Intelligent Technique for Improved Transient and Dynamic Response of Bidirectional DC-DC Converter

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Abstract— **This paper aim to design a intelligent technique for BDC converter. The converter contains non-linear elements making the mathematical model more complex which instigate the use of FLC. The nature of FLC has adaptive characteristics that can achieve robust response to a system with uncertainty, parameter variation, and load disturbance. In order to see the advantages of FLC, classical PI control has applied to the BDC converter under same circumstances and has been compared. Simulation results demonstrate that the converter can be regulated with good dynamic performance irrespective to input disturbance and load variation. The presented FLC approach can be applied to any DC-DC converter topologies.**

***Index Terms*--Fuzzy Logic Control (FLC), Coupled Inductor (CI), Bidirectional DC-DC (BDC) converter, Battery storage system**

I. INTRODUCTION

THE DC-DC conversion technique has been greatly developed to achieve high-efficiency, cheap topology in simple structure and without extreme duty ratio. The Uninterruptible Power Supply (UPS) systems employed in computer industry typically provide ten to thirty minutes reverse time, which is highly inadequate for telecommunication system. The convergence of computer and telecommunication industries makes the 48V DC battery plant as an innate choice to offer long backup during AC mains' outages [1]-[3]. It is more economical for storage batteries to use a few large-capacity cells than many small-capacity cells, and for that reason the number of cells used in small/micro power grid is limited. Thus, batteries need high voltage diversity ratio in discharging, and charging modes. The above shortcomings can be fulfilled by using bidirectional DC-DC (BDC) converters between the storage devices and grid supply/load. The conventional based BDC topologies [4]-[6] reported in the literature are uncompetitive for high voltage diversity and high efficiency. In order to overcome the above problems, high performance coupled inductor (CI) DC-DC converters are proposed [8]-[12] which gives high-efficiency, high-voltage diversity without utilizing extreme duty ratio. Here, in this paper authors propose the CI-BDC converter. The detailed design principles of proposed converter are reported in the literature [13].

The control strategy is the heart of DC-DC converters as concern to the output regulation irrespective of the source and the load disturbances. In contrast, quite commonly used control techniques for DC-DC converters are voltage mode control, and current mode control techniques. However, each controller has its own merits and demerits. In this paper, the voltage mode control is used due to its simplicity, and good load regulation characteristics. In recent years, the Fuzzy Logic Control (FLC) has become more popular in many applications. These FLCs provides a method of nonlinear control using piece-wise linear functions to apply varying gains depending on the error signal between the desired output and the actual output. FLCs have already been incorporated in various DC-DC converter systems and applications [14]-[21]. The fuzzy logic controller is advantageous over classical controls where the gains are fixed. The FLCs gives nonlinear control with fast response and virtually no overshoot. An FLC allows the proportional, integral, and derivative gains to be adjusted to achieve optimal control system, and thus provides robust control of DC-DC converters [14]-[21]. In this paper, fuzzy logic based control of CI-BDC converter has been examined through computer simulation. In order to see the advantages of fuzzy logic control, classical PI control has applied to the same BDC converter under same circumstances and been compared.

II. CONVERTER OPERATION AND CONTROLLER DESIGNS

A. Converter Operation

The BDC converter operation can be identified in two modes. One is discharge mode during which the BDC is

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used to boost the battery voltage to a suitable high level DC bus voltage. Second is the charging mode during which the BDC is used to buck the DC bus voltage to a suitable low level battery voltage. The converter operation in continuous conduction mode (CCM) is a suitable choice to get a better dynamic response and also a tight regulation of output voltage for the entire load variation. The proposed BDC converter topology is depicted as in Fig. 1(a). The converter operation is categorized into four modes. In mode-1 and mode-2 converter operates in forward boost mode, the power flow is from battery to DC bus. In mode-3 and mode-4 the converter operates in reverse buck mode, the power flow will reverses and is now flow from DC bus to the battery. Fig. 2 illustrates the key waveforms of CI-BDC converter for boost and buck modes respectively. The detailed converter operations and design principles are presented [13] in the literature.

