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Comparison of Output Parameters of Two-Phase Interleaved Buck Converter Using Different Type Control Methods

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***Abstract*—Electrical power converters are widely used in electrical and electronics area. In this study, the continuous conduction mode of the interleaved buck converter; the unit power factor (UPF) and the total harmonic distortion (THD) of the input current are investigated using proportional-integral (PI) control and average sliding mode control (ASMC). The Buck Converter simulates MATLAB / Simulink at 1kW power and 20 kHz switching frequency and analyzes the control methods. In the analyzes, the THD effect of the converter's response to the load changes in the control methods and other parameter changes was investigated.**

Keywords—interleaved buck converter; proportional-integral (PI) control; avarage sliding mode control (ASMC); unit power factor (UPF); total harmonic distortion (THD).

I. INTRODUCTION

The widespread use of semiconductor switches has accelerated the pace of development of the technology, which has brought with it some electrical problems. At the beginning of these problems, the harmonics in the electricity distribution system increase, and the sinusoidal current waveform deteriorates. Many researchers are working on different types of circuit designs to reduce the harmonics in the currents feeding the systems that contain the power switches.

The power sources used in power electronic converters draw non-sinusoidal and harmonic currents from the network. These currents drawn from the system cause low power factor (PF) and high line currents to be generated. Decreasing the quality of the current drawn from the network; Resulting in deterioration of the mains voltage, increased losses, the emergence of electromagnetic parasites and inefficient use of consumed power [1]. Many researchers are working on different types of circuit designs to meet the electrical quality standards introduced by some international organizations and to improve the power coefficient. Based on these standards, using passive circuits, techniques such as reducing harmonic components, correcting active power coefficient and active rectifiers are used to derive electrical adverse effects [2]. There are different circuit topologies of power converters for correcting the power factor such as buck, boost, flyback, interleaved structure [3-7].

Most DC/DC converters are usually provided a low output voltage and high output current to load. Therefore, a conventional interleaved buck converter (IBC) as shown in Figure 1 is widely adopted, because it has a simple structure, high output current density and low output current ripple. However, in high step-down voltage applications, it suffers from extremely short duty ratio and high component stresses, resulting in low conversion efficiency [8-11].

II. INTERLEAVED BUCK CONVERTER

The circuit diagram of IBC is given as shown in Figure 1. This is equivalent to a parallel combination of two sets of switches, diodes and inductors connected to a common filter capacitor and load [12]. The switches are operated out of phase. Assume the converter operates with duty ratio less than 50% and in continuous conduction mode [13].

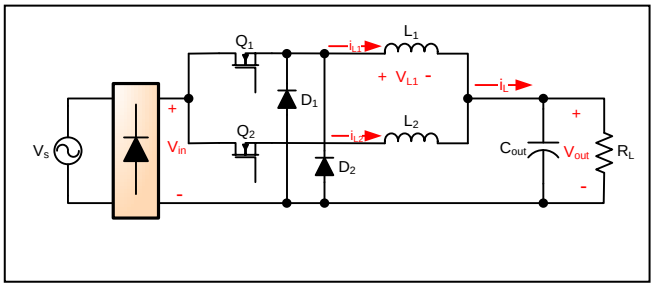

Fig. 1. Simple circuit diagram of 2 phase IBC

A two phase IBC will operate in four different modes and is explained as follows.

A. IBC Mode-1

In Operation mode-1 switch Q_1 is turned on by giving a gate pulse. At the same time switch Q_2 is off. Current flows through the switch Q_1, inductor L_1 and load, making current through L_1 to increase as long as Q_1 is turned on. During this time current in L_2 decreases linearly. The equivalent circuit is as in Figure 2. The variations of i_{L1} and i_{L2} during T are given by,

