Parasitic Effect Considerations in Modeling of CI-BDC Converter and its Voltage Controller

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***Abstract*--This paper emphasize on the investigation of small-signal behavior of a Coupled Inductor Bidirectional DC-DC (CI-BDC) converter being controlled by a Voltage Mode Control (VMC) technique. The small-signal model including converter parasitics is derived using the SS averaging technique. This linearised converter modeling makes the design of closed loop controller much easier. The closed loop model has also been developed and simulated using SIMULINK/MATLAB software. The parasitic effects on stability and closed loop regulation have been made extensively. Simulation results of closed loop controlled CI-BDC converter show the good regulation and stability over wide range of load variations. The analyses show that the proper consideration of parasitics is also a very important for controller design.**

***Index Terms*-- Bidirectional DC-DC converter (BDC), Coupled Inductor (CI), State Space (SS) Modeling, Voltage Mode Control (VMC), and Parasitics.**

I. Introduction

THE inherent switching operation of power electronic converters results in the circuit components being connected together in periodically changing configurations, each configuration being described by a separate set of equations. The transient analysis and control design for converters is therefore difficult, since a number of equations must be solved in sequence. The technique of averaging provides a solution to this problem. A single equation may be formed to describe the converter approximately over a number of switching cycles by simply taking a linearly weighted average of the separate equations for each switched configuration of the converter. State-Space (SS) averaging [1, 2, 3] has proven, in the past, to be very popular analysis technique for PWM power conversion circuits. Middlebrooke have been discussed the detailed SS technique approach in [1]. Use of this approach has been made in deriving converter models to assess small-signal [1, 3] and large-signal performances [7, 12]. Small-signal models provide a means of assessing local stability and are of great importance in the design of the feedback loop in regulated converters. On the other hand, large-signal models are obtained mainly in assessing the spectral purity of waveforms in system where the integrity of the wave shape is important. Here in DC-DC converters; the response actually be small-signal, thus the standard terminology of small-signal can sometimes be somewhat of a misnomer [9]. A large-signal analysis entails not only finding the response of the fundamental frequency component by using the small-signal model but also involves in determining the harmonic frequency content [7, 12]. Thus the large-signal analysis provides an assessment of the harmonic distortion performance of the system. It is readily seen that the converter analysis approach is analogous to ordinary transistor circuit analysis whereby the nonlinear device is replaced by its circuit model. In this paper a state-space modeling approach is used to describe the analysis of Coupled Inductor (CI) Bidirectional DC-DC (CI-BDC) converter with it parasitic elements. The voltage controlled CI-BDC have been developed in Simulink/Matlab environment and analyzed. The detailed operation and analysis is reported in [16].This paper, presents five sections which includes section-I, section-II discuses detailed modeling of the CI-BDC converter, section-III provides modeling and design of Voltage Mode Control (VMC); section-IV emphasizes on simulation results and analyses, and in section-V discusses the concluding remarks.

II. Modeling of CI-BDC Converter

The converter structure is highly constrained by the existing trade-off between simplicity and performances of the resulting topologies. In this sense, there is presently a practical limit located in the fourth order converters, whose most representative elements are the Cuk and the SEPIC switching cells. Due to their significant properties, both converters have been extensively used and a large number of papers have been devoted to the modeling, analysis and applications of these structures. However, BDC technology has been in the reasonably development stages for DC-DC conversion with high efficiency and reduced stress on switches. Fig.1 depicts the proposed CI-BDC converter, for which, small-signal modeling and control behavior has been made. In order to examine the dynamic behavior of the proposed converter, averaged modeling and steady state analysis are discussed using SS technique. Here, all switches and diodes are considered to be non-ideal, and thus the parasitic effects. The averaged equations frequently contain product of the system variables which are nonlinear, in order to derive linear transfer

