}}$$

.... (4.11)

Where I_{in_rms} is the rms value of the input current.

Fig.5.4 (a) input voltage and current (b) output voltage waveforms with constant-duty-cycle control boost converter-R-L Load

Comments: Fig.5.4 (a) Shows input voltage and current waveform form in this we can observe that the input power factor is .934 and the output voltage with constant-duty-cycle control is 40VDC with the voltage ripple is 6%. In this circuit the voltage boost up from 12VAC to 40VDC and the line current harmonics are neglected.

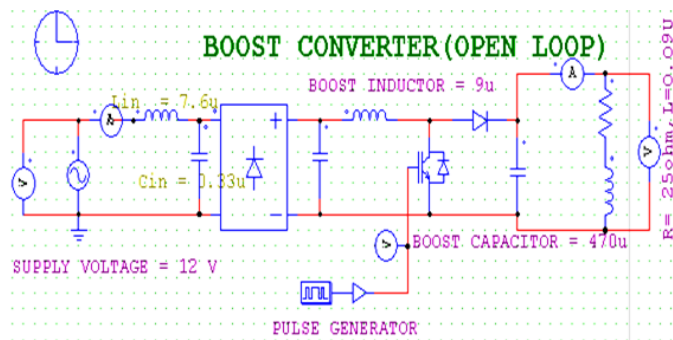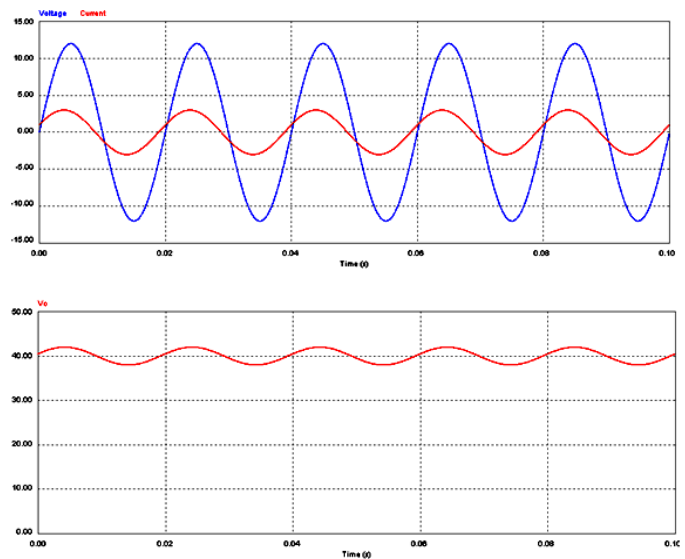## V. DCM BOOST PFC CONVERTER WITH CONSTANT-DUTY-CYCLE CONTROL (OPEN LOOP)

Fig.5.3 DCM Boost PFC converter with constant-duty-cycle control-R-L Load

Circuit specifications: Supply Voltage = 12 V

Filter inductor Lin = 7.6u , Filter capacitor Cin = 0.33u

Boost Capacitor = 470u , Boost Inductor = 9u

R=25ohm, L=0.09u,Pulse Generator Frequency = 10khz

Duty Ratio=0.7

Simulation waveforms

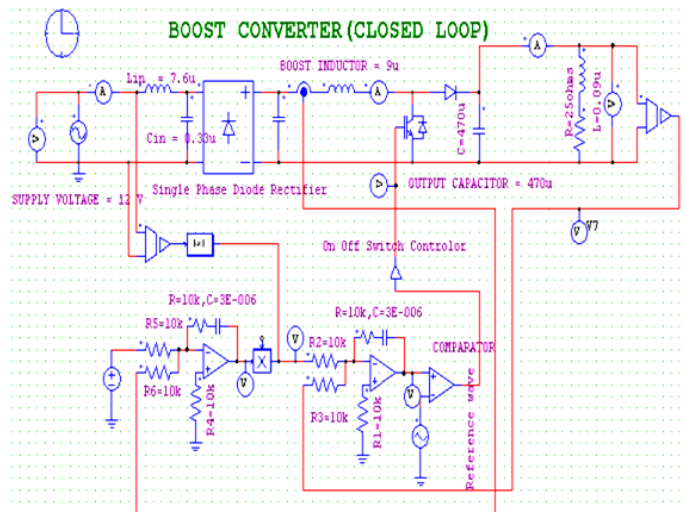## VI. DCM BOOST PFC CONVERTER WITH VARIABLE-DUTY-CYCLE CONTROL (CLOSED LOOP)

