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Improvement of Power Quality in an Adaptive Boost PFC Converter with Generation of PWM Control Signal by Cascading Power Factor and Chaos Controller Circuits

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***Abstract:** This work discusses about a digital controller system for reduced effect of chaos and improved power factor of a 1-phase AC-DC converter system. It is shown that, the proposed controller technique is able to suppress the chaos at variable load condition of a boost power factor correction (BPFC) converter. Furthermore, a systematic methodology based on bifurcation diagram from tuning the controller is proposed. To achieve improved power quality in BPFC converter, combination of average and peak inductor current mode control methods are performed. In the MATLAB/SIMULINK environment, simulation circuit for the BPFC converter with average current control method is developed to improve power factor. Further, to reduce the effect of chaos produced in converter, peak inductor current mode with delayed feedback control method is adopted. At an output power of 650 W operating at 130K Hz switching frequency, this converter provides Total Harmonic Distortion (THD_i) reduction of 20% and improved Power Factor (PF) of input current compared to other conventional converter. For real time operation of the system, rapid prototyping test is carried out using DAQ (Data acquisition) board NI 6351. The delayed feedback control has a better performance than any other methods proposed earlier.*

***Keywords:** THD, chaos, converter, PWM*

I. INTRODUCTION

In the recent years, AC-DC converters followed by a DC-DC converter have reached a full-fledged level of improved features with respect to reduction in harmonics, power factor correction (PFC), regulation of output voltage for change in load or input voltage and high power density. In these converters, various types of DC-DC converter topologies can be used for PFC, to meet international standards, such as IEC-1000-3-2 and IEEE -519, which are defined to suppress the harmonic content on the grid current. However, DC-DC boost converter is a best choice of selection to achieve high power factor compared to other DC-DC converter topologies with various control techniques [1,2]

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where series connected boost inductor with the source can easily shape the converter current to follow grid utility current. DC-DC converters exhibit different types of non-linear behaviors such as bifurcation, chaos and sub harmonics in the continuous conduction mode (CCM), discontinuous conduction mode (DCM) and mixed conduction mode (MCM) of operation [3-5]. These nonlinear behaviors in any DC-DC converter result in random unpredictable movement of trajectories within a bounded state-space. In particular, numerical and experimental results of any DC-DC converter have shown that, chaos behavior is very sensitive to the initial conditions of the non-linear system with classical control strategies [5, 6] and limits the operating range of converter system [7]. Converters operating at a constant switching frequency and peak amplitude control have harmonics leading to chaotic behavior whereby frequency spectrum of sub harmonics is continuous. Several methods have been reported in the research literature, to minimize effect of chaos in DC-DC converters. The simple chaotic control technique by modulating the system parameters is proposed in [8, 9] which is a simple technique and intuitive in nature. But this technique is subjected to only small scope of change in parameter and has a limitation to change the system design to fulfill the required operation [10]. Ott, Grebogi and Yorke (OGY) method in [3, 7] has been suggested to eliminate chaos in DC-DC converters, where the stabilization of unstable periodic orbits within its chaotic attractor through time-dependent perturbation of system parameters is proposed. However, this method limits the correction of parameter and which may give rise to driving of small noise, leading to the occasional bursts of the system. Interestingly, a chaos control theory is effectively used to control chaos by varying switching frequency of switch, with respect to generated random signal, and hence to reduce the effect of electromagnetic interference (EMI) in DC-DC converter [11], but this approach suffers from difficulty in producing real random signals and it is difficult to design EMI filter at input of converter, as switching frequency is varied. The use of digital controllers for power control has been met with significant interest over the past decade. Low cost, faster devices and feature-packed digital controllers provide incentive for designers to employ digital control methods. In comparison to their analog controlled counterparts, advantages such as less susceptibility to noise, reduced parametric variation of passive components and simplicity in tuning makes the migration of control to the digital domain an attractive option [12-14]

Most importantly, digital controllers have performance advantages that would be impossible to achieve through analog control methods. Hence, a novel technique is proposed through a digital controller to minimize the chaos effect with a primary objective of achieving near unity power factor of AC-DC converter. The proposed AC-DC Boost PFC has a power rating of 650 W, operates at switching frequency of 130K Hz, with an AC input voltage of 230 V/50 Hz. It has applications in power sources to computer, telecommunication devices, and distributed power system and so on. The chaos effect control for DC-DC boost converter especially at low switching frequency and low power have been reported in the literature. However, the cascading of power factor (PF) and chaos control circuits in 1-phase AC-DC followed by boost converter operating at high switching frequency of 130K Hz for medium power applications has not been noticed. Hence, effort is made, to improve the quality of input power and to minimize the chaos effect in 1-phase AC-DC converter suitable for medium power applications. Optimization and improvement of stability performance of the converter over the different load conditions has been addressed by [15, 16].

Subsequent sections of this paper are organized as follows: In section 2, types of inductor current modes, average current mode control, system diagram and operation of an adaptive BPFC converter are presented. In section 3, bifurcation diagram and flow chart are presented. In section 4, chaotic process, operation of boost converter, delayed feedback control system and control of chaos in an adaptive BPFC converter are presented. In section 5, results of chaos control of an adaptive BPFC converter system are presented, including the discussion on comparison of THD_i and PF with and without chaos control circuit, followed by conclusion in section 6.