$$\Delta i_{L!} = \left(\frac{V_{in} + V_{out}}{L_1} \right) T_1 \qquad (1)$$

$$\Delta i_{L2} = \left(\frac{-V_{out}}{L_2}\right) T_1 \quad (2)$$

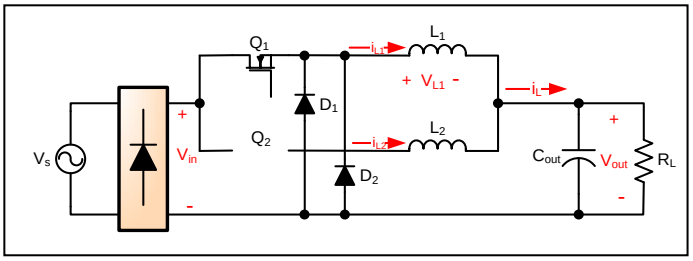

Fig. 2. Equivalent Circuit of IBC in Mode 1

B. IBC Mode-2

Since IBC operates with a duty cycle less than 0.5, in this mode both the switches are OFF. Diodes D_1 and D_2 are the conducting devices. The equivalent circuit is illustrated in Figure 3.The energies stored in L_1 and L_2 are released to the load through the forward biased diodes. So i_{L1} and i_{L2} are decreased linearly. Thus the variations in i_{L1} and i_{L2}during T_2 are given by,

$$\Delta i_{L!} = \left(\frac{-V_{out}}{L_1}\right) T_2 \quad (3)$$

$$\Delta i_{L2} = \left(\frac{-V_{out}}{L_2}\right) T_2 \quad (4)$$

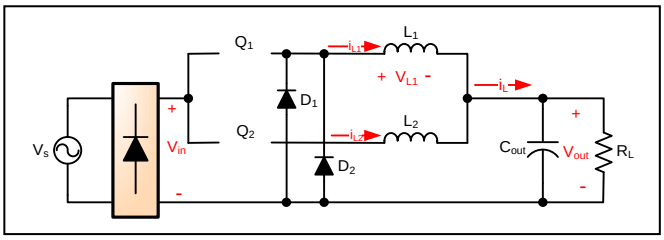

Fig. 3. Equivalent Circuit of IBC in Mode 2

C. IBC Mode-3

During T_3 Q_2 is turned On and Q_1 turned off. The equivalent circuit is illustrated in Figure 4. The turning on of Q_2 charges the inductor L_2 and since Q_1 is off inductor L_1 is discharged to the load. The variations in i_{L1} and i_{L2} during T_3 are given by,

$$\Delta i_{L!} = \left(\frac{-V_{out}}{L_1}\right) T_3 \quad (5)$$

$$\Delta i_{L2} = \left(\frac{V_{in} - V_{out}}{L_2}\right) T_3 \quad (6)$$

Equation (5) shows i_{L1} linearly decreasing during T_3 since the slope is negative and a constant.

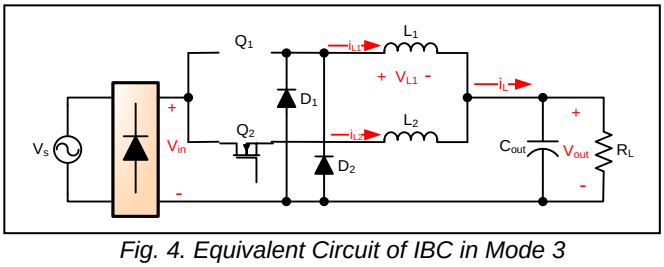

Fig. 4. Equivalent Circuit of IBC in Mode 3

D. IBC Mode-4

The operating mode is same as mode 2. The variations in i_{L1} and i_{L2} during T_4 are given as in equation (3) and (4).