Fig.6.3 DCM Boost PFC converter with Variable-duty-cycle control-R-L Load

Circuit specifications Supply Voltage = 12 V

Filter inductor Lin = 7.6u ,Filter capacitor Cin = 0.33u

Boost Capacitor = 470u, Boost Inductor = 9u, R=25ohm,

Reference wave frequency 100khz,

Switching Frequency = 100k
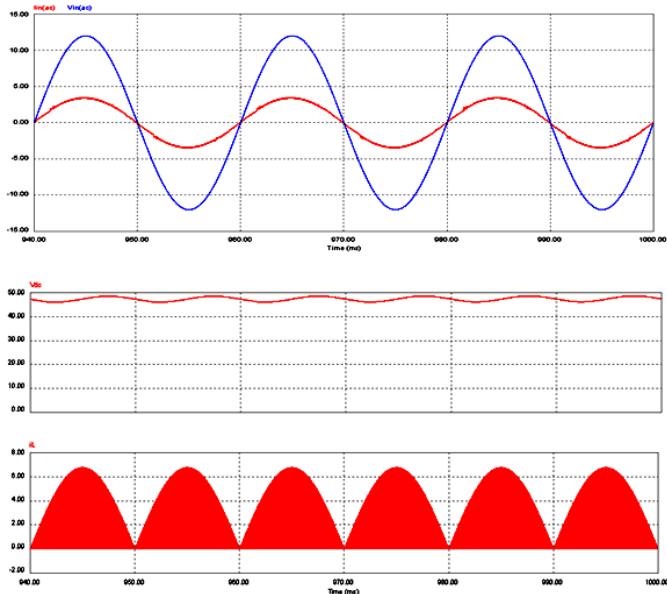
Simulation waveforms

Fig.6.4 (a) input voltage and current (b) output voltage (c) Boost inductor current waveforms with Variable-duty-cycle control boost converter-R-L Load

Comments:

Fig.6.4 (a) Shows input voltage and current waveform form in this we can observe that the input power factor is 0.9984, Fig.6.4 (b) Shows output voltage waveforms with Variable-duty-cycle control in this the voltage ripple is 2% Fig.6.4 (c) Shows Boost inductor current waveforms here the switching frequency is 100khz and the inductor

Current is zero for each switching interval.
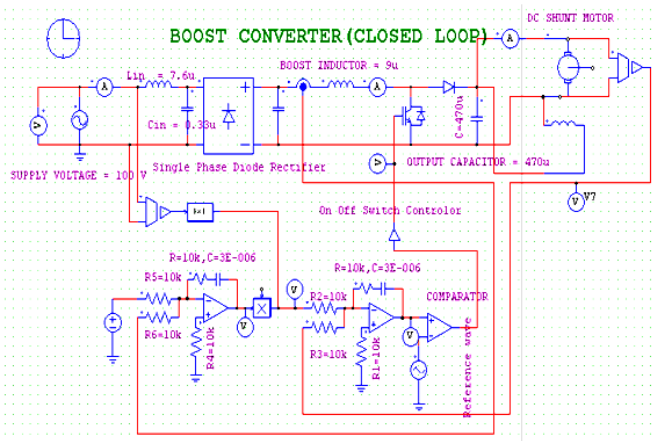
Dc motor load

Fig.6.5 DCM Boost PFC converter with Variable-duty-cycle control-DC Motor Load

Circuit specifications

Supply Voltage = 12 V, Filter inductor Lin = 7.6u

Filter capacitor Cin = 0.33u, Boost Capacitor = 470u

Boost Inductor = 9u,

Reference wave frequency 100khz

Switching Frequency = 100k,
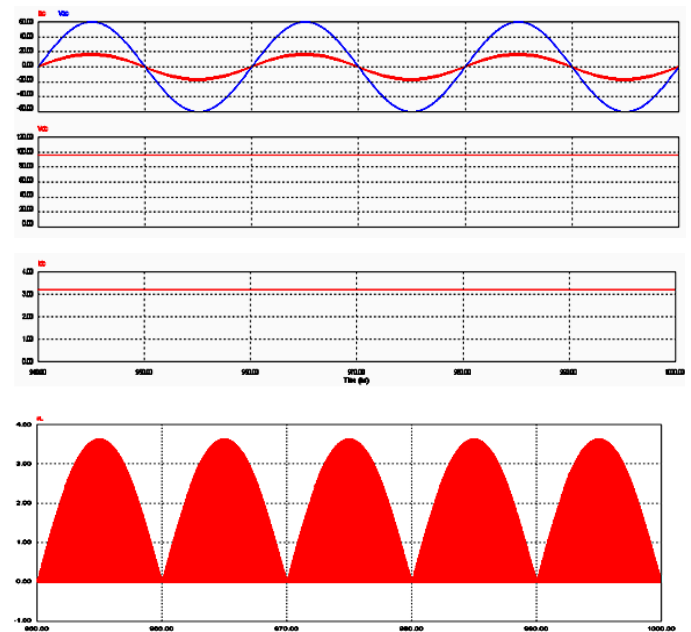
DC Shunt motor parameters

Simulation waveforms

Fig.6.5 (a) input voltage and current (b) output voltage (c) load current (d) Boost inductor current waveforms with Variable-duty-cycle control boost converter-DC motor Load

CONCLUSION

In DCM, the input inductor is no longer a state variable since its state in a given switching cycle is independent on the value in the previous switching cycle. The peak of the inductor current is sampling the line voltage automatically. This property of DCM input circuit can be called "self power factor correction" because no control loop is required from its input side.

It can conclude that the basic boost converter and buck-boost converter have excellent self PFC capability naturally. Among them, boost converter is especially suitable for DCM PFC usage and buck-boost is not widely used because of the drawbacks such as: the input voltage and the output voltage don't have a common ground due to the reversed output voltage polarity, etc. Hence, this converter is the most preferable by the designers for the power factor correction purpose. Other converters may be used only if their input V-I characteristics have been modified (linear zed), or when they operate in a continuous inductor conduction mode. To conclude, a 500 W, 40 kHz variable duty cycle DCM boost

PFC converter has been analyzed, simulated and results are presented in this thesis. The proposed converter gives around 0.9977 (almost unity) power factor with an efficiency of around 98%.

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BIOGRAPHIES

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