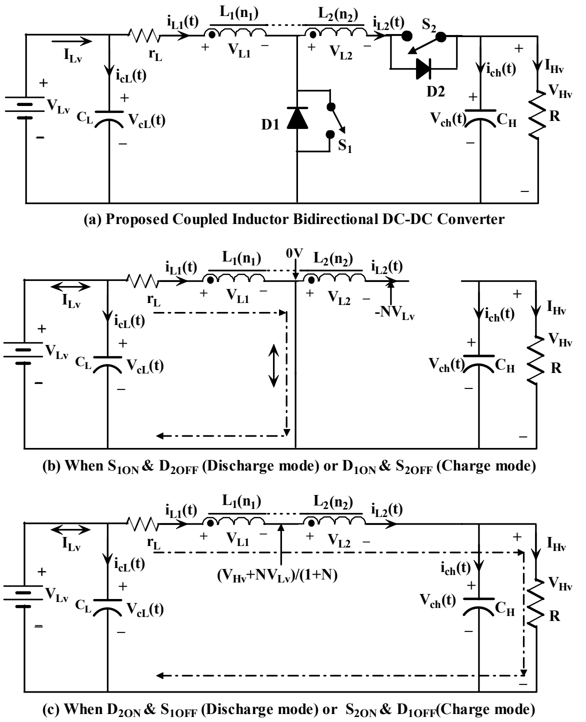

Fig. 1 Proposed converter and equivalent circuits for operating modes

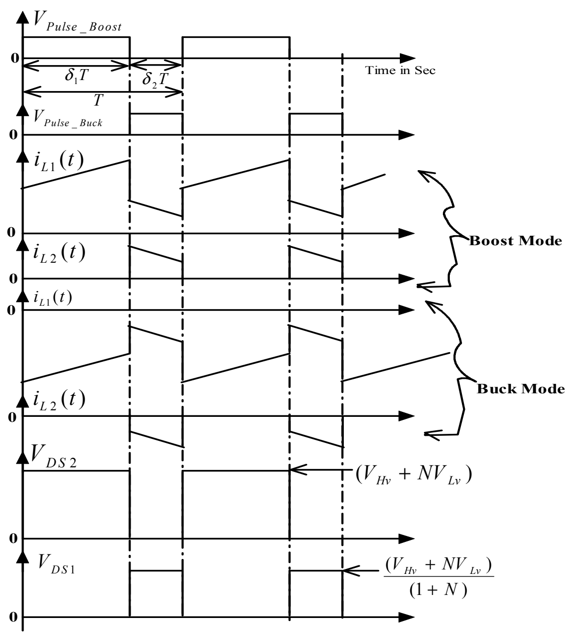

Fig. 2. Key waveforms of CI-BDC converter

The minimum value of inductance (L_{1min}) can be obtained [13] as

$$L_{1\min} = \frac{V_{LV}\ (1-\delta_1)\delta_1 T}{2\, I_{HV}\, V_{HV}\ (N+1)} \tag{1}$$

Where δ_1 is the duty ratio of the switch S_1 for boost mode and $\delta_2=(1-\delta_1)$ is the duty ratio of the switch S_2 for buck mode, T is the switching period, and $N=n_2/n_1$ is the turn's ratio winding L_1 and L_2 of coupled inductor.

For continuous current conduction the selected value of $L_1 >> L_{1\min}$ and vice versa for discontinuous current conduction. Finally equivalent inductance ($L_m=L_1$) and secondary coupled inductor (L_2) can be obtained as follows

$$L_m = (1+N)^2 L_1 = (1+\frac{1}{N})^2 L_2 = (L_1 + L_2 + 2M) \tag{2}$$

B. Fuzzy Logic Controller Design

The dynamics of DC-DC converters is non-linear with uncertain parameters owing to uncertain output voltage during the operation. These problems are efficiently dealt with in FLC. In general, fuzzy expert system is applicable wherever the knowledge base of expert system contains fuzziness. The converter control regulates nominal operating point of the converter. Fig. 3 depicts the block diagram of the fuzzy control scheme for BDC converter. The output voltage amplitude is determined and compared with reference voltage, which is taken as proportional to the rated terminal voltage of the converter. The voltage error (E) and change in voltage error (CE) is determined and processed through FLC. The resulting output is processed through a PWM generator where it is compared with symmetrical triangular wave to obtain suitable pulse. The fuzzy controller [14]-[18] is divided into five sections: fuzzifier, knowledge base, rule base, decision making and defuzzifier as shown in Fig. 3. The inference system block uses the rules in the format of "if-then-else". The inputs of the fuzzy controller are the error and change in error is defined as follows;

$$E(n) = V_{ref}(n) - V_o(n) \tag{3}$$

$$CE(n) = E(n) - E(n-1)) \tag{4}$$

Where, V_{ref} and V_o are terminal voltage and reference voltages at n^{Th} sampling time.