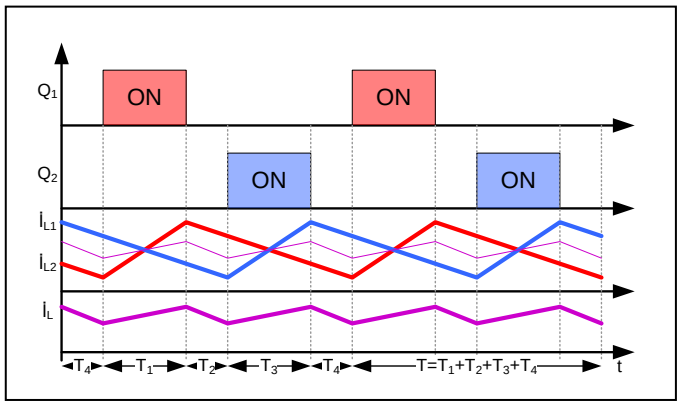

Fig. 5. Inductor Current Waveforms

III. System Control Loop

The converter is controlled with a voltage mode control scheme. The PWM module is configured for IBC mode with an independent time-base. The DC Link voltage is measured by the voltage sensors and sent to DSP control. This value is subtracted from the voltage reference in software to obtain the voltage error. The voltage error is then fed into a control algorithm that produces a duty cycle value based on the voltage error, previous error, and control history. The output of the control algorithm is also clamped to minimum and maximum duty cycle values for hardware protection. The voltage mode control algorithm must be executed at a fast rate in order to achieve the best transient response. Therefore, the control algorithm is executed in the ADC interrupt service routine, which is also assigned the highest priority in the UPS code. A block diagram of the push-pull converter control scheme is shown in Figure 6.

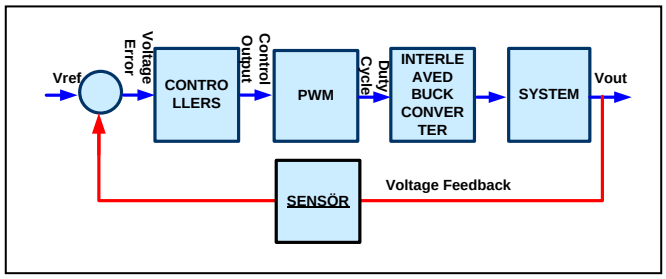

Fig. 6. A Block diagram of IBC voltage control loop

IV. Control Systems Models

The only difference in control methods for interleaved converters is the number of feedback cycles. For the N-phase converter, there is N number of feedback cycles. Additional circuitry is needed to enable phase shift operation in the interleaved loop. Hence, all control techniques are designed according to single phase and D duty ratio is shifted by phase difference. This section describes control methods that synchronize the input current with the basic component of the input voltage [14].

A. *Proportional Integral (PI) Control*

Proportional-integral (PI) controller is one of the commonly used techniques to correct the power factor. In this method, the average inductor current is taken and this average value is controlled by switching.

$$I_{ref} = \left[\left(V_{ref} - V_{out}\right)V_{EAV}\right]V_{in}| \quad (7)$$

$$D = D_1 = \left(I_{ref} - |I_{in}|\right)V_{EAI} \quad (8)$$

$$V_{EAV} = \left(K_{pv} + \frac{K_{iv}}{s}\right) \quad (9)$$

$$V_{EAI} = \left(K_{pi} + \frac{K_{ii}}{s}\right) \quad (10)$$

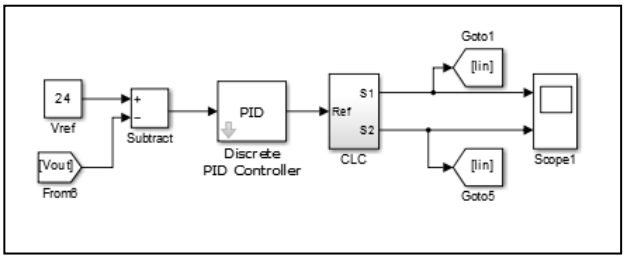

Fig. 7. PI controller block for Simulink Model of IBC

In equations, V_{EAV}, Proportional-integral controlled voltage error amplifier, V_{EAI}, Proportional-integral controlled current error amplifier, D, duty cycle. In the proportional-integral controller, K_p and K_i can be selected according to the method of Ziegler-Nichols. The PI control method follows the actual current reference current to provide a unit power factor and low THD [14]. Figure 7 shows the proportional integral control method.

B. *Average Sliding Control Method*

Control of systems with nonlinear and complex dynamics is very difficult with classical supervisory methods. The Average Sliding Control Method (ASCM) can be an effective control method in the control of such systems. The purpose of applying the ASCM method to closed-loop control systems is to push the error to the sliding surface or, alternatively, to the switching surface and keep it at that surface.

Since the slip surface is defined as a function which is a linear combination of state variables, the state variables are linearly dependent on this surface. In this case, the system is reduced to a level independent input variable, and the system is controlled by a reduced control rule [15].