II. ADAPTIVE DIGITAL BPFC CONVERTER

The adaptive digital control technique proposed for BPFC converter plays a vital role in achieving near unity power factor & reduction in the effect of chaos. This adaptive digital control technique provides a systematic approach for automatic adjustment of feedback controller in real time operation of BPFC converter. In this controller, the variables of converter adapt themselves to the desired conditions from actual conditions of the converter operation. Hence, the inductor current $i_L(t)$, of BPFC, automatically adapts to either CCM or DCM mode of operation. In the proposed research work, power quality improvement is achieved by operating BPFC converter with PWM control in two stages. In the first stage, the DC-DC converter is operating in average current mode control to reduce the harmonics, and hence the improvement in the power factor. In the second stage, the digital controller effectively uses delayed feedback control technique to control the chaos effect of BPFC converter.

A. Inductor Current Modes of the BPFC Converter

BPFC converter operates in three modes, where each mode is found in single switching cycle of the $i_L(t)$ modes are

- Continuous conduction-mode (CCM)
- Boundary conduction-mode (BCM)
- Discontinuous conduction-mode (DCM)

The BPFC converter is said to be in mixed conduction mode (MCM) mode, if it is functioning in both DCM and CCM in a period of cycle. These modes are depicted in Fig.1

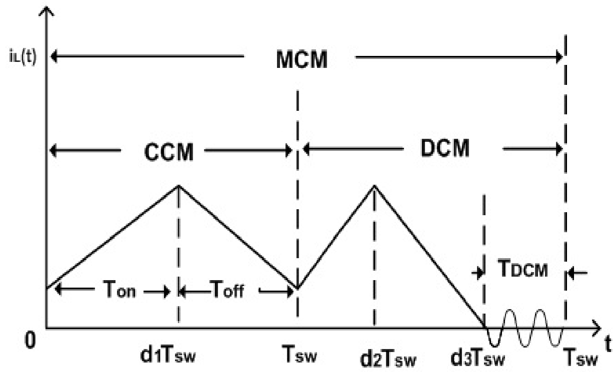

Fig.1 BPFC inductor current working in both CCM and DCM, corresponding to MCM operation.

In Fig.1, d_1 and d_2 indicate the duty ratios of CCM and DCM respectively. The relation between d_1 and d_2 is given by (1)

$$d_2 = (1 - d_1) \qquad (1)$$

The forward voltage conversion ratio of converter, when operating in MCM, is given by equation (2)

$$V_0/V_{in} = (d_1+d_2)/d_2 \qquad (2)$$

Where V_0 is output voltage of the DC-DC converter and V_{in} is input voltage of the DC-DC converter Substituting equation (1) in equation (2), and simplifying the equation, gives output voltage expression for CCM operation of proposed converter.

B. Average Current Mode Control (ACMC)

The ACMC method is a popular method of inductor current control, especially for boost PFC converter, which provides low harmonic distortion and hence, achieves high power factor in converter. Fig. 2 shows the rectified input voltage and inductor current of BPFC converter of ACMC method. In this method, the inductor current is sensed and its average value over a period of cycle is made to follow rectified reference signal (i_{ref}) of AC input voltage. The detailed description of voltage loop compensation and current loop regulation of ACMC method are presented in [17–19].

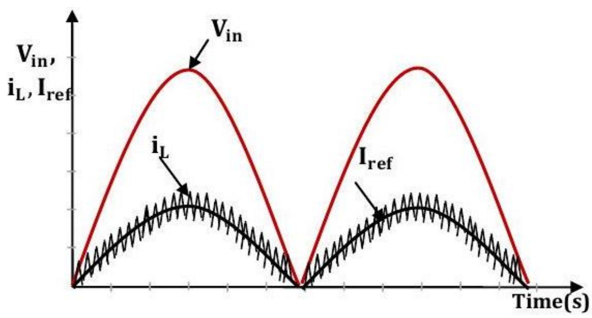

Fig. 2. Input voltage and inductor current wave forms

C. Overall Block Diagram of System

Fig. 3 shows the simplified block diagram of BPFC converter with digital controller. As depicted in Fig. 3, AC input voltage is rectified by a rectifier and its output voltage is fed to boost PFC converter. The proposed digital controller is connected to a power converter, which is operating in MCM operation. Here, digital controller essentially uses two ACMC compensators i.e., DCM and CCM compensators. Operation mode selection is done by using a comparator as DCM detector technique reported in [20, 21].

