Current Mode Control Techniques for the Reduction of THD using Fuzzy Logic

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Abstract: Typical electronic equipment requires dc power supply and an AC-DC power converter serves this purpose. These AC/DC power converters are connected to ac mains and they introduce harmonic current in the utility. The injection of harmonics in utility currents, caused by uncontrolled or phase-controlled rectifiers, distorts current and voltage waveforms thereby reducing power factor and produces negative effects in the neighbor loads and the power distribution network. This project is proposed to implement the current mode control techniques for the ac-dc converters to reduce the total harmonic distortion (THD). The performance of peak and average current mode controls are compared. Also ACMC is implemented in fuzzy logic because of its advantages over PCMC.

Keywords: Peak current mode control (PCMC), Average current mode control (ACMC), Active power factor correction (APFC), Switched mode power supply (SMPS), Total harmonic distortion (THD).

I. INTRODUCTION

Regulations such as IEC-61000-3-2 demand some sort of input current shaping for single-phase equipment. Active current shaping is usually used in the power range around 2 kW in order to reduce the volume of the converter, and it usually consists of a conventional diode bridge followed by a dc–dc switch-mode converter, which shapes the current. Generally, the control strategies for DC-DC converters can be classified into two main categories, namely voltage-mode control (VMC) and current-mode control (CMC). In VMC the output voltage is sensed and subtracted from an external reference voltage in an error amplifier. The error amplifier produces a control signal which is compared to a constant amplitude saw-tooth waveform. The comparator produces a PWM signal which is fed to the drivers of the controllable switches of the converter. While in VMC only output voltage is sensed and compared to the reference value, in CMC both output voltage and inductor current are sensed and used for output voltage regulation. Actually, in a CMC scheme there are two control loops, namely voltage control loop (which is the outer loop) and current control loop (which is the inner loop). Inductor current feedback in CMC allows for fast response to variations in the input voltage. Furthermore, the current mode DC-DC converter shows superior dynamic characteristics than the voltage mode dc-dc converter. The current-mode control strategies are divided into peak current mode control (PCMC), average current-mode control (ACMC).

Over the past decade, many approaches have been proposed for current-mode control in DC-DC converters. Most of these techniques rely on mathematical models of the power converters. However, the inherent nonlinearity and time varying characteristics of CMC power converters hinder the accurate mathematical modeling of the converters, which is a pre-requisite for control design.

The fuzzy logic controller (FLC) is indeed capable of providing the high accuracy required by high performance drive system without the need of mathematical model.FLC accommodates non-linearity without utilization of mathematical model. The fuzzy logic controller uses fuzzy logic as a design methodology, which can be applied in developing nonlinear system for embedded control. Simplicity and less intensive mathematical design requirements are the most important features of the FLC. Fuzzy Logic controller is an attractive choice when precise mathematical formulations are not possible applications in many industries, in that ac–dc conversion of electric power is widely used in several applications such as adjustable-speed drives (ASDs), switch-mode power supplies (SMPSs), uninterrupted power supplies (UPSs), and battery energy storage. Traditionally, the diode bridge rectifier is used for AC-DC power conversion. This rectifier has the advantages of a simple circuit configuration and a low cost. Nevertheless, this rectifier results in some power pollutions, such as a high pulsating input current, a low power factor,

and a high total harmonic distortion of the input current (THD). In order to improve these power pollutions and to meet the requirements set by international regulatory standards, such as the international electro technical commission (IEC) and IEEE-519, power factor correction (PFC) topologies have been investigated. These PFC circuits are used to cascade a DC-DC converter for DC power-supply applications.

The CMC techniques such as PCMC and ACMC are explained in sections II and III respectively. Tuning of PI controller is described in section IV. FLC used in this paper is explained in section V. Section VI gives the simulation results and VII conclusion respectively.

II. PEAK CURRENT MODE CONTROL

Peak Current Control mode is a well established control technique in power conversions. More recently, it has been applied widely in PFC pre-regulator converters. The basic scheme of the peak current controller is shown in Fig.1.
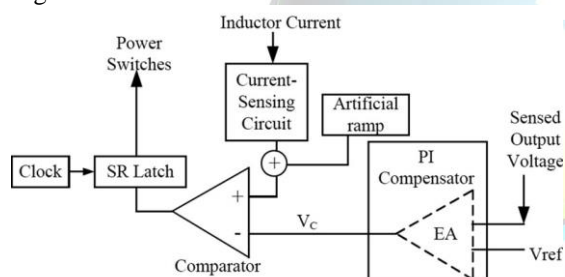

Fig.1 Peak current mode control

The switch is turned on at constant frequency by a clock signal, and is turned off when the sum of the positive ramp of the inductor current (i.e. the switch current) and an external ramp (compensating ramp) reaches the sinusoidal current reference. This reference is usually obtained by multiplying a scaled replica of the rectified line voltage times the output of the voltage error amplifier, which sets the current reference amplitude. In this way, the reference signal is naturally synchronized and always proportional to the line voltage, which is the condition to obtain unity power factor. The main concern in designing the current loop is the slope of the compensation ramp. A steeper artificial ramp results in a more stable system at the price of sacrificing the advantage of a peak current mode control system. Conventionally, both the output of the current sensing and the compensation ramp are expressed in voltage form. A summing amplifier is necessary to add the compensation

ramp to the sensed current signal. Another solution is to convert the current information and compensation ramp to current form by voltage to current converters. Then these two are added together to get the summing voltage through a single resistor. These methods require multiconverts with complex circuits, and correspondingly, inducing more distortion to the desired signal. One of the common choices for the slope is to set it equal to the falling slope of the inductor current feedback.