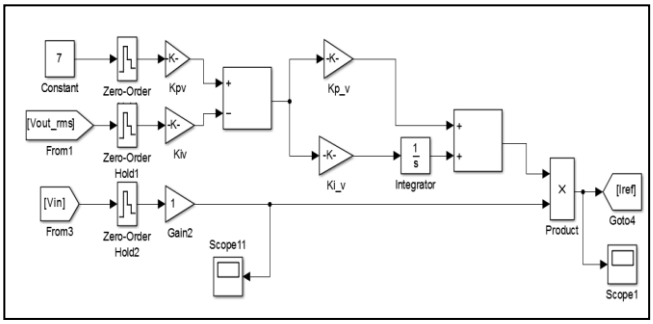

Fig. 8. Voltage controller block for Simulink Model of IBC

The voltage controller has the same structure as shown in Figure 8 according to all control methods. Figure 9 shows the average sliding mode control method.

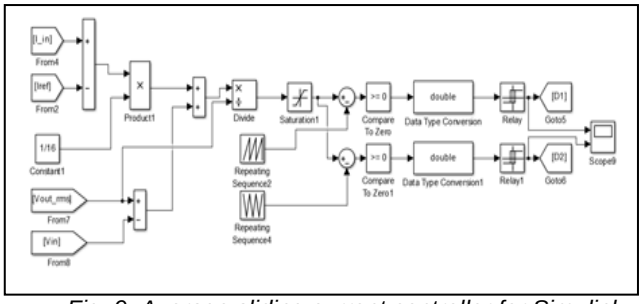

Fig. 9. Average sliding current controller for Simulink Model of IBC

V. Simulation Of The Full System

Simulation studies were performed using the MATLAB / Simulink program. Selected parameters in simulation studies are given in Table 1. The two-cell interleaved buck converter is shown in Figure 10.

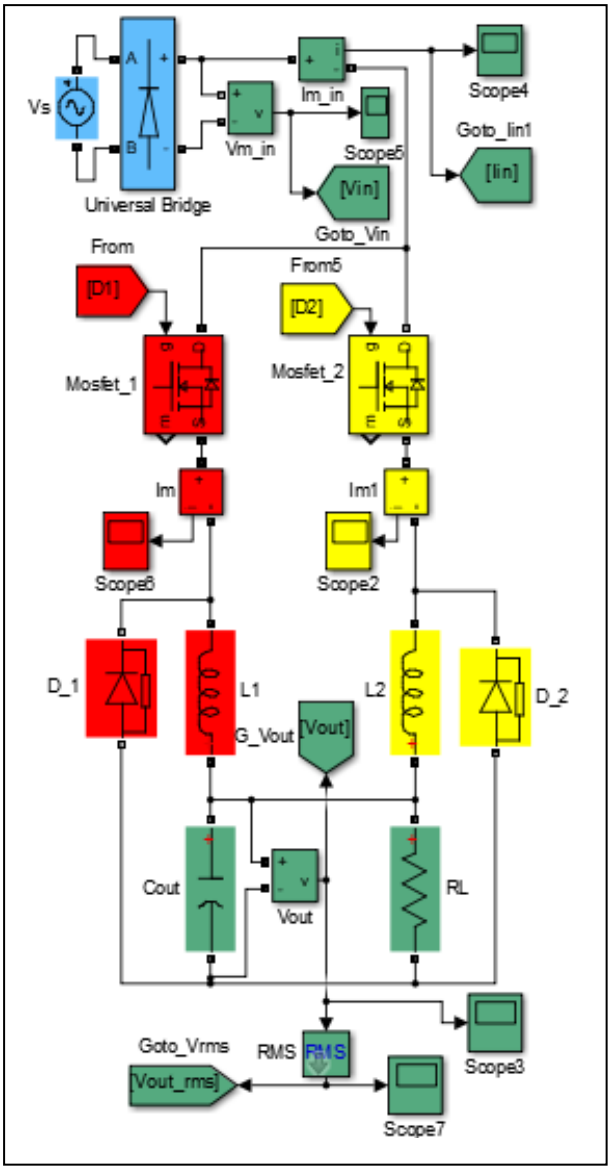

Fig. 10. Simulink Model of IBC

TABLE I. IBC SIMULATION PARAMETERS

Parameters	***Symbol***	***Value***
Number of Phases	N_{phase}	2
Input Voltage	V_{in}	150 - 200 V
Output Voltage	V_{out}	24 V
Switching Frequency	F	65 kHz
Per phase Ripple current	ΔI	%10
Output Current	I_{out}	5A
Indutors per phase	L_1, L_2	100 µH
Output voltage ripple	V_{o_ripple}	≤ 20 mV
Output Capacitor	C_{out}	22 µF