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functions of the system, small-signal linearization technique is used. Here, two state variables, inductor current $i_L(t)=X_1(t)$, and capacitor voltage $v_C(t)=X_2(t)$ are considered. Due to the bidirectional current ability, discontinuous current does not takes place, therefore, in continuous conduction mode two equivalent configurations are depicted as in Fig. 1(b) and Fig. 1(c) respectively. For these two configurations, the converter can be represented by two piecewise-linear vector differential equations as follows:

$$\dot{X} = A_{ON} X + B_{ON} U \quad for \quad 0 < t \le \delta T \tag{1}$$

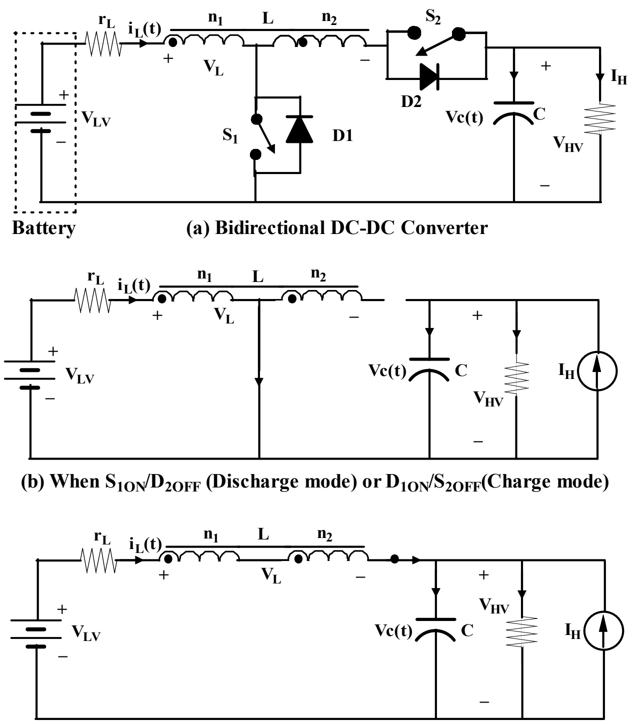
$$\dot{X} = A_{OFF} X + B_{OFF} U \quad for \quad \delta T \le t < T \tag{2}$$

The output equations are described as

$$Y = C_{ON}\, X + D_{ON}\, U \quad for \quad 0 < t \le \delta T \tag{3}$$

$$Y = C_{OFF}\, X + D_{OFF}\, U \quad for \quad \delta T \le t < T \tag{4}$$

Where, Y is the output vector, T is the switching frequency and δ is the duty cycle for switch (S_1) and its complement is the duty cycle for switch (S_2).



(a) Bidirectional DC-DC Converter

(b) When S_{1ON}/D_{2OFF} (Discharge mode) or D_{1ON}/S_{2OFF}(Charge mode)

(c) When S_{2ON}/D_{1OFF}(Charge mode) or D_{2ON}/S_{1OFF} (Discharge mode)

Fig. 1. Proposed Bidirectional DC-DC converter and its equivalent circuits

Where, $X = \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} \quad \dot{X} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_C}{dt} \end{bmatrix} \quad U = \begin{bmatrix} V_{LV} \\ I_H \end{bmatrix}$

$$A_{ON} = \begin{bmatrix} \frac{-(r_L + r_{ds})}{L} & 0 \\ 0 & \frac{-1}{(R+r_C)C} \end{bmatrix} \quad B_{ON} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{R}{C(R+r_C)} \end{bmatrix}$$

$$C_{ON} = \begin{bmatrix} 0 & \frac{R}{(R+r_C)} \end{bmatrix} \quad C_{OFF} = \begin{bmatrix} \frac{R*r_C}{(R+r_C)} & \frac{R}{(R+r_C)} \end{bmatrix}$$

$$D_{ON} = D_{OFF} = [0]$$

$$A_{OFF} = \begin{bmatrix} \frac{-1}{L(1+N)}\left[(r_L + r_F) + \frac{R*r_C}{(R+r_C)}\right] & \frac{-R}{L(1+N)(R+r_C)} \\ \frac{R}{C(R+r_C)} & \frac{-1}{(R+r_C)C} \end{bmatrix}$$

$$B_{OFF} = \begin{bmatrix} \frac{1}{L(N+1)} & 0 \\ 0 & \frac{R}{C(R+r_C)} \end{bmatrix}$$

$$A_{ON} = \begin{bmatrix} t_1' & t_2' \\ t_3' & t_4' \end{bmatrix} \qquad B_{ON} = \begin{bmatrix} t_5' & t_6' \\ t_7' & t_8' \end{bmatrix}$$