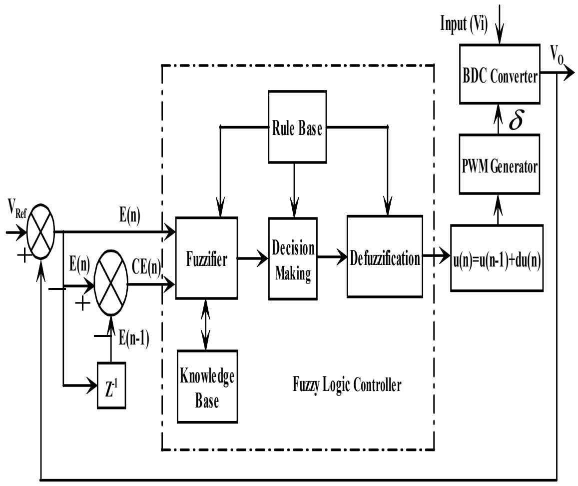

Fig.3 Fuzzy logic control scheme for BDC converter system

The input variables are converted into labels of fuzzy sets in terms of suitable linguistic values, this is called fuzzification process. The scaled inputs are crisp values limited to the universe of discourse of input variables. The Membership Function (MF) is used to convert each of input variables into membership value between 0 and 1. The overall performance of the system is affected by shapes and number of MFs that are chosen according to experience of expert people about the process. The several procedures are reported [14]-[21] that can be used to build MFs. The triangular MFs are chosen to evaluate the degree of membership of input crisp values. The output of fuzzy controller is the control signal 'u' which is used to produce modulating pulses which drives the switches of the BDC converter. The proposed fuzzy system consists of seven MFs for error (E), change in error (CE), and seven MFs for output control signal (u). A number of fuzzy reasoning methods are reported in the literature [17]-[18] such as; Mamdani's, Larsen's, Sugeno's and Tsukamoto's methods. Herein this work, Mamdani fuzzy reasoning method is used to obtain the inference result from a system. The fuzzy reasoning strategy of this method is based-on the MAX-MIN composition. Fig. 4 and Fig. 5 illustrates fuzzy input MFs plots of the variables E (voltage error), and CE (change in error) respectively. Fig. 6 illustrates fuzzy output control variable. The each input and output MFs are divided into seven linguistic variables namely NB(negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium) and PB (positive big). The knowledge base is defined in the form of linguistic rules. By naming the numbered symbols (0→zero, 1→positive small, 2→ positive medium . . ., -1→ negative small, -2→ negative medium . . .), we recognize the classical antidiagonal rule base [21] proposed by Macvicar-Whelan. The Table-I shows the corresponding rule table for the controller. The top row and left column of the matrix indicate the fuzzy sets of the variable E and CE respectively, and the MFs of output variable (du) are shown in the elements of the matrix. For improving the controller performance, membership functions are further adjusted based on trial and error procedure. The sensitivity of a variable determines the number of fuzzy subsets, respectively. Before fuzzification, the input variables are normalized with respect to reference voltage (V_{ref}). This gives the system an adaptive characteristic and enables the optimal operating point to be found effectively. The fuzzy inference includes the process of fuzzy logic operation, fuzzy rule implication and aggregation. In the fuzzy inference system, the fuzzified input variables are processed with fuzzy operators, and the IF-THEN rule implementation. The proposed system has 49 (7x7) possible rules as described in Table-I that can build by crossing the fuzzy sets considered for each input. Where a rule read as:

$$\text{if } E{=}NB \text{ and } CE{=}Z \text{ then } du{=}NM \tag{5}$$

The value of output signal is determined in accordance with the linguistic rules. The required rules and data are supplied by the rule base. The linguistic output data is converted back into crisp output data by defuzzification. The membership of the corresponding output is taken as minimum membership value for the two respective inputs. Mathematically,

$$\alpha = \min\left[\mu(input\ 1) \quad \mu(input\ 2)\right] \tag{6}$$

$$Crisp \quad Output = \frac{\sum p(m)\alpha}{\sum \alpha} \tag{7}$$

Where, μ refers to membership value, the output membership is stored in α and p(m) refer to location of peak of membership function. The defuzzified (crisp) value multiplied by a scale factor and integrated to obtain the output (u).

