approach, fuzzy controllers are designed by using the output voltage error and the change of voltage error. But in this work, a mixture of these two parameters is fed to the fuzzy controller and an easier and simpler implementation has been achieved. The fuzzy controller inference is based on only two rules and the output of fuzzy controller is the change to control voltage. The computer simulation results and experimental measurements of the closed loop performance for the line and load regulations of a 500W boost rectifier validate the proposed scheme. The experimental measurements of the closed loop performance are very close to the simulation results. The results show that the system posseses a high power factor as well as a good dynamic response.

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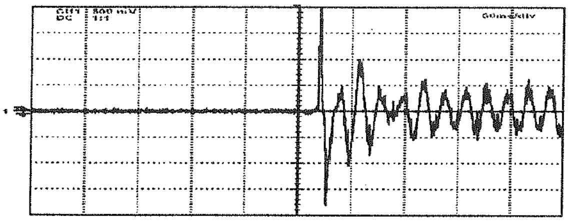


Figure 12: Input current waveform during converter startup [Ch1: Current (5A/div), Time base: 50ms/div]

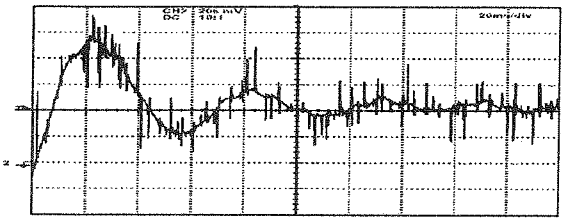


Figure 13: Control voltage waveform during converter startup [Ch2: Voltage (266 mV/div), Time base: 20ms/div]

Fig.14 shows steady state input voltage and input current waveforms. It can be seen that the current is in phase with the voltage. Rated input current THD is 11.76% and power factor equals to 0.992. The PFC converter full load efficiency is 91.2%.

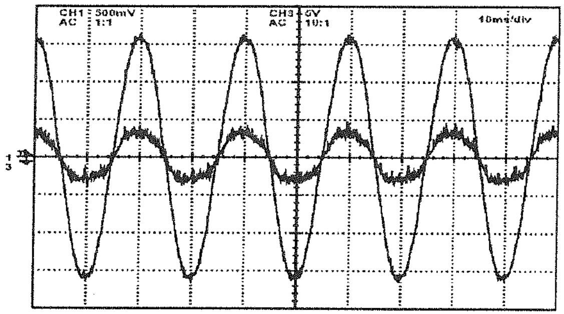


Figure 14: Steady state input voltage and current [Ch1: Current (5A/div), Ch3: Voltage (100V/div), Time base: 10ms/div]

Fig.15 shows the input current during a step change in R_o from 320 Ω to 640 Ω.

Figure 15: Input current during step change in $R_o(320\Omega \rightarrow 640\Omega)$ [Ch1 (2.5A/div), Time base: 50ms/div]

Fig.16 shows the output voltage and control voltage during a step change in R_o from 320 Ω to 640 Ω. Switching noises are visible on control voltage. Output voltage has 4% overshoot.

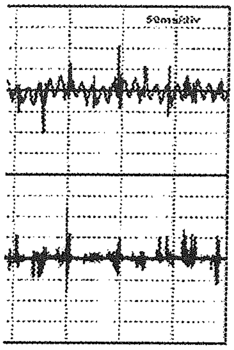


Figure 16: Output Voltage (AC part) and Control voltage during Step change in $R_o(320\Omega \rightarrow 640\Omega)$ [Ch1: output voltage (10V/div), Ch2: Control Voltage (250mV/div),Time base: 50ms/div]

Verifying of line regulation of the experimental converter has been carried out by sudden change in input voltage from 220V to 150V and vice versa with R_o unchanged.

Fig.17 shows the output voltage and control voltage during input voltage change from 220V to 150V. Output voltage has about 5% undershoot and it does not go outside of 5% band.

Fig.18 shows the input current during input voltage change from 220V to 150V.