$$A_{OFF} = \begin{bmatrix} t_1'' & t_2'' \\ t_3'' & t_4'' \end{bmatrix} \qquad B_{OFF} = \begin{bmatrix} t_5'' & t_6'' \\ t_7'' & t_8'' \end{bmatrix}$$

$$A_{ON} = \begin{bmatrix} t_1' & t_2' \\ t_3' & t_4' \end{bmatrix} \qquad B_{ON} = \begin{bmatrix} t_5' & 0 \\ 0 & t_6' \end{bmatrix}$$

$$A_{OFF} = \begin{bmatrix} t_1'' & t_2'' \\ t_3'' & t_4'' \end{bmatrix} \qquad B_{OFF} = \begin{bmatrix} t_5'' & 0 \\ 0 & t_6'' \end{bmatrix}$$

The averaged model can be represented as

$$\dot{X} = AX + BU \quad Y = C^T X \quad for \quad 0 < t < T \tag{5}$$

Under steady-state $\quad \dot{X} = AX + BU = 0 \quad (6)$

Where, $\quad A = A_{ON}\,\delta + A_{OFF}\,\delta^1 \quad B = B_{ON}\,\delta + B_{OFF}\,\delta^1$

$$C^T = C^T_{ON}\,\delta + C^T_{OFF}\,\delta^1 \quad \delta^1 = 1-\delta$$

As shown in Fig.1, $N=n_2/n_1$ is the turn's ratio of the coupled inductor *(L)*.

$$\begin{aligned} A &= \begin{bmatrix} t_1 & t_2 \\ t_3 & t_4 \end{bmatrix} = \begin{bmatrix} t_1' & t_2' \\ t_3' & t_4' \end{bmatrix}\delta + \begin{bmatrix} t_1'' & t_2'' \\ t_3'' & t_4'' \end{bmatrix}\delta^1 \\ B &= \begin{bmatrix} t_5 & 0 \\ 0 & t_6 \end{bmatrix} = \begin{bmatrix} t_5' & 0 \\ 0 & t_6' \end{bmatrix}\delta + \begin{bmatrix} t_5'' & 0 \\ 0 & t_6'' \end{bmatrix}\delta^1 \end{aligned} \tag{7}$$

Therefore, the steady-state averaged model of the converter can be described as

$$X_{SS} = -A^{-1}BU \quad and \quad Y_{SS} = -C^T A^{-1}BU \tag{8}$$

Using equation (7) and (8), the steady-state variables can be obtained. The inductor current and capacitor voltage ripples can be obtained in matrix form [4] as

$$\Delta X = (A_{ON} X_{SS} + B_{ON} U)\delta T \tag{9}$$

Also, at this stage by using Laplace transform to (2), steady-state DC transfer functions can be easily obtained. However, the control input to the converter, the duty ratio appears within the B matrix of the averaged model rather than as an element in the input vector. The averaged model is therefore time varying and difficult to solve. To simplify the model, (5) is linearised by considering small perturbations in the variables. Each variable is written as the sum of a steady-state DC component and a small-signal AC component denoted by tilde (~) as follows;

$$x = x + \widetilde{X}, u = u + \widetilde{U} \quad and \quad \delta = \delta + \widetilde{\delta} \qquad (10)$$

Where, $\widetilde{X} << x \quad \widetilde{U} << u \quad \widetilde{\delta} << \delta$

Using the small-signal assumptions for ac perturbations, after separating the steady-state DC quantities, and the second order non-linear terms which are smaller in compared to the first order ac-terms can be neglected. Therefore, the small-signal dynamic model [1]-[3] of the converter is described by

$$\dot{\widetilde{x}} = A\widetilde{x} + B\widetilde{u} + E\widetilde{\delta} \quad \widetilde{y} = C^T\widetilde{x} + F\widetilde{\delta} \qquad (11)$$

Where, $E=(A_{ON}-A_{OFF})X+(B_{ON}-B_{OFF})U$, $F=(C^T_{ON}-C^T_{OFF})X$ and $\widetilde{x}$ $\widetilde{u}$ $\widetilde{\delta}$ $\widetilde{y}$ are the small perturbations of the state vector, input vector, duty cycle and output vector respectively.

$$E = \begin{bmatrix} t_7 & t_8 \\ t_9 & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} t_{10} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{LV} \\ I_H \end{bmatrix} \qquad (12)$$

The perturbed SS description is nonlinear owing to the presence of the product of the two time dependent quantities $\widetilde{x}$ *and* $\widetilde{\delta}$.