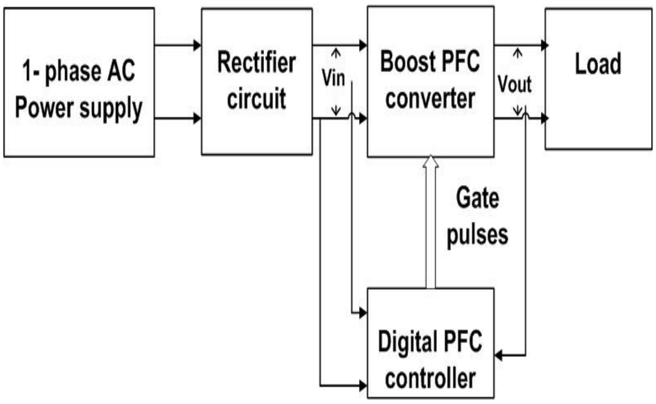

Fig. 3. Basic block diagram of PFC control system

This current control method is constructed based on the small signal modeling of PFC converter. Similarly to regulate the output voltage of converter, a discrete proportional integral (PI) controller is used in the outer voltage loop of controller. Arrangement is made, in such a way that, digital devices sense the inductor current in the power circuit and voltage divider networks sense the input and output voltages of converter. The complete control architecture is separated into two loops (a high-frequency inner current loop and a low-frequency outer voltage loop) by which both PFC and output voltage regulation can be achieved.

Fig. 4 shows proposed adaptive BPFC converter with an average inductor current control unit in feedback system. The outer voltage loop is responsible for regulating the output voltage across the resistive load R_L. The voltage control loop utilizes discrete PI compensator, which minimizes the error in output of converter and its output decides amplitude required for the reference signal i_{ref} . The sinusoidal wave shape of i_{ref} is obtained from the input rectified voltage of the converter system. The final i_{ref} , is a product of rectified voltage and output of the compensator voltage, which follows a shape of rectified sine signal. The inputs of inner current loop are i_{ref} and actual inductor current i_L. The difference of these two currents is current error i_{err}. The mode of operation is detected by sensing the zero inductor current by using comparator as DCM detector is shown in Fig. 4.

The controller provides separate DCM and CCM average-mode current compensators. Based on the mode of operation, multiplexer selects the suitable compensator with Digital Pulse Width Modulation (DPWM) block, which essentially generates switching pulses for power MOSFET, to operate at high switching frequency, which results in minimization of total harmonic distortion (THD_i) on input side of proposed converter.

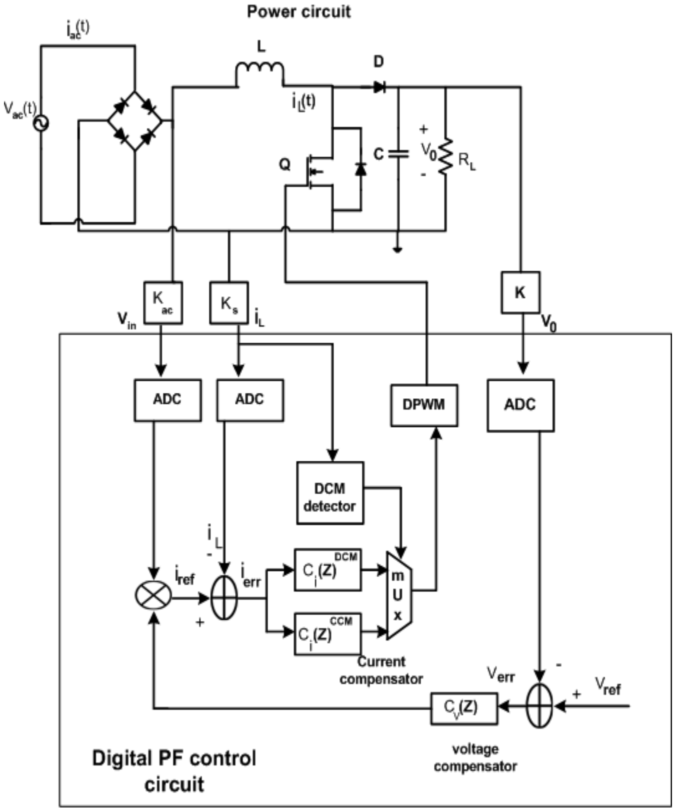

Fig. 4. Block diagram of an adaptive BPFC converter with PF Control circuit

III. FLOW CHART FOR BIFURCATION ALGORITHM AND BIFURCATION GRAPH

The theory of Bifurcation developed by Poincare [22] is used to show the change in system behavior, by varying the control parameters of the system. To study and analyze the system dynamics, bifurcation graph is constructed, which shows the changes in state variables with control parameters. The bifurcation graph of the proposed system for the boost converter is obtained by developing a MATLAB program and execution.

From the graph, range of the chaos effect of the control parameter is determined and used to choose reference value in the proposed system. A flowchart for the algorithm is shown in Fig. 5. The programming of bifurcation diagram for the controller is developed and executed based on the algorithm and flowchart shown in Fig. 6. Fig. 6 shows the bifurcation graph with I_{ref} as bifurcation control parameter. It is seen from the bifurcation diagram that the system shows High chaotic behavior at lesser values of inductor current i_L or lower values of output load. The chaotic effect reduces as the inductor current magnitude increases or as output load increases with respect to reference current I_{ref} . It has been noticed in the proposed system that, at higher loads chaos effect is almost negligible.