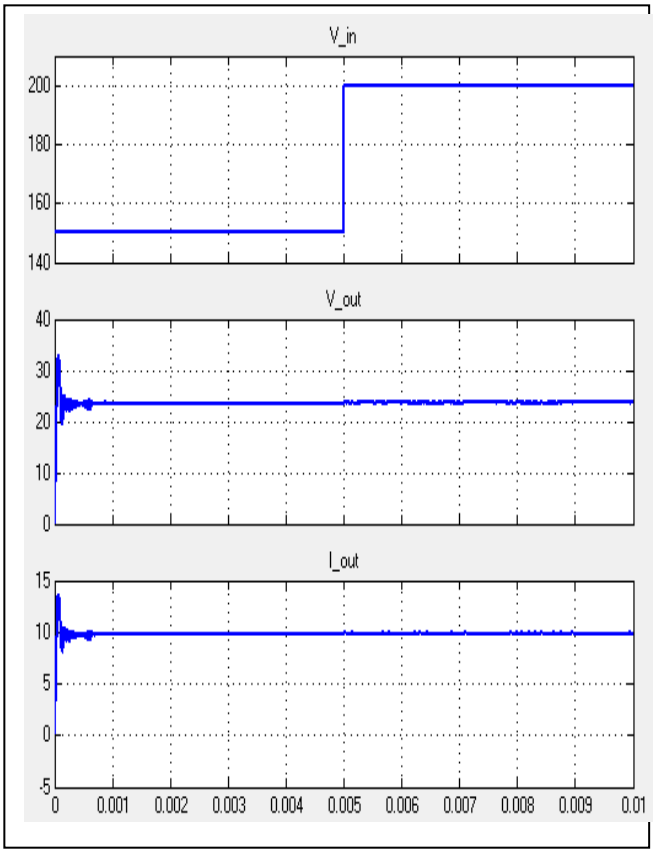

Fig. 11. In PI-controlled IBC, input voltage Vin, output voltage Vout and output current I_{out}

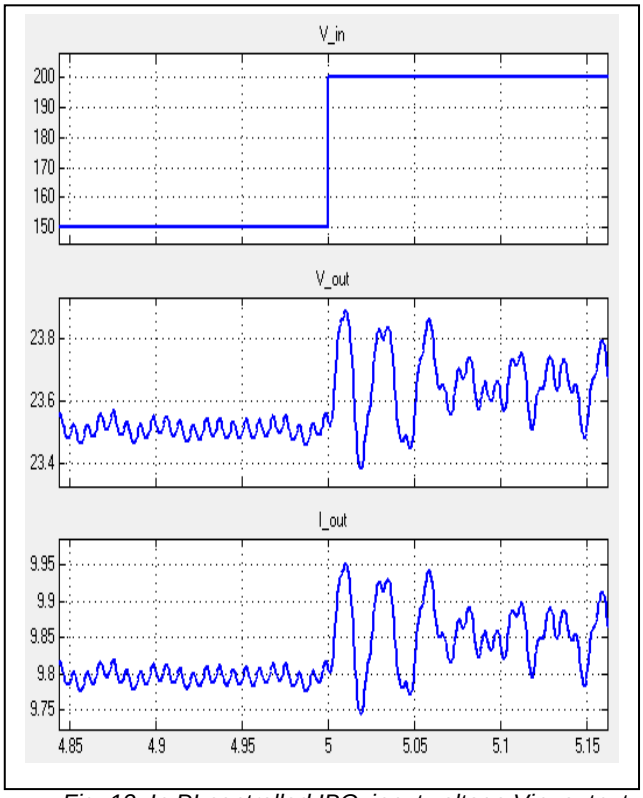

Fig. 12. In PI-controlled IBC, input voltage Vin, output voltage Vout and output current Iout detailed analysis in 5ms