The equation (11) represents the two-state small signal low frequency model of the converter working in continuous conduction mode. Using equation (11) and the matrix coefficients of A, B, C and E vectors, the small-signal dynamic model of the BDC converter in boost mode is expressed as follows;

$$\frac{d\widetilde{i}_L(t)}{dt} = t_1 * \widetilde{i}_L(t) + t_2 * \widetilde{V}_C(t) + t_5 * \widetilde{V}_{LV}(t) + [t_7 * I_L(t) + t_8 * V_C(t) + t_{10} * V_{LV}]\widetilde{\delta} \quad (13)$$

$$\frac{d\widetilde{V}_C(t)}{dt} = t_6 * \widetilde{I}_H + t_3 * \widetilde{i}_L(t) + t_4 * \widetilde{V}_C(t) + [t_9 * I_L(t)]\widetilde{\delta} \qquad (14)$$

The equation (13) and (14) are also valid for the buck operation by simply replacing the δ by δ^1 and vice versa, I_H (DC bus high voltage side current) by I_{LV} (Battery charging current) and V_{LV} (Battery voltage) by V_{HV} (DC bus high voltage $V_C(t)$). By using equation (13) and (14), block diagram model of small-signal equations may be constructed relating both the control and input to the inductor current and capacitor voltage as shown in Fig. 2. The block diagram was used in Simulink to examine the characteristics of the model and aid the design of the controller. By applying Laplace transform, and setting $\tilde{i}_H=0$ $\tilde{V}_{LV}=0$ in (13) and (14), control to output transfer function is developed as

$$G_{vd} = \frac{\widetilde{V}_C(t)}{\widetilde{\delta}} = \frac{m_1(s - m_2)}{S^2 + S * t_4 - m_3} \qquad (15)$$

Where, $m_1 = t_9 * I_L(t)$ $\quad m_2 = \dfrac{t_3 * [t_7 * I_L(t) + t_8 * V_C(t) + t_{10} * V_{LV}]}{t_9 * I_L(t)(1 - t_1)}$ $\quad m_3 = \dfrac{t_3}{1 - t_1}$

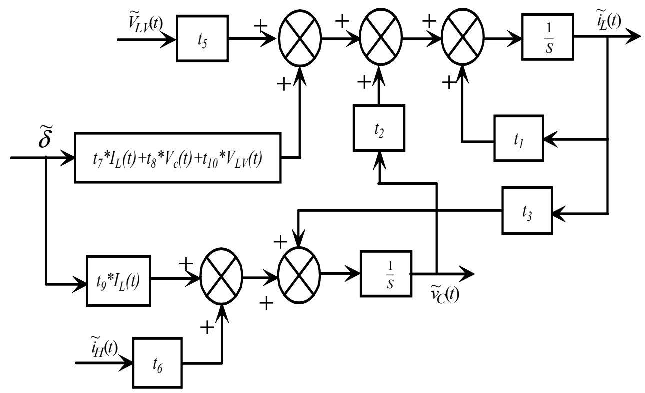


Fig. 2. Block diagram of small-signal BDC converter model

III. Controller Modeling and Design

Generally, DC output voltage of the converters is used as a feedback in closed loop control. The usual requirement of a control system for the converter is to maintain the output voltage constant irrespective of the source and the load disturbances. According to the steady-state equation, the output voltage is independent of load conditions. However, load changes affect the output voltage transiently, possibly causing significant deviations from the steady-state level. Furthermore, in a practical system circuit losses introduce an output voltage dependency on steady-state load current which must be compensated by the control system. To design effective compensator, it is necessary to have accurate small signal models of the plant. Fig. 3, illustrate the small-signal model of the converter with voltage controller. The designs of the controller parameters are undertaken in the frequency domain, and bode plots are used throughout the design process.