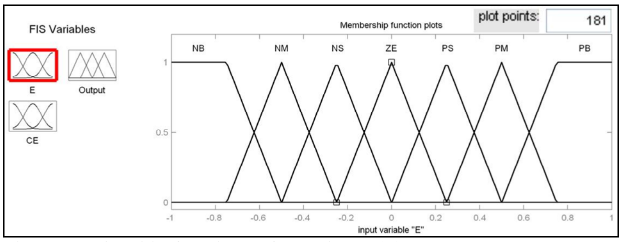

Fig. 4 Membership functions of error input (E)

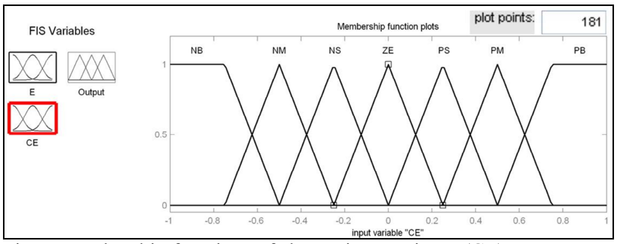

Fig. 5 Membership functions of change in error input (CE)

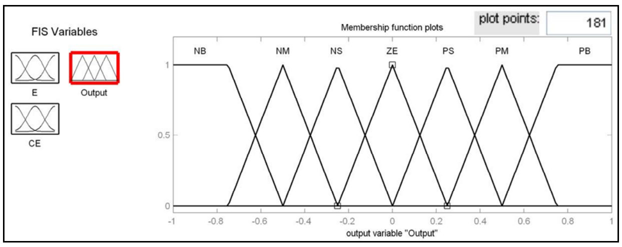

Fig. 6 Membership functions of control output (u)

TABLE-I
FUZZY RULE BASE MATRIX

E(PU) / CE(PU)	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	NC
NM	NB	NB	NB	NM	NS	NC	PS
NS	NB	NB	NM	NS	NC	PS	PM
Z	NB	NM	NS	NC	PS	PM	PB
PS	NM	NS	NC	PS	PM	PB	PB
PM	NS	NC	PS	PM	PB	PB	PB
PB	NC	PS	PM	PB	PB	PB	PB

C. PI Controller Design

In order address the benifits of FLC controller, the classical proportional-Integral (PI) controller has implemented for same CI-BDC converter and compared. The control strategy is normally implemented in two parts. In the first part of control, essential variables used in control are sensed and scaled to feed to the processors for use in control algorithm as a feedback signals. The second stage of control is the control technique responsible for the high-level transient and steady-state performance of the converter. Thus, the output voltage in respective modes (discharging/charging) is regulated by closing a feedback loop between the output voltage and duty-ratio signal. The control to output transfer functions of the converter in boost and buck mode are obtained [22] respectively, as follows;

Boost mode transfer function is given by

$$G_{vd1}(S) = \frac{(1.667 * 10\hat{}6 S + 1.496 * 10\hat{}9)}{S^2 + 1002 S + 7.469 * 10\hat{}6} \quad (8)$$

Buck mode transfer function is given by

$$G_{vd2}(S) = \frac{(2 * 10\hat{}5 S + 1.013 * 10\hat{}9)}{S^2 + 1002 S + 4.223 * 10\hat{}7} \quad (9)$$

The PI voltage controller $G_{c1(2)}(S)$ for boost mode or buck mode of the converter and its transfer function is given by

$$G_{c1(2)}(S) = \frac{K\left(S + \tau_z^{-1}\right)}{S} \quad (10)$$

The controller gain (K) is designed using converter transfer functions of boost and buck mode respectively. The controller is chosen to have an integral characteristic at low frequency in order to ensure zero steady-state error. The control parameters are tuned in frequency domain, bode plots are used throughout the design process. The boost mode controller is designed at crossover frequency around 2.2 kHz. The one zero is placed at 13.333krad/sec, and one pole is placed at origin, approximately twice the target crossover frequency. Similarly the buck mode controller is designed at crossover frequency approximately 1.5 kHz. Fig. 7 frequency responses of open and closed loop converter system