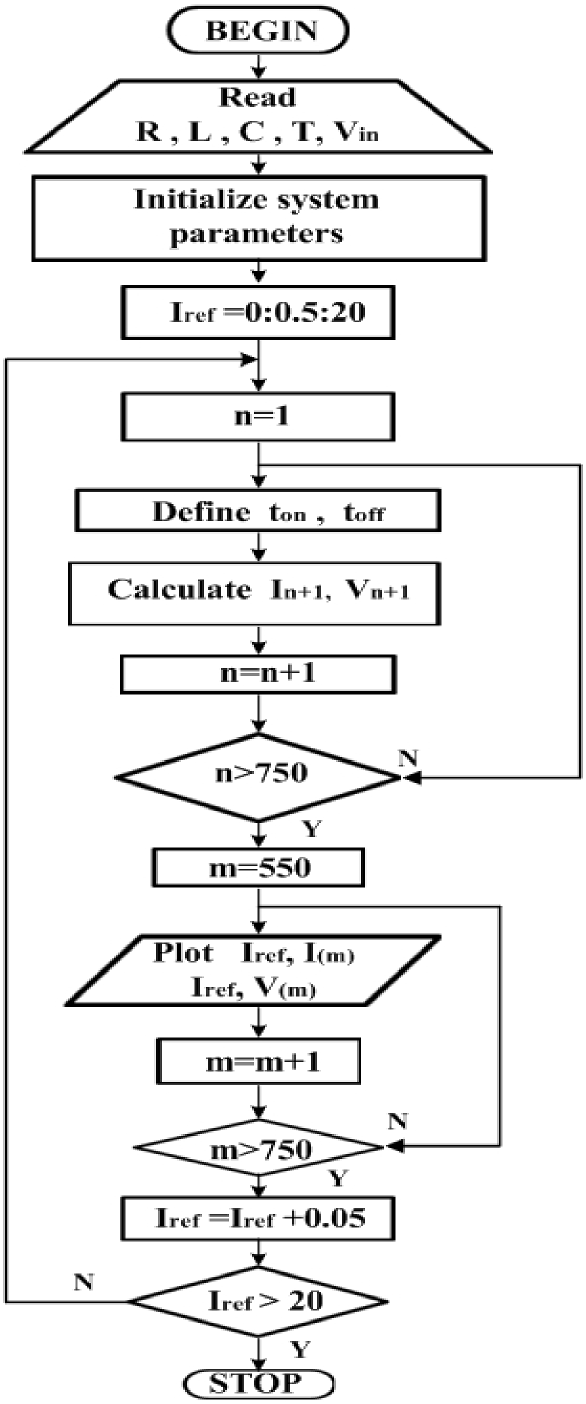

Fig. 5. Flow chart for bifurcation program

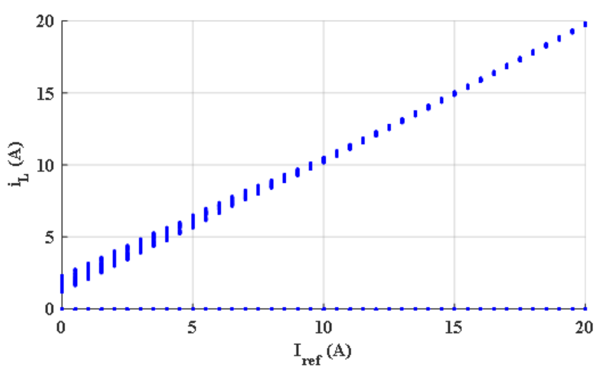

Fig. 6. Bifurcation graph with I $_{ref}$ as bifurcation parameter

IV. CHAOTIC PROCESS AND CONTROL

A. *Operation of Basic Boost converter*

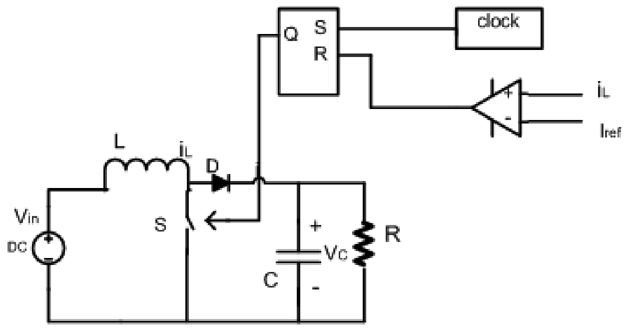

Fig. 7. Basic boost converter circuit

Fig. 7 shows a circuit diagram for the boost converter, which represents discrete control of semiconductor switch through current feedback loop. The current feedback loop is composed of a fixed frequency clock, a flip-flop and comparator. Switch is turned on by the high (Q) output of flip-flop. During the on period of switch, the current in the inductor increases and stores the energy in the form of magnetic field. When the switch is turned-off, as per the Lenz's law a voltage induced across the inductor maintaining the current flow in same direction, makes the diode D to become forward biased and hence the stored energy of inductor is transferred to the capacitor C and load R. When the inductor current magnitude i_L is greater than reference current level I_{ref} , the period doubling will occur and there will be an effect of chaos in the inductor current i_L, as well as change in the pulse width of the clock. When $i_L \leq I_{ref}$, there will be no effect of chaos and no change in clock time period. Hence, this approach is adapted in the proposed system.