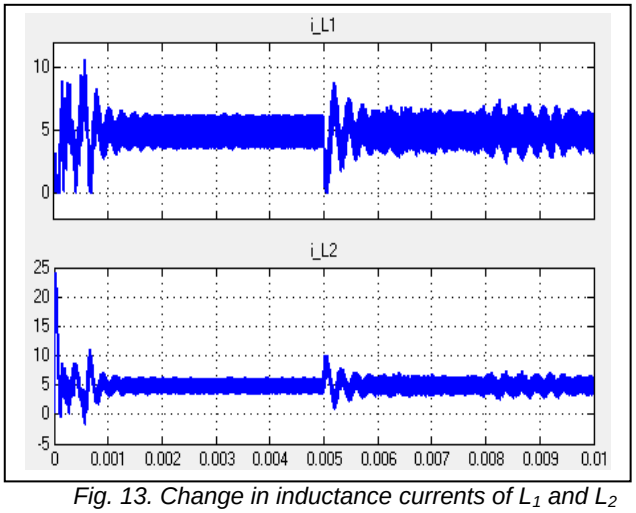

Fig. 13. Change in inductance currents of L_1 and L_2

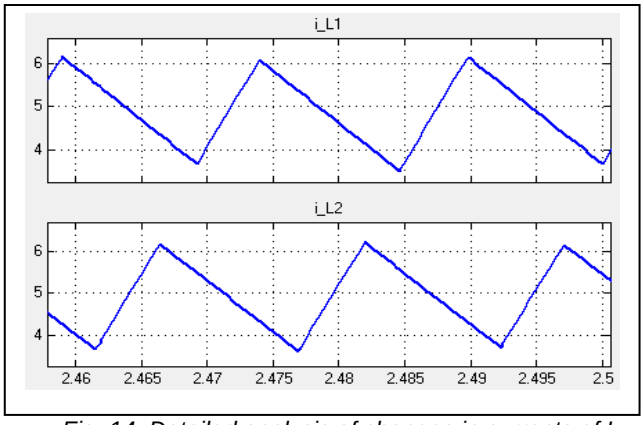

Fig. 14. Detailed analysis of changes in currents of L_1 and L_2

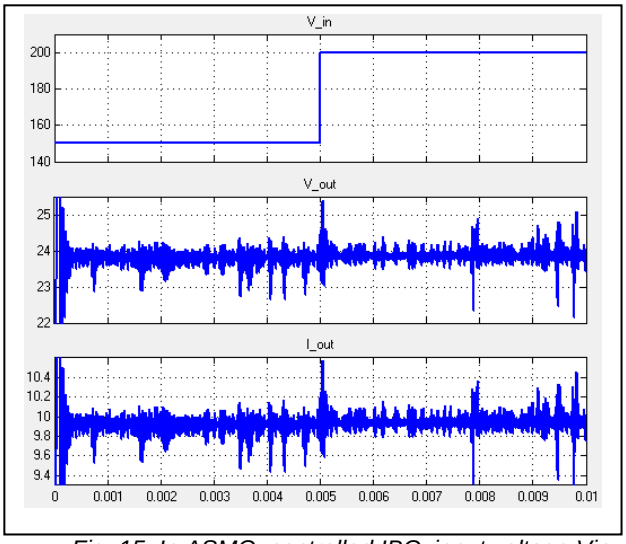

Fig. 15. In ASMC- controlled IBC, input voltage Vin, output voltage Vout and output current Iout

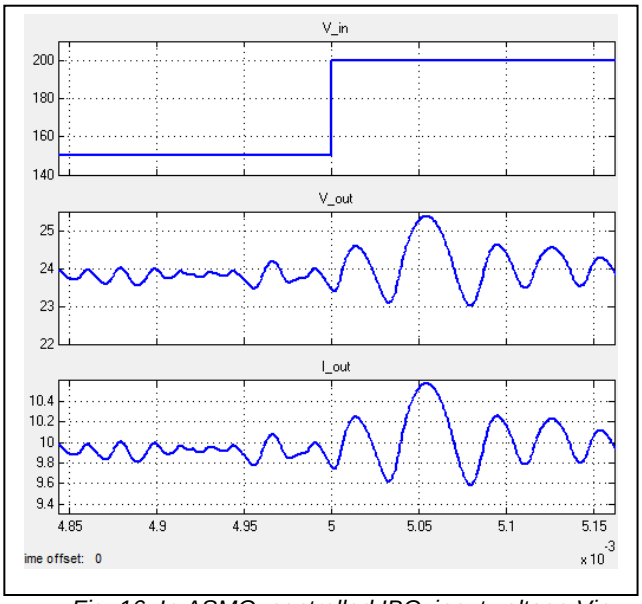

Fig. 16. In ASMC- controlled IBC, input voltage Vin, output voltage Vout and output current Iout detailed analysis in 5ms