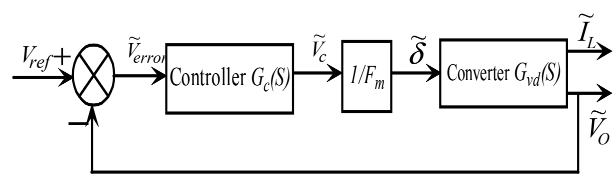


Fig. 3. Closed loop system with voltage mode control of the converter

The modulator gain is given by $F_m = \frac{1}{V_p}$

Where V_P is the peak value of the ramp signal

The controller $G_c(S)$ used for the proposed converter is a combination of PI and lag- lead compensator given by

$$G_c(S) = \frac{K(S + \tau_z^{-1})^2}{S^2 + S * \tau_p^{-1}} \qquad (16)$$

Where τ_Z^{-1} *and* τ_P^{-1} is the zero and pole frequencies of the controller.

This controller is chosen to have an integral characteristic at low frequency in order to ensure zero steady-state error. A compensation term is added at higher frequency to provide a satisfactory crossover frequency and stability margin. The crossover frequency of the control loop is typically restricted to around one-tenth of the switching frequency since this usually provides an acceptable compromise between speed of response and avoiding switching frequency related instabilities. The averaged models are typically accurate up to around one-third of the switching frequency, usually the value of 0-dB cross over frequency is lower than one-third of the switching frequency. Here, the controller is designed to achieve a crossover frequency to one-tenth the switching frequency (i.e. 5 kHz). The two zeros are placed at 10krad/sec, and high frequency pole is placed at 60krad/sec, approximately twice the target crossover frequency. The final selection of forward gain (*K*) is made by comparing the transient performances of the closed loop step performances for different gains as illustrated in Fig. 5 to Fig. 8. Therefore, to achieve fast response with less overshoot, *K* value is chosen to be 0.25 for boost and buck mode operation respectively. The open loop transfer function of the converter system is given by

$$G_{OL} = G_{Vd} G_c F_m = \frac{m_1(s-m_2)}{(S^2 + S*t_4 - m_3)} * \frac{K(s+\tau_Z^{-1})^2}{S^2 + S*\tau_P^{-1}} \qquad (17)$$

The closed loop transfer function of the converter from reference (V_{ref}) to output (V_O) is given by

$$G_{CL} = \frac{G_{OL}}{(1 + G_{OL})} \qquad (18)$$

The converter is represented by the small-signal state-space averaged model*,* the coefficient elements in the matrices being evaluated using the parameter values listed in table-I.

IV. Simulation Results and Analysis

In order to authenticate the modeling of proposed CI-BDC converter and control technique; specifications and design values are obtained [16] as described in table-I. By considering the variations in parasitic inductor resistance (r_L); transient and stability analysis of the converter system with VMC has been synthesized using Matlab/Simulink simulation. For inductor winding resistances of 0.5Ω and 10.5Ω the CI-BDC converter performances without controller are illustrated in Fig. 4. From these step and frequency responses shown in Fig. 4(a) and Fig. 4(b) it can be clearly understand that the improvements in settling time and the overshoot for higher values of r_L with improved frequency response. Thus, the effort of closed loop controller may reduce by considering the optimum value of inductor winging resistance. However, the resulting high transient overshoots and slow response tends to deteriorates converter, and hence all these aspects are need to be improved. Fig. 5 to Fig. 8 gives the comparative performances analyses of the controllers in boost and buck mode for two values of r_L. Thus, from these figures, it is well noticed that the improvement in system performance with higher value of r_L for all values of K considered here in this paper. Therefore, to understand the effect of using this resistance (r_L); closed loop state space model of the converter with lag-lead feedback compensator using Simulink software have been developed as shown in Fig. 9.

TABLE-I
CI- BDC CONVERTER SPECIFICATIONS AND DESIGN VALUES

Parameter	Boost Mode	Buck Mode
Input voltage	V_{LV}=24±20%	V_{HV}=200±20%
Output voltage	V_{HV}= 200 V	V_{LV}=24V
ΔVo (Ripple)	≤0.5%	≤0.5%
Output Power	400 Watt	384 Watt
Output Current	2A	16A
Switching Frequency	50 kHz	
Turns Ratio	2	
Duty Cycles	δ=0.71, δ^1=1- δ	
Inductor	L_1=50μH, L_2=200μH, M=98μH (L=348 μH)	
Resistors	R_{HV}=100 Ω, R_{LV}=1.44 Ω	
Capacitor	C=10μF,	
Parasitic Elements	r_L=0.5Ω & 10.5Ω & ; r_C=0.001Ω; r_{ds}=0.27Ω; r_F=0.85Ω;	