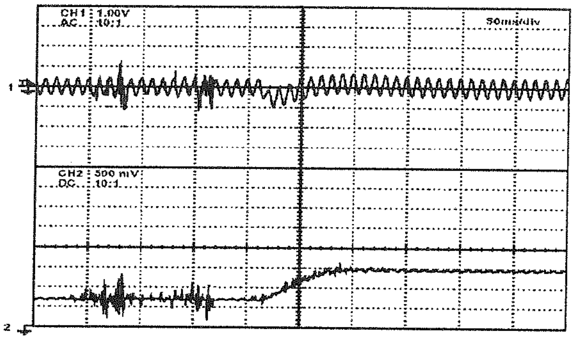


Figure 17: Output Voltage (AC part) and Control voltage during step change in input voltage (220V to 150V) [Ch1: output voltage (20V/div), Ch2: Control Voltage (500mV/div), Time base: 50ms/div]

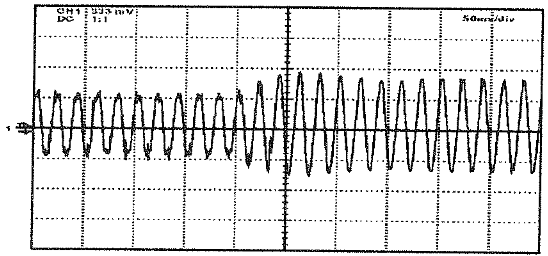


Figure 18: Input Current during step change in input voltage (220V to 150V) [(3.33A/div), Time base: 50ms/div]

7. CONCLUSION

Control of a power factor correction Boost rectifier based on a nonlinear carrier control is addressed in this article. In this control algorithm, a single input single output fuzzy logic controller is introduced. In classical

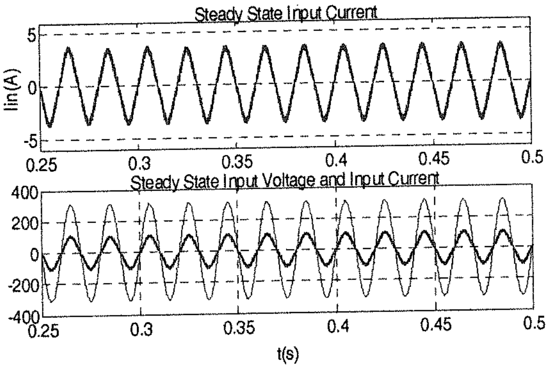


Figure 7: Steady state input voltage and input current

To verify the converter performance in respect to load-regulation when the system has been entered into steady state, there is a step change in R_o from 320 Ω to 640 Ω and vice versa.

The waveforms of output voltage, input current and control voltage are shown in Fig.8 during transient period.

In Fig.8 output voltage has 4.37% overshoot during load change from 320 Ω to 640 Ω and it has 5.25% undershoot when R_o switched back to 320 Ω and settling time is 13ms within 5% band.

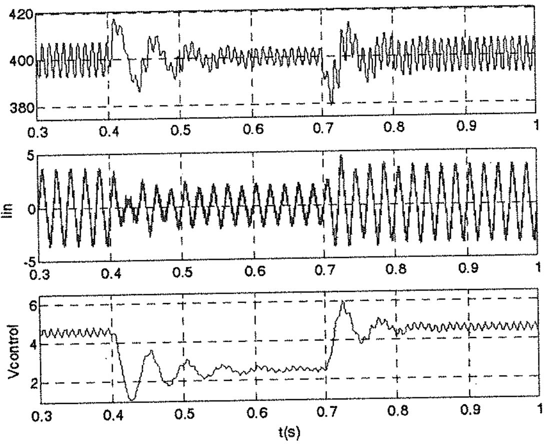


Figure 8: Output voltage, Input current and Control Voltage during step change in $R_O(320\Omega \rightarrow 640\Omega \rightarrow 320\Omega)$

Another test for verifying the line regulation has been performed. In this test input voltage changed from 220V to 150V and vice versa with R_o unchanged. Fig.9 shows the Output voltage, Input current and Control voltage in this test.