B. *Delayed Feedback Control System*

Pyragas suggested about the elimination of chaotic nature by using the delayed current control system as depicted in Fig. 8. In this technique, the difference between the current (actual) value of system variable Y (t) and the value of Y (t) with seconds delay τ is the feedback control signal F (t). F (t) is obtained by multiplying difference in magnitude of Y (t) and Y (t - τ) and feedback gain constant K as shown in equation (3) and is applied to chaotic process. The concept of a chaotic attractor is developed by a countable set of unstable periodic orbits with different periods. Chaos will be reduced When delay time is same as time period T of the stable orbit [7, 22]. In this work delay time τ = 4μ s is chosen within the switching time period T and K = 1 for better performance of Chaos control.

$$F(t) = K[Y(t - \tau) - Y(t)] \qquad (3)$$

C. *Control of Chaos in an Adaptive BPFC Converter*

The block diagram of proposed adaptive boost PFC converter comprises of power circuit, digital PF control circuit and chaos control circuit, is shown in Fig. 9. The standard procedure is considered for designing inductor L & capacitor C components of power converter, which are described by below equations (4) and (5).

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$$L >> (d_1 (1 - d_1)2R) = 2f \quad (4)$$
$$C >> (V_0 d_1)/ (\Delta V_0 f R) \quad (5)$$

The chaos control circuit is implemented using delayed feedback control system in the BPFC converter. The value of I_{ref} is chosen in a chaotic range of bifurcation diagram, which causes period doubling required for chaos control in DC-DC converter. When the inductor current i_L is greater than I_{ref}, it will be affected by chaos. Truth table logic is implemented [23] by setting the output Q of truth table to one for every clock pulse and to zero for the following equation.

$$i_L(t) = I_{ref} - K[i_L(t - \tau) - i_L(t)] \quad (6)$$

The importance and controllability of the controller is justified using simulation and experimental results [24].

V. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulated Results

In simulation, 650 W, 1-phase AC-DC boost PFC proposed converter with chaos control has been carried out in MATLAB/SIMULINK software platform. The proposed converter system parameter are listed in Table I.

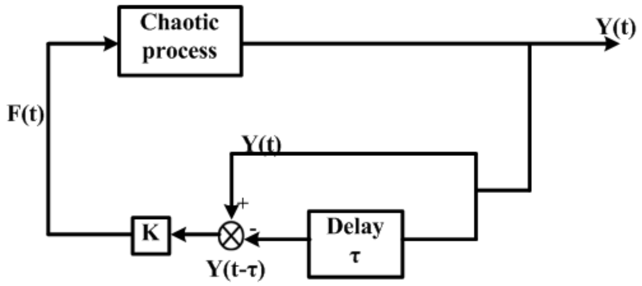


Fig. 8. Delayed feedback control system

Table - I: System parameters for switching frequency 130K Hz and input AC supply voltage of 230 V/50 Hz

Parameters	Values
Switch time period T	7.69 µ s
Input voltage V	230 V
Frequency f	50 Hz
Inductor L	200µ H
Capacitor C	300µ F
Load resistor R	264 Ω / 650 W
Time delay τ	4µ s

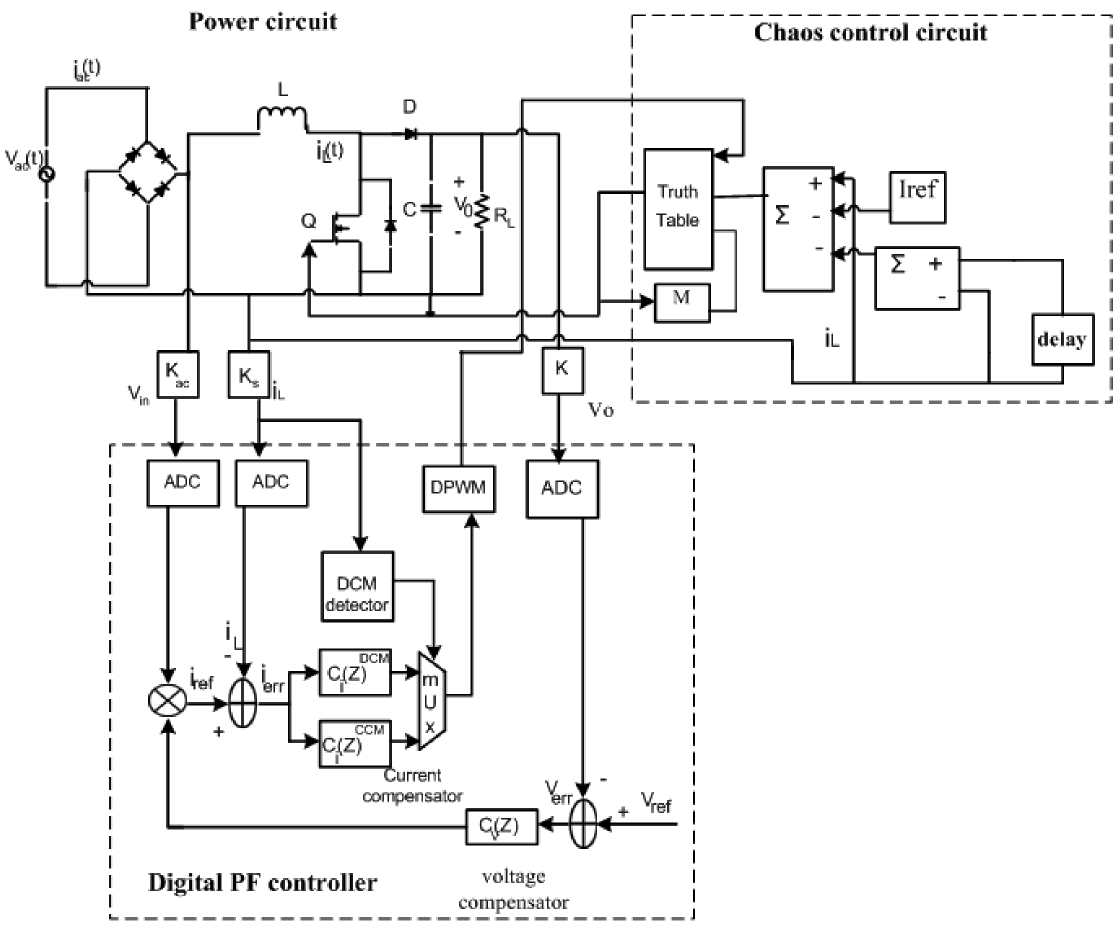
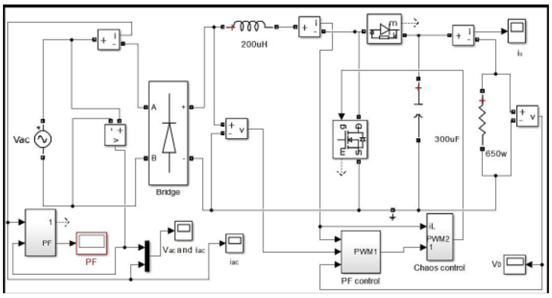