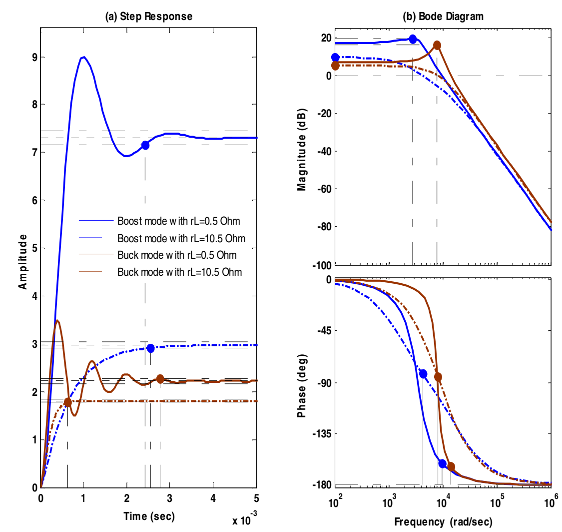


Fig. 4. CI-BDC converter performances without controller for r_L=0.5Ω and r_L=10.5Ω.

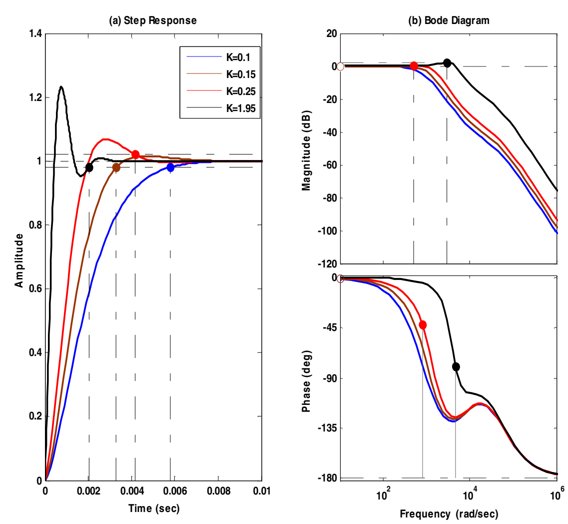


Fig. 5. Step and frequency responses of boost mode with r_L=10.5Ω for different gain (K) values

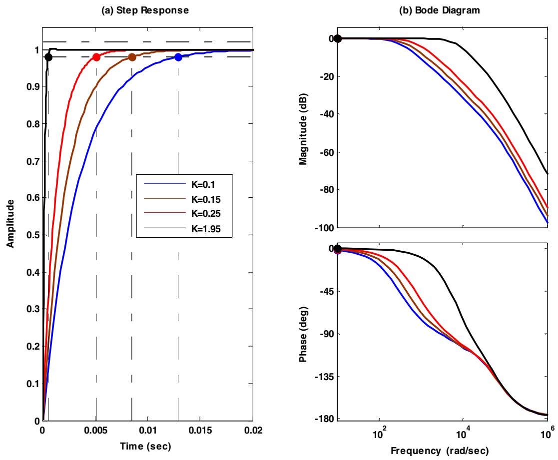


Fig. 6. Step and frequency responses of buck mode with r_L=10.5Ω for different gain (K) values

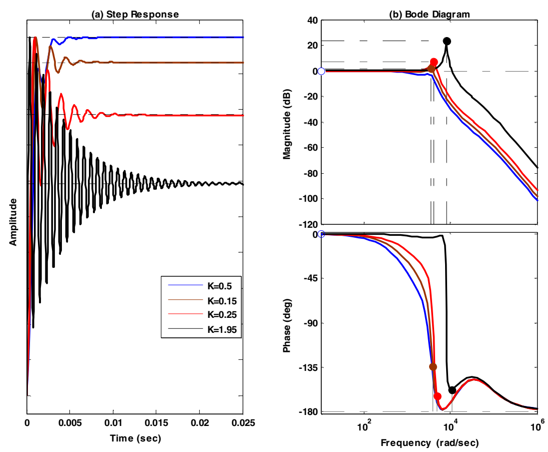


Fig. 7. Step and frequency responses of boost mode with r_L=0.5Ω for different gain (K) values