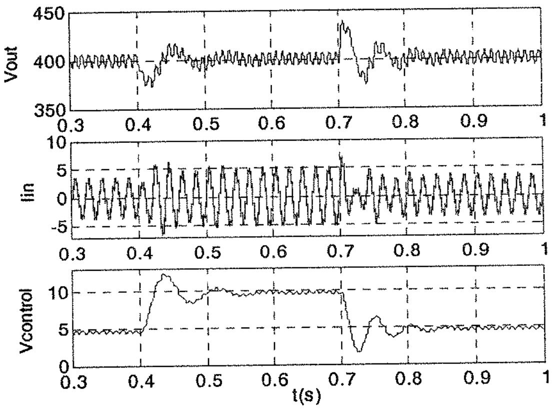


Figure 9: Output voltage, Input current and Control Voltage during step change in (220V → 150V → 220V)

In Fig.9, output voltage has 6.5% undershoot during input voltage change from 220V to 150V and settling time is 24ms . When the input voltage switched back to 220V, there is a 9.1% overshoot and the settling time is 43ms within 5% band.

6. EXPERIMENTAL VERIFICATIONS

A boost rectifier with the same specification as simulated rectifier has been built and tested. The fuzzy controller has been implemented by an EPROM-based circuit and fuzzy computation has been pre-calculated and has been stored in memory. After generation of S_p by analog circuits, it is fed into the digital part of controller. Block diagram of the experimental fuzzy controller is shown in Fig.10.

Sampling frequency has been selected as 40 kHz, half of the switching frequency, to provide enough time for A/D and D/A conversion and also data fetching process from EPROM.

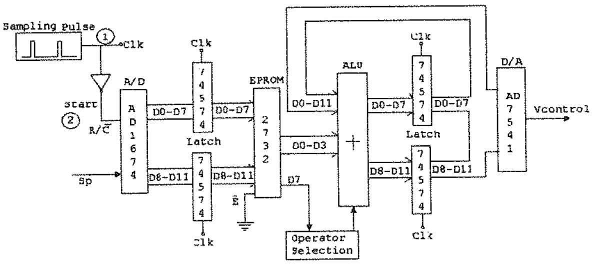


Figure 10: Block diagram of experimental Fuzzy Logic controller

Fig.11 to Fig.13 show the waveforms of output voltage, input current and control voltage during startup.

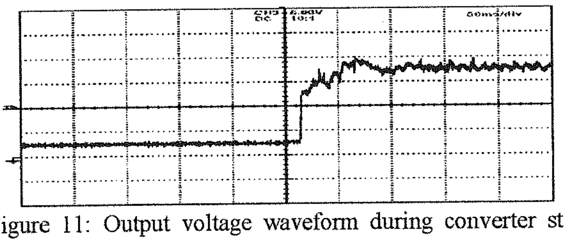


Figure 11: Output voltage waveform during converter startup [Ch1: Voltage (133V/div), Time base: 50ms/div]

In classical fuzzy controllers, which are used to control the DC/DC converters, two linguistic variables "output voltage error" and "change of output voltage error " are defined as inputs and "change of control voltage" is defined as output [8],[10],[11]. By using the sliding mode fuzzy controller with boundary layer control concept, these two linguistic variables can be mixed together and a new single input single output fuzzy controller appears. The general approach for controller design is the division of the phase plan into two semi-planes by means of a switching line. Within the semi-planes positive and negative control outputs are produced, respectively. The magnitude of the control outputs depends on the distance of the state vector from the switching line [16]. For a second order system with a state vector

$$X = (e, \dot{e}) \qquad (17)$$

The switching line is defined as

$$S(X,t) = \dot{e} + \lambda e = 0 \qquad (18)$$

By normalization of the state vector a new normalized state plan generates and in the normalized plane we obtain,