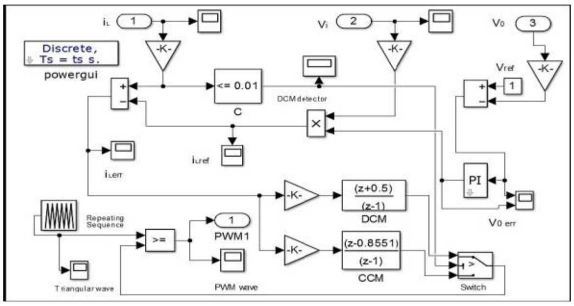
Fig. 9. Proposed diagram of an adaptive boost converter with delayed feedback chaos control system

Fig. 10, shows a complete schematic of proposed BPFC converter with chaos control technique, developed in MATLAB environment. Fig. 10(a) shows the block diagram of the model. Fig. 10(b) and Fig. 10(c) shows the internal architectures of power factor control and chaos control units respectively. The power factor control architecture is designed and developed with outer voltage loop and two inner current loops to achieve near unity power factor of the converter.

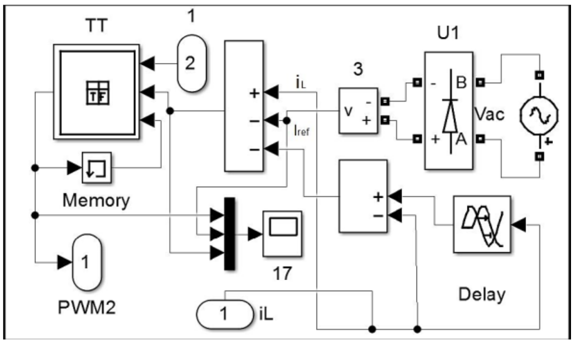
The function of internal architecture of chaos control system is developed through delayed feedback control to minimize the effect of chaos especially in inductor current of proposed converter. The simulation results are evaluated and obtained for both proposed converter with chaos control and converter without chaos control.



(a)



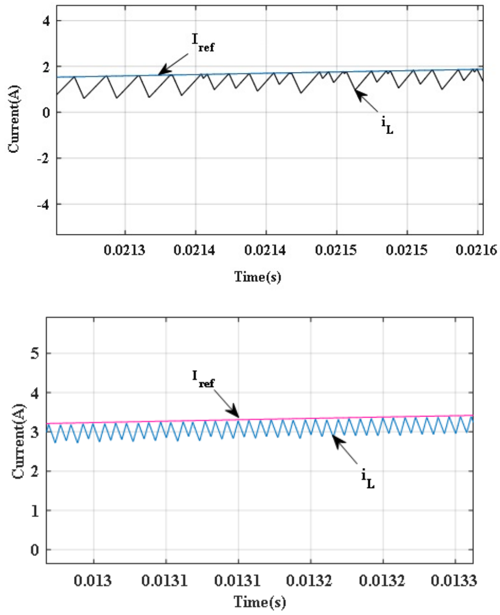
(b)



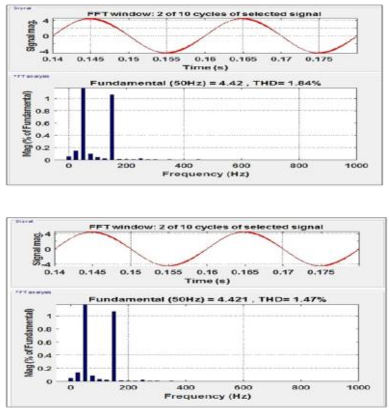
(c)

Fig. 10. MATLAB/SIMULINK model of an adaptive digital
BPFC converter with chaos control (a) Block diagram of the
model (b) Internal architecture of PF control (c) Internal architecture of chaos control