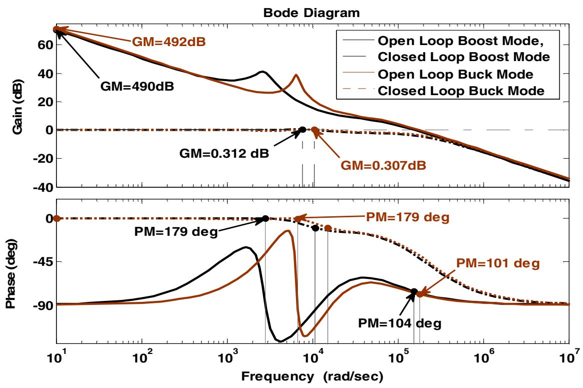

Fig. 7 Frequency responses of open and closed loop converter system

III. Results and Discussions

The design specifications of the CI-BDC converter are obtained as described in table-II. The Simulink model of the BDC converter with FLC, and classical PI control techniques has been developed as depicted in Fig. 8 and Fig. 9 respectively. Thus, the performance analysis in open loop and closed loop has been evaluated extensively and compared. Fig. 10 illustrates the open loop steady-state performances of CI-BDC converter. Fig. 11 to Fig. 12 illustrates the closed loop performances of the fuzzy controlled CI-BDC converter for various load conditions.

TABLE II
CONVERTER SPECIFICATIONS

Parameter	Boost mode	Buck mode
Input voltage	V_{LV}=24V	V_{HV}=200V
Output voltage	V_{HV}=200V	V_{LV}=24V
ΔV_o *ripple voltage*	≤0.5%	≤0.5%
Output power	400 watt	384 watt
Switching frequency	50kHz	
Turns ratio(N)	2	
Duty ratio's	δ1=0.71, δ2=(1- δ1)	
Inductors	L_1=50µH, L_2=200µH, M=98µH	
Resistors	R_{HV}=100 Ω, R_{LV}=1.5 Ω, r_L=0.001Ω	
Capacitors	C_L=C_H=10µF	

The load regulations under wide range of load conditions have been made extensively. As shown in Fig. 12 and Fig.

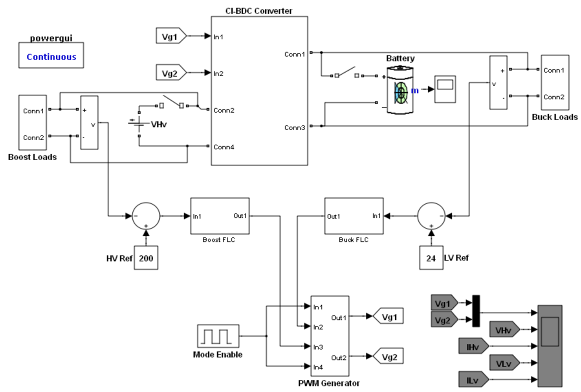

Fig. 8 Simulink model of Fuzzy logic controlled BDC converter

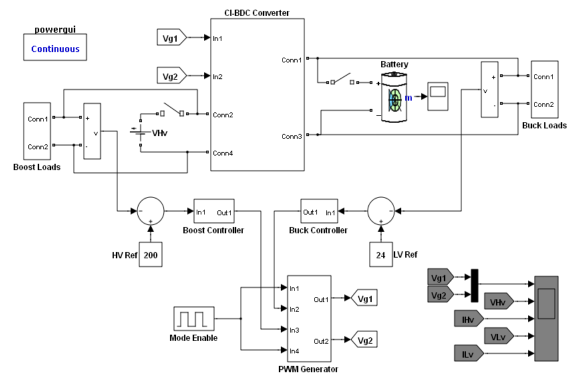

Fig. 9 Simulink model of PI controlled BDC converter

13, the effect of step load change are observed at 0.0075sec for boost mode, and at 0.0225 sec for buck mode respectively. From Fig. 12, it can be observed that at any