$$\dot{e}_N + \lambda_N . e_N = 0 \qquad (19)$$

by means of relationships

$$e_N = e/\alpha \qquad (20)$$

$$\dot{e}_N = \dot{e}/\beta \qquad (21)$$

where α, β are normalization factors and

$$\lambda_N = \frac{\alpha}{\beta}\lambda \qquad (22)$$

It has been shown in [16] that a new index which contains both the sign and magnitude of the control action can be defined as,

$$S_p = \frac{e_N + \dot{e}_N}{\sqrt{2}} \qquad (23)$$

With this approach, S_p is the unique input of the fuzzy controller and the change of control voltage δv_c is the output of the controller.

Fig.5 shows the block diagram of this fuzzy controller. α and β, the normalization factors are shown and η is the gain factor of the controller.

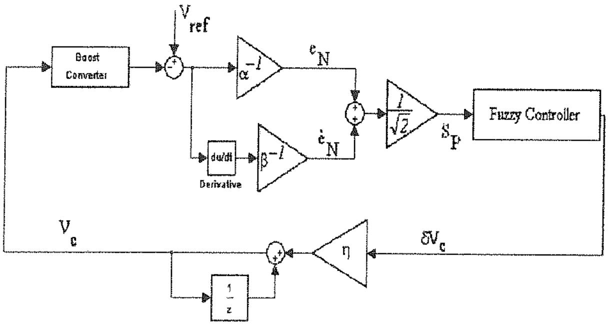


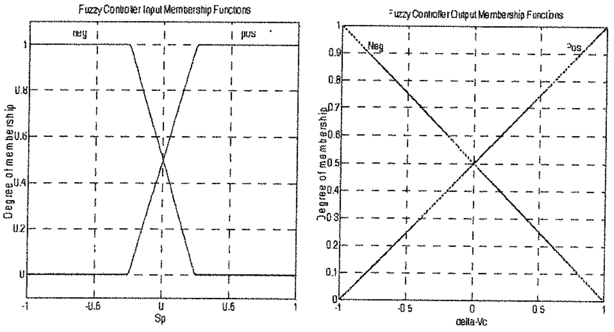
Figure5: Single Input Single Output Fuzzy Controller scheme

Two linguistic membership functions, "Positive" and "Negative" is defined for both input S_p and output, δv_c [17]. Their distribution on the universe of discourse is shown in Fig.6.

Because of unique input and only two membership function for it the rule base can be limited to the following two control rules,

If S_p is Negative δv_c is Negative.

If S_p is Positive δv_c is Positive.



(a) (b)

Figure 6: (a) Input Membership Functions,
(b) Output Membership Functions

Mamdani's min fuzzy implication and center of gravity defuzzification method is selected for the controller.

5. SIMULATION RESULTS

In this part the fuzzy controller for a 500 Watt Boost Rectifier is verified by simulation. The component values are $L=2.5mH$, $C=300\mu F$. The switching frequency is 80 kHz and output voltage is 400V.The nominal value of load resistance R_o, is 320 Ω and nominal input voltage is 220V at 50 Hz.

Fig.7 shows the steady state input current and input voltage. It can be seen that input current is sinusoidal and in phase with input voltage.

is small, the peak current of switch, $i_{s,peak}$ can be approximated by input average current during a switching cycle. With these criteria, the input current or inductor current can be directly used instead of switch current.

$$i_{s,peak} \approx i_g \tag{9}$$

According to (8) by choosing large values for L and f_s, the terms which correspond to v_k can be neglected and this yields to a simpler linear carrier,

$$\begin{aligned} &v_c(t) = v_m(1-\frac{t}{T_s}) \quad ,0 \le t \le T_s \\ &v_c(t) = v_c(t+T_s) \end{aligned} \tag{10}$$

This carrier is a negative slope ramp similar to the classical PWM carrier but the magnitude is adjustable by voltage loop compensator ($H_v(s)$).