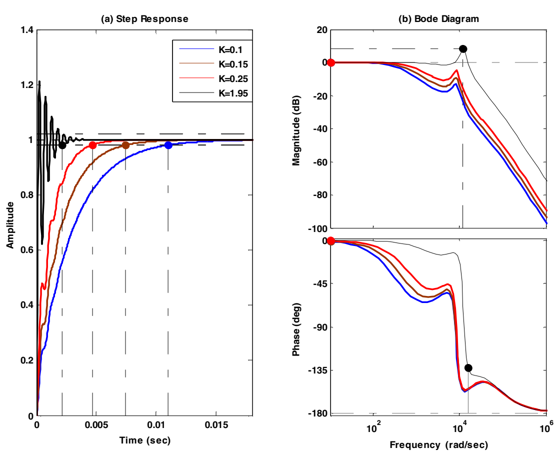


Fig . 8. Step and frequency responses of buck mode with r_L=0.5Ω for different gain (K) values

Herein this model, the controller gain (K) of 0.25 is used based the performances analyses made in Fig. 5 to Fig. 8. Fig. 9 illustrates the Simulink model of the CI-BDC converter with voltage mode control. Thus, converter system in closed loop is analyzed for wide range of load conditions. Fig. 10 depicts the results obtained for different load conditions with r_L of 0.5Ω & 10.5Ω respectively. These results show that after the initial transients; output voltage and inductor current settles down to the desired values irrespective of the change in load conditions. Moreover, these results show that the improved transient and dynamic responses with r_L of 10.5Ω as compared to r_L of 0.5Ω. In Fig. 10(a), the effect of step load change with r_L of 0.5Ω is observed at 0.01sec (0.5A), and at 0.02 sec (3.5A) for boost mode, at 0.04 sec (32A) and at 0.05 sec (16A) for buck mode respectively. We can notice, at these instants of load changes, output voltage shoots up and immediately settles down to 200V in boost mode and to 24V in buck mode respectively. In Fig. 10(b), the effect of step load change with r_L of 10.5Ω is observed at 0.01sec (0.5A), and at 0.02 sec (3.5A) for boost mode, at 0.04 sec (32A) and at 0.05 sec (16A) for buck mode respectively. We can notice, at these instants of load changes, output voltage is maintained constant at 200V in boost mode and to 24V in buck mode respectively. More specifically we can also observe that the less overshoot and good dynamic response with higher values of winding resistance (r_L).

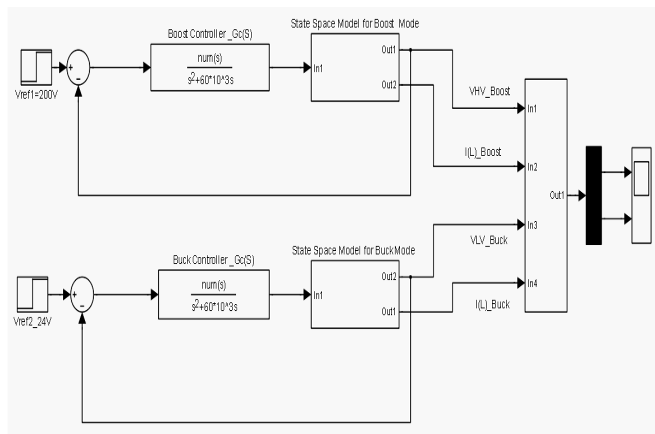


Fig. 9. Simulink model of closed loop CI-BDC converter system

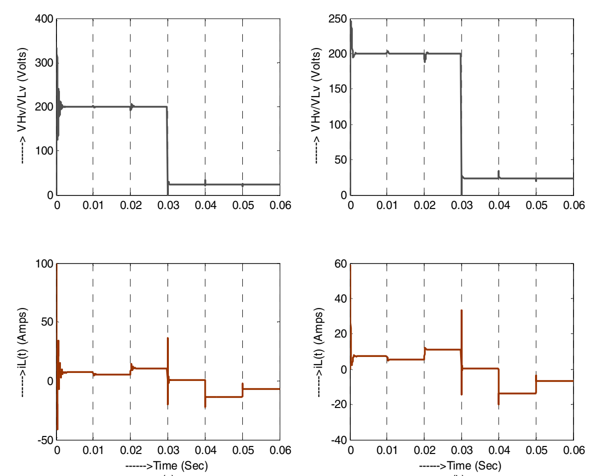


Fig. 10. output voltage (upper) and inductor current (lower) waveforms in boost and buck modes with step load changes (a) r_L=0.5Ω (b) r_L=10.5Ω