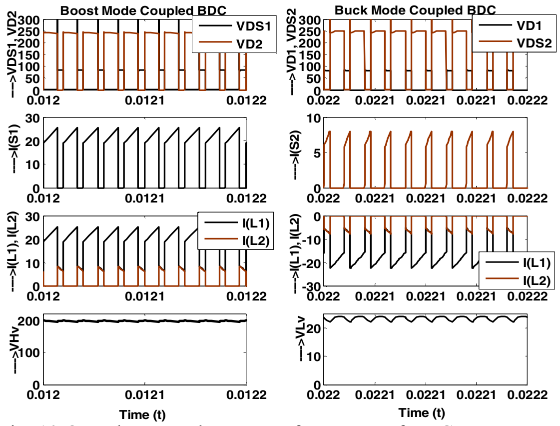

Fig. 10 Open loop steady-state performances of BDC converter

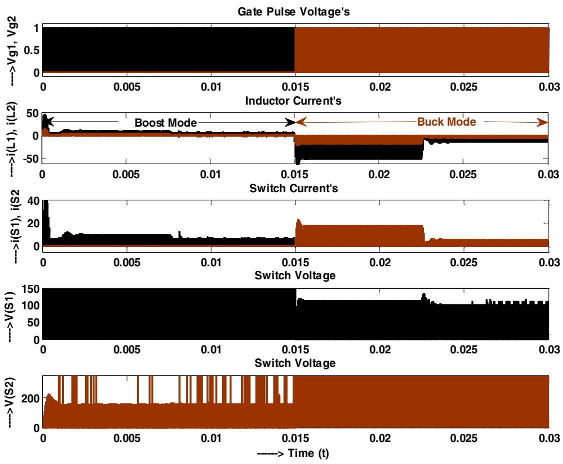

Fig. 11 Closed loop performances of fuzzy controlled converter with load changes

instants of load changes, output voltage get stabilizes at faster rate to the desired value (200V) in boost with small overshoot as compared to classical PI controller response shown in Fig. 13. Similarly, in buck mode output voltage get stabilizes at very faster rate to the desired to value (24V) in buck mode with smaller overshoot particularly at light load conditions as compared to classical PI controller response shown in Fig. 13. Thus, it confines the superiority of FLC technique over classical PI controller technique in terms of load regulation and dynamic performances in both boost and buck mode.

IV. Conclusions

For the design specifications of proposed CI-BDC converter, FLC, and classical PI controller are designed and discussed in detail. The model of fuzzy logic controlled, and classical PI controlled CI-BDC converter with voltage mode control has been developed in Simulink environment. Thus, the steady-state, and transient performance analysis in open loop and closed loop has been evaluated extensively. The closed loop regulation is evaluated for wide range of load conditions which shows improved dynamic and transient performances of fuzzy logic controller as compared to the classical PI controller.

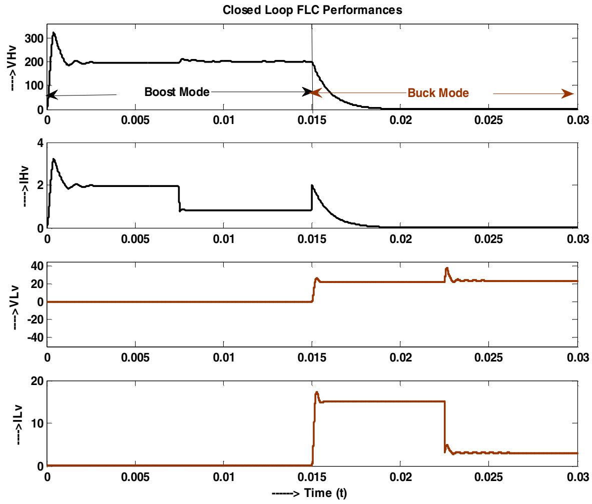

Fig. 12 Closed loop performances of fuzzy controlled converter with load changes from full load to light load

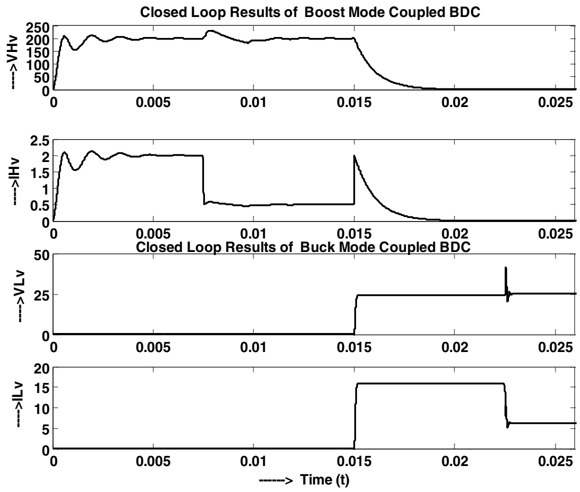

Fig. 13 Closed loop performances of classical PI controlled converter with load changes from full load to light load

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