3. BOOST RECTIFIER MODELING

Switching Function concept is used to model the Boost converter. By this method, the performance of the converter can be accurately examined without long simulation run time and convergence problems [14]. To obtain a nonlinear model for a power electronic converter in this section, only Kirchhoff's circuit laws are applied.

To avoid the use of complex mathematics, the electrical and semiconductor devices must be represented as ideal components (zero on voltages, zero off currents, zero switching times). Therefore, auxiliary binary variables can be used to determine the state of the switches. It must be ensured that the equations obtained by the use of Kirchhoff's laws should include all the permissible states due to power semiconductor devices being on or off [15].

At the first stage, state variables of the converter are selected to write its switched state-space model. Then, all the conditions of semiconductor devices are determined. The entire continuous and discontinuous conduction modes should be covered by the Kirchhoff's circuit laws. Power circuit of the Boost converter is shown in Fig.3.

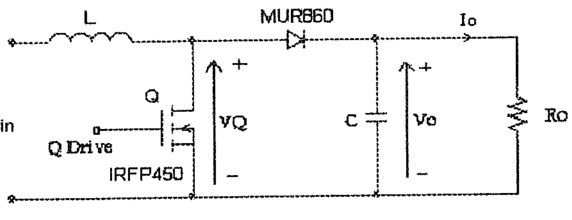


Figure 3: Boost Converter Power circuit

Binary variables γ_Q and γ_D define the states of transistor (Q) and Diode (D), respectively as

$$\gamma_Q = \begin{cases} 1 & Q\_On \\ 0 & Q\_Off \end{cases} \tag{11}$$

$$\gamma_D = \begin{cases} 1 & Q\_Off \quad and \quad (i_L > 0) \\ 0 & Q\_On \quad or \quad (i_L \le 0) \end{cases} \tag{12}$$

Depending on, γ_Q, γ_D and i_L, voltage across the switch Q (V_Q) can be V_{in}, V_{out} or zero. The value of V_Q is generated via an m file and appears as a Matlab Function in Simulink/Matlab.

Inductor current and capacitor voltage are chosen as state variables for Boost converter. State-space equations are as

$$\frac{di_L}{dt} = \frac{V_{in} - V_Q}{L} \tag{13}$$

$$\frac{dV_0}{dt} = \frac{i_D - i_o}{C} \tag{14}$$

Diode and output currents of the converter can be written as

$$i_D = i_L \cdot \overline{\gamma_Q} \tag{15}$$

$$i_o = \frac{V_o}{R_o} \tag{16}$$

R_o in (16) is the load resistance. Block diagram of the boost converter is shown in Fig.4. The Flip Flop which is used in block diagram is for modeling the discontinuous conduction mode.

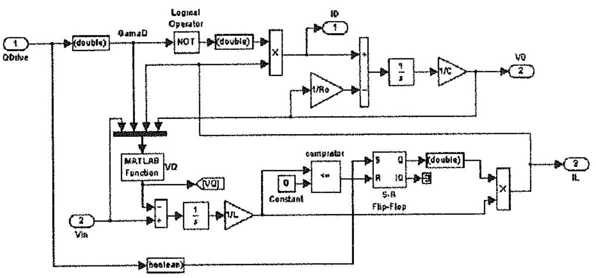


Figure 4: Block diagram of the modeled Boost Converter

4. FUZZY LOGIC CONTROLLER

Generally each kind of controller, linear or nonlinear controller can be applied as voltage loop compensator. In this work, fuzzy control is selected because it does not require obtaining the small signal model of the converter which usually is a long and laborious task.

output information, and an error amplifier in current loop to extract the difference between the input current and the reference to generate the control signal for modulating the input current. Therefore, as shown in Fig.1 the circuit implementation is complex.