III. AVERAGE CURRENT MODE CONTROL

In the average current mode control there are two control loops. The outer voltage control loop and the inner current control loop. Here the inductor current is sensed and filtered by a current error amplifier whose output drives a PWM modulator. In this way the inner current loop tends to minimize the error between the average input current and its reference. The current reference is obtained by multiplying the output voltage control loop error with the scaled replica of the rectified input voltage. The converter works in Continuous inductor current mode, so the same considerations done with regard to the peak current control can be applied.

Using average current mode control the whole converter is seen by the supply as an equivalent resistor whose value varies continuously with the sinusoidal cycle of the input voltage in such a way that the average power remains balanced between the input and the output. The current control loop is used to control the average input current of the converter to make it in the same wave shape and in phase with the input voltage, thus achieving unity power factor.
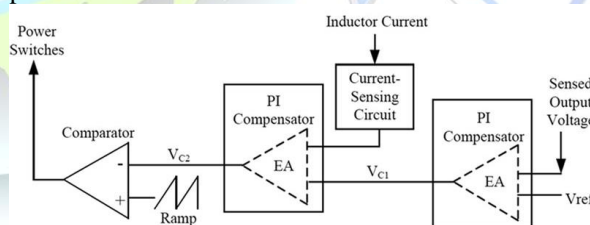

Fig.2 Average current mode control

The voltage control loop is used to regulate the dc output voltage. The gain modulator and the voltage control loop work together to sample the input current and output voltage, respectively. These two measurements are taken and then compared against each other to determine if a gain should be applied to the input of the current control. This decision is then compared against a sample of the output current to determine the duty cycle of the PWM.

IV. PI CONTROLLER TUNING

PI controller was tuned using Ziegler-Nichols tuning method. In this method, the integral and derivative gains are first set to zero. The proportional gain is increased until it reaches the critical gain (Kcr) at which the output of the loop starts to oscillate. Kcr and Pcr are used to set the gain as shown in TableI.

TABLE I   ZIEGLER-
NICHOLS SECOND METHOD OF TUNING PID CONTROLLER

PID Type	K_p	T_i	T_d
P	$0.5 K_{cr}$	∞	0
PI	$0.45 K_{cr}$	$\dfrac{P_{cr}}{1.2}$	0
PID	$0.6 K_{cr}$	$\dfrac{P_{cr}}{2}$	$\dfrac{P_{cr}}{8}$

V. FUZZY LOGIC CONTROL

The fuzzy controller is designed to achieve zero steady-state error in the average load voltage on the dc side, while generating the correct current reference signal to attain near unity power factor on the ac line side.
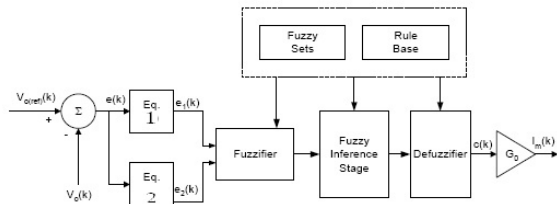

Fig3. Block diagram of fuzzy controller

The inputs to the controller are the error-dependent variables, *e1(k)* and *e2(k)* which are defined respectively as*:*

$$e_1(K) = [K_e + K_i T].e(K) + e_1(K-1) \qquad (1)$$

$$e_2(K) = K_{\delta e}\frac{e(K)-e(K-1)}{T} \qquad (2)$$

where *e(k)* represents the error between the reference and actual output voltages, at the *k*th sampling instant, and *T* is the sampling time period. The integral term in Eq. 1 ensures that the steady-state error of both the inductor current and average load voltage are zero. K_e, K_i and $K_{\delta e}$ are the input gains to the fuzzy controller. These input gains, along with the output gain, G_0, are tuned to obtain the desired voltage and current tracking performances. The output of the fuzzy controller provides the current amplitude reference, $I_m(k)$. Five membership functions are used to describe each of the input and output variables of the controller. The *min* operator is used for premise quantification and determination of the implied fuzzy set for each rule that is active. Once the implied fuzzy sets are formed, a real valued output needs to be computed so as to apply the required control action to the current command. In this paper, the Centre of Gravity (CoG) defuzzification method is used to compute the current command amplitude. The crisp output, *c(k)*, generated from the controller, is proportional to the required inductor current amplitude, I_m.

TABLE II
RULE-BASE FOR PROPOSED FUZZY CONTROLLER

e \\ e*	NB	NS	ZE	PB	PS
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

VI. SIMULATION RESULTS

The performance of the proposed controller is evaluated through computer simulation using Simulink software. The parameters of the APFC circuit are given in Table III. The dc side inductance is chosen so that the line current can change rapidly to track the sinusoidal reference variation. The input and output gains of the fuzzy controller were tuned iteratively until the desired inductor current and load voltage tracking performances were obtained.

TABLE III
RECTIFIER/ BOOST CONVERTER POWER CIRCUIT PARAMETERS