Fig. 11 shows the simulation results comparison of BPFC converter with and without chaos control. Fig. 11(a) represents the boost inductor current response in both cases of operation of converter. From this response, it can be concluded that, the inductor current with chaos control has reduced effect of chaos and exhibits smooth operation of a converter compared with converter without chaos control. Fig. 11(b) shows the harmonic spectrum of a input current of both converters under comparison. The evaluation gives input current THD_i of value at full-load condition 1.47% in BPFC with chaos control, which corresponds to a power factor of 0.9998. This value is improved value of power factor when compared with THD_i converter without chaos control. From this, it is concluded that, proposed BPFC converter with chaos control reduces the THD_i by 20%, when compared with BPFC converter without chaos control.



(a) Boost inductor current response



(b) Harmonic spectrum of input current

Fig. 11. Simulation results of an adaptive BPFC converter at 650 W (i) without and (ii) with chaos control

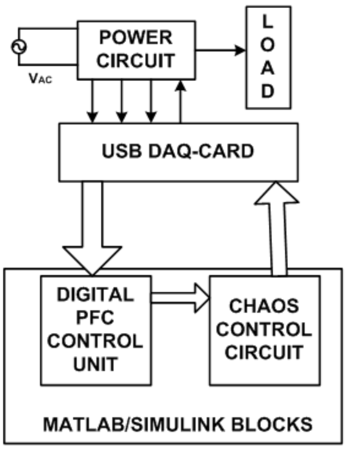


Fig. 12. Block diagram of experimental setup.

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B. Experimental Results

To verify the theoretical analysis of the proposed BPFC converter, a 650 W prototype is implemented, operated and tested for both cases, i.,e (i) with chaos control and (ii) without chaos control. The specifications of Converter are as follows:

a) Input voltage: V_{ac} (rms) = 230 V
b) Output voltage: V_0= 400 V
c) Maximum output power: P0=650 W
d) Switching frequency of DC-DC converter: f_s=130K Hz

Fig. 14, represents the input voltage and current waveforms of proposed BPFC converter operating at rated load 650 W condition.

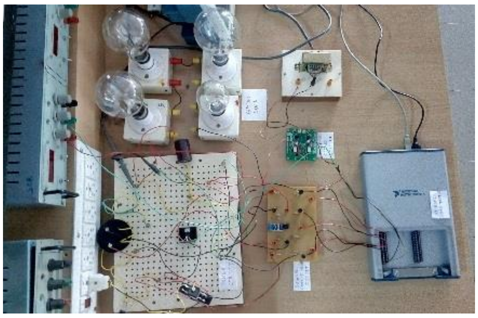
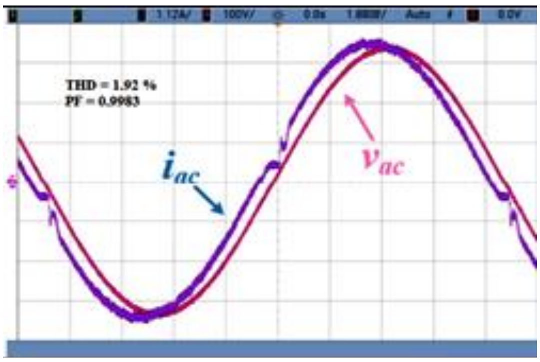


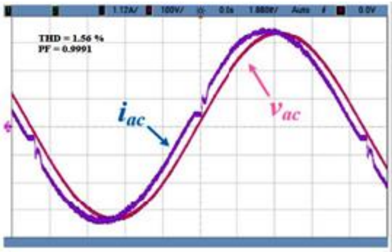
Fig. 13. Snapshots of experimental setup

Fig. 14(a) depicts that, input voltage and current wave-forms of BPFC converter without chaos control, where it can be observed that, the AC input current i_{ac} is distorted near zero

crossing and at peak of the signal in both positive and negative half cycles. The THD_i of this converter is of 1.92% and its corresponding power factor is found to be 0.9983. The voltage and current wave-forms for BPFC converter with chaos control is presented in Fig. 14(b). As this proposed chaos control converter operates based on the selection of current compensators in discrete control mode, the chaos effect near zero crossing of the positive half cycle is minimized in comparison to converter without chaos control, resulting into a reduced THD_i on the input current waveform. The THD_i of input current of converter with chaos control is 1.56%, which is well within the limit and is reduced by 18.75%, compared to THD_i of input current of converter without chaos control. Hence, the improved power factor of the proposed BPFC converter with chaos control is 0.9998 and the efficiency of the prototype under nominal input and full load condition is 89.25%.



(a)



(b)

Fig. 14. Input voltage and current waveforms of proposed BPFC converter at load 650 W (a) Without chaos control at full load (b) With chaos control at full load.

Table II shows comparison of different digital control at V_{ac}= 230 V, f = 50 Hz. It is observed that combined effect of using two control units (PF controller and chaos controller) has improved the overall power quality of the converter when compared with existing digital controller. Since two controller circuits are integrated as a single unit it is cost effective and simple.