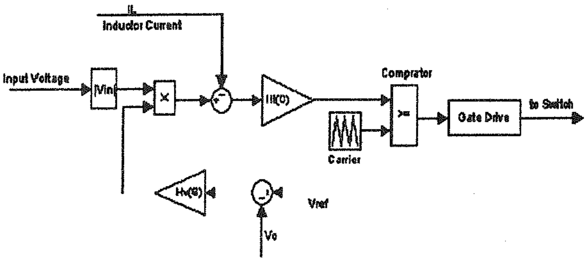


Figure 1: Boost Rectifier Average Current Control Method

Recently, to reduce the complexity of the conventional control technique, different control techniques are presented in [12], [13]. Nonlinear Carrier Control (NLC) is one of the best schemes [12]. In this control technique, the switch current is sensed and compared with a nonlinear carrier waveform in each switching period to achieve a sinusoidal input current and also a high power factor. With small modifications in this method, nonlinear carrier can be replaced by a saw tooth waveform [11].

The block diagram of the proposed control scheme is shown in Fig.2. In this scheme, there is no need to input voltage sensing, error amplifier in current feedback loop and multiplier/divider which are required in Average current control method. It is only necessary to sense the slow varying output voltage v_o, while the fast varying input current $i_g(t)$, is compared with the product of the voltage loop compensator, $H_v(s)$ and a negative slop ramp carrier.

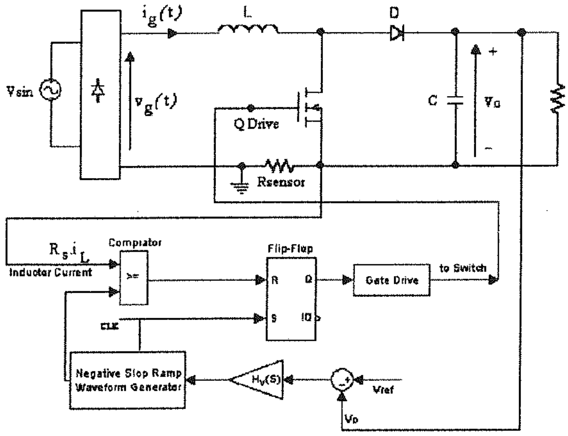


Figure 2: Boost Rectifier with Proposed Control

According to the Peak Current Nonlinear Control method which has been depicted in [12], the relation between switch maximum current $i_{s,peak}$ and the input average current during a switching cycle i_g, can be derived as,

$$i_{s,peak} = i_g + \frac{v_g}{2Lf_s}.d \tag{1}$$

where v_g is the average of the input voltage $v_g(t)$ during a switching cycle, f_s is switching frequency, L is the Boost Inductance and d is the switch duty cycle.

If the waveform of input current $i_g(t)$ varies proportionally with input voltage $v_g(t)$, then the converter can be realized as a resistive load at the input terminal. When converter is operating in CCM,

$$v_g = (1-d)v_o \tag{2}$$

where v_o is the output voltage and

$$R_e = \frac{v_g}{i_g} = \frac{1-d}{i_g}v_o \tag{3}$$

Here R_e is the emulated input resistance.

By substituting (3) into (1),

$$i_{s,peak} = \frac{v_o}{R_e}(1-d) + \frac{v_o}{2Lf_s}.d(1-d) \tag{4}$$

and, in other words, it can be written,

$$i_{s,peak} = \frac{v_o}{R_e}(1-\frac{t_{on}}{T_s}) + \frac{v_o}{2Lf_s}.\frac{t_{on}}{T_s}(1-\frac{t_{on}}{T_s}) \tag{5}$$

$$t_{on} = d.T_s \tag{6}$$

In equation (6), $T_s = 1/f_s$ is the switching period.

If the duty cycle in a switching cycle varies in such a way that satisfies (5) in each switching cycle, the average input current follows the line voltage. Therefore, a reference signal is generated to ensure that switch duty cycle varies in this manner,

$$\begin{aligned} &i_c(t) = (i_m + \frac{v_o}{2Lf_s}.\frac{t}{T_s})(1-\frac{t}{T_s}) \quad ,0 \le t \le T_s \\ &i_c(t) = i_c(t+T_s) \end{aligned} \tag{7}$$

where, $i_c(t)$ is the nonlinear current carrier.