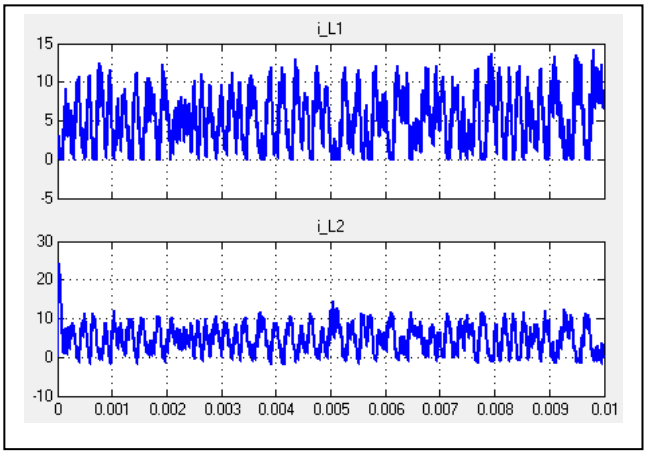

Fig. 17. Change in inductance currents of L_1 and L_2

TABLE II. SIMULATION RESULTS

Simulations	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
Power (kW)	1	1	1	1	0,5	1	1	1
L_1=L_2 (mH)	100	100	100	100	80	50	50	50
C_{out} (µF)	22	22	22	22	22	22	22	22
V_{out} (rms)	200	100	250	220	200	200	150	100
Proportional-Integral Control Method								
Power Factor (PF)	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
THD (%)	5,1	2,0	6,3	4,7	5,2	23,1	8,5	4,5
Average Sliding Control Method								
Power Factor (PF)	0,99	1	0,99	0,99	0,99	0,99	0,99	0,99
THD (%)	4,8	1,4	5,4	3,9	4,2	15,2	6,3	3,9

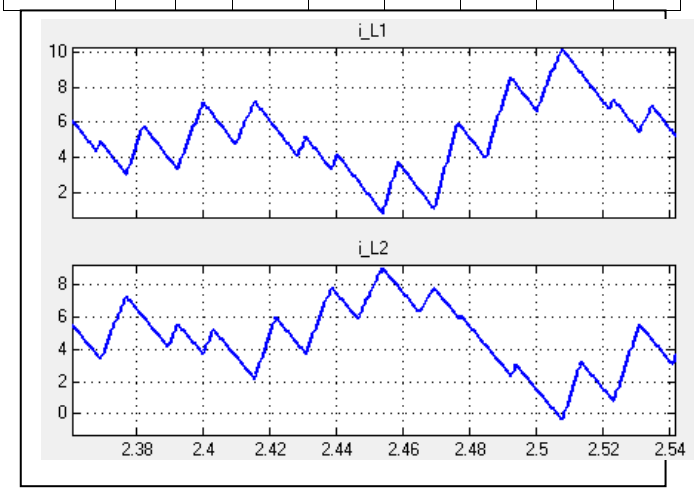

Fig. 18. Detailed analysis of changes in currents of L_1 and L_2

VI. CONCLUSION

In this study, proportional-integral and average sliding mode network current control methods are applied to a two-cell buck-type power factor correcting circuit and simulated in Matlab / Simulink program. The results obtained are very close to each other. The control techniques used have been based on practical work using fixed switching frequency. It has been

observed that both of the tested control techniques exhibit a structure resistant to output load changes, as can be seen from the graphs. It has been observed that the proportional-integral control technique in the designed 100W simulation circuit is more sensitive to inductor variations than the average floating mode control technique. It has been observed that when the inductor value is reduced, the proportional-integral controller coefficient adjustments must be made again and the average sliding mode method maintains its performance. Capacitor change affects output voltage fluctuation.

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