Fig. 15 shows Comparison of efficiency of different BPFC converter system at different load conditions. The comparative line graph for experimental results of PF for the conventional, Proposed Digital Controller with chaos control and without chaos control are shown in Fig. 16 for the output power Pout ranging from 49W to 650Wat V_{ac} = 230 V. The comparative line graph for experimental results of THD_i for the conventional, Proposed Digital Controller with chaos control and without chaos control are shown in Fig. 17 for the output power Pout ranging from 49 W to 650 W at V_{ac} =230 V.

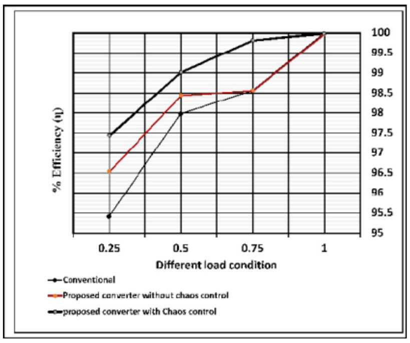


Fig. 15. Comparison of efficiency of different BPFC converter system at different load conditions

Table -II: Summary of experimental PF and THD_i for various output power

P [W]	Conventional Controller		Proposed Controller (without Chaos control)		Proposed Controller (with Chaos control)	
	PF	*THDi [%]*	*PF*	*THDi [%]*	*PF*	*THDi [%]*
49	0.8032	42.54	0.8034	42.84	0.8531	39.72
98	0.8904	36.09	0.896	34.14	0.9243	32.12
195	0.9541	31.42	0.9653	18.27	0.9743	16.24
260	0.9701	14.33	0.9789	11.02	0.9852	10.12
325	0.9797	11.65	0.9844	8.76	0.9901	7.81
390	0.9761	8.46	0.9845	6.54	0.9932	5.83

455	0.9812	5.86	0.9835	5.48	0.9972	4.61
520	0.9855	4.63	0.9855	4.5	0.9982	3.24
585	0.9885	3.83	0.9985	2.75	0.9993	2.1
650	0.9709	3.29	0.9997	1.82	0.9999	1.46

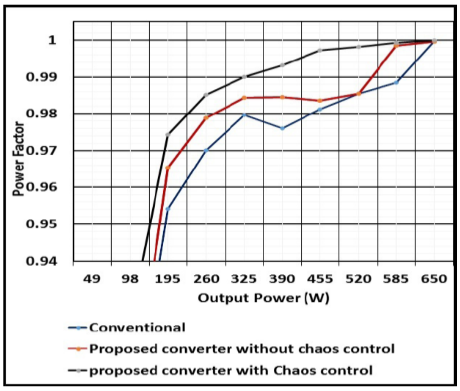


Fig. 16. PF experimental results for the Conventional and Proposed Digital controller with chaos control and without chaos control for the output power P_{out} ranging from 49 W to 650 W at V_{ac} = 230 V

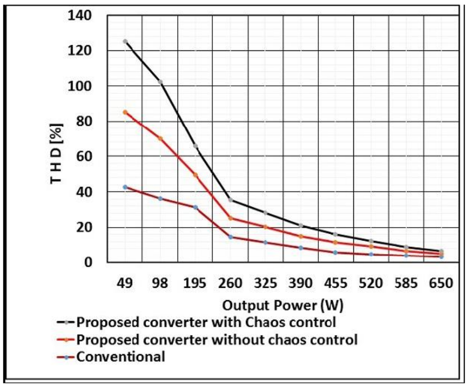


Fig. 17. THD_i experimental results for the Conventional and
Proposed Digital controller with chaos control and without
Chaos control for the output power P_{out} ranging from 49 W to 650 W at V_{ac} = 230 V

Comparison of THDi (%) and PF results with chaos control and without chaos control circuit at I_{ref} = 4.5 A are summarized in Table 2. With the obtained results at 650 W, it can be observed that 20% of THD_i is decreased and PF is increased little bit with delayed chaos control circuit. In digital controller with chaos control, %THD is reduced with comparison with digital control without chaos control.

VI. CONCLUSION AND FUTURE WORK

- In a single phase AC-DC converter, Reduction of chaos effect is done by using delayed feedback control method.
- Improvement of power factor by using average current mode control method.
- Improvement of Power quality using Cascaded control of chaos and power factor is accomplished.
- Chaos behavior of converter is investigated through Bifurcation method and when compared to other methods complex generation of Chaotic PWM is avoided.
- Matlab Simulink model of cascaded control was developed and analyzed.
- Laboratory mode prototype using NI 6351 DAQ has been developed to predict the circuit behavior for converter with and without chaos control circuit and this justifies reduction of harmonics in the model.
- It is observed that, the converter with chaos control exhibits reduction of 20% THD_i and an increase of 0.02% PF.
- DC-DC boost converters are regularly used in photovoltaic (PV) systems for power conditioning, to step up the voltage for storage or for export to the energy grid. Converters used for these type of applications will have a failure rate higher than normal. The consequences of chaos on series/ parallel type of converters need to be investigated. The prototype of this work can further be implemented using FPGA, DSP Integrated Circuits.
- This system can be extended for large scale system to avoid failure of the power conditioning and can be accomplished either for individual array by using multiple small converters or at the overall system level by using one big converter. The economics of each techniques is currently being investigated.

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