By using a resistor sensor R_s to sense the switch current, equation (7) yields to

$$\begin{aligned} &v_c(t) = (v_m + v_k.\frac{t}{T_s})(1-\frac{t}{T_s}) \quad ,0 \le t \le T_s \\ &v_c(t) = v_c(t+T_s) \end{aligned} \tag{8}$$

where, $v_m = R_s.i_m$, $v_k = (v_o.R_s/2Lf_s)$ and v_m is the voltage loop compensator output signal which varies at double frequency of utility. In this method, the switch is turned on at the beginning of a switching cycle and it turns off when the signal $R_s.i_s$ which is proportional to instantaneous switch current reaches the carrier $v_C(t)$ and switch remains off till the next cycle.

If the rectifier operates in CCM and the current ripple

A Novel Fuzzy Logic Controller for a Boost Power Factor Corrector

Arash Khoshooei[i]; Javad S. Moghani[ii]

ABSTRACT

Power electronics converters, because of their nonlinear dynamics and switching operation, are the main source of harmonic injection to the utility, which results in poor power factor.Boost rectifier due to its simple topology and good performance in power factor correction is the most used scheme. Design of a single input fuzzy controller for high power factor boost converter is described in this article. The computer simulation of the proposed fuzzy controller held in MATLAB-SIMULINK on a 500W boost rectifier and closed loop performance of the Converter in respect to Line and Load Regulations are evaluated. Experimental measurements of closed loop performance validate the proposed scheme.

KEYWORDS

Power Factor Correction, Boost Converter, Fuzzy Logic Controller

1. INTRODUCTION

With increasing demand for more power capability and better power quality from the utility line, power factor correction (PFC) techniques have attracted much more attention [1,2]. For most power factor correction circuits which have proposed in [3,4], Boost converter which operates in continuous conduction mode (CCM) performs much better than other circuits in terms of efficiency, power factor and simplicity of gate drive circuit. Several control methods that are commonly used as feedback control of the PFC converter are presented in [4,5]. Among them, the average current mode control is the more advantageous method. Traditionally, frequency methods for design of controllers for power converters are based on small signal model of the converter [6]. The small signal model of the converter has restricted validity and changes due to variations in operating point. Moreover, the performance of the controllers designed by frequency domain methods is dependent on the operating point, the parasitic elements of the system, and the load and line conditions. Recant research has been directed at applying nonlinear control principles to the dynamic control of the converters. Many articles [7, 8, 10] address performance and design issue of using fuzzy logic to perform nonlinear control of power electronics converters. No exact mathematical model of the converter is required and system is controlled by a fuzzy control algorithm, in which a set of linguistic rules written in accordance to experience and intuitive reasoning.

The fuzzy controller proposed in [7, 9] uses output voltage error, inductor current error and inductor current as its three input variables. Fuzzy controller consists of two separated *P* (Proportional) and *I* (Integral) fuzzy controllers which yields to complicated implementation. In [8, 10, 11], a fuzzy controller scheme addressed with output voltage error and the change of voltage error as inputs. For the input variables similar membership functions has been defined. The number of fuzzy rules equals to multiplication of number of membership functions assigned to each input. Larger number of fuzzy rules increase the time needed to compute a fuzzy control law.

In this paper, the authors focus on reducing the number of inputs and also the membership functions. The controller circuit is simpler than the previous works and also has more suitable operation.

The control method derived is based on Nonlinear Carrier Control (NLC) method which is depicted in [12]. The boost converter is modeled by the means of Switching Function concept. Then, the derivation of fuzzy control algorithm for regulating the converter is described in detail. The proposed controller is evaluated by computer simulations as well as experimental measurements of the closed-loop performance of a 500W prototype converter in respect to line and load regulation.

2. DERIVATION OF CONTROL ALGORITHM

The Average Current Control is the traditional method to control the boost rectifier. In this method, an input voltage sensing required to obtain a sinusoidal reference, an analog multiplier to combine this reference with the

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