V. Conclusions

The averaged and small-signal modeling approaches of PWM converters are powerful methods to analyze nonlinearity converters. Therefore, the detailed modeling of CI-BDC converter with its parasitic elements and voltage mode controller is presented in this paper. The converter model has been developed in Simulink/Matlab, and converter in both modes is analyzed. The stability analysis of the converter has been extensively studied for wide range of load conditions. Also, the impact of inductor winding resistance on the stability and dynamic performance of the converter are analyzed. From the analyses, it is well notice clear that the improvement in the closed loop converter performance with higher values of inductor winding resistance. Thus, it is very important to consider the parasitic elements in designing of the closed controller. Also, it was shown that the converter output voltage can be satisfactorily controlled by the use of single loop output voltage feedback.

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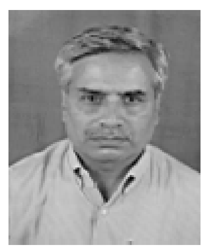
VI. Biographies

Narasimharaju B. L (S'10) was born in Beeramangalla (V), Gowribidhanur, Karnataka, India on May 20, 1975. He received B.E and M.E in Electrical Engineering from University Visveswaraya College of Engineering Bangalore, India in 1999 and 2002 respectively.

He worked as Project Assistant in ABB Bangalore from March 2001 to August 2001, since then worked as Project Trainee in Electronics and Radar Development Establishment (LRDE), DRDO, Ministry of Defense, India till 2002. He worked as Guest lecturer/Teaching Associate in UVCE, Bangalore University from 2002 to 2003. He is a Lecturer since 2003 in Manipal Institute of Technology, Manipal University, India. He is a life member of Indian Society for Technical Education (ISTE), IIT Delhi Campus, and life member of System Society of India (SSI). He is currently pursuing PhD at Indian Institute of Technology Roorkee, India. His current research interest includes modeling, design and analysis of Bidirectional DC-DC converters, digital PWM techniques, and fuzzy based logic controller algorithms for power quality improvements.

Dr. S. P. Dubey was born in Raipur, Chhattisgarh, India in 1971. He received B.E. (Electrical Engg.) from NIT Raipur (Formerly GEC Raipur), C.G., India in 1995, and M.E. (Power Apparatus and Electrical Drives) from Indian Institute of Technology Roorkee, India in 2000. He obtained Ph.D. degree from Birla Institute of Technology and Science, Pilani, India in 2006.

He worked as Lecturer for six years and as Assistant Professor for one year in the Electrical and Electronics Engineering Group at Birla Institute of Technology and Science, Pilani, and as an Assistant professor in the Department of Electrical Engineering, Indian Institute of Technology Roorkee, India. He is currently a Professor in the Department of Electrical Engineering, Rungta College of Engineering & Technology, Bhilai, INDIA. His current research interests include power converters Active Filtering, Power Conditioning, AC and DC Drives, Neural Network and Fuzzy Logic based Controller Design for Electrical Drives, Genetic Algorithm Optimization technique for LC Filter Design.



Dr. S. P. Singh (M'10) was born in Kamalpur, Aligarh, UP, India in 1956. He received the B.Sc. degree in electrical engineering from Aligarh Muslim University, Aligarh, India, in 1978. He also, obtained M.E. and Ph.D. degrees from Indian Institute of Technology Roorkee, India in 1980 and 1993 respectively. He is currently a Professor in the Department of Electrical Engineering, Indian Institute of Technology Roorkee India. His current research interests include power converters and control, Active power filters for power quality improvements, renewable energy systems, self and line excited induction generators and wind power generation. Authored more than 60 technical articles and presented in various forums, chaired many technical sessions in conferences/seminars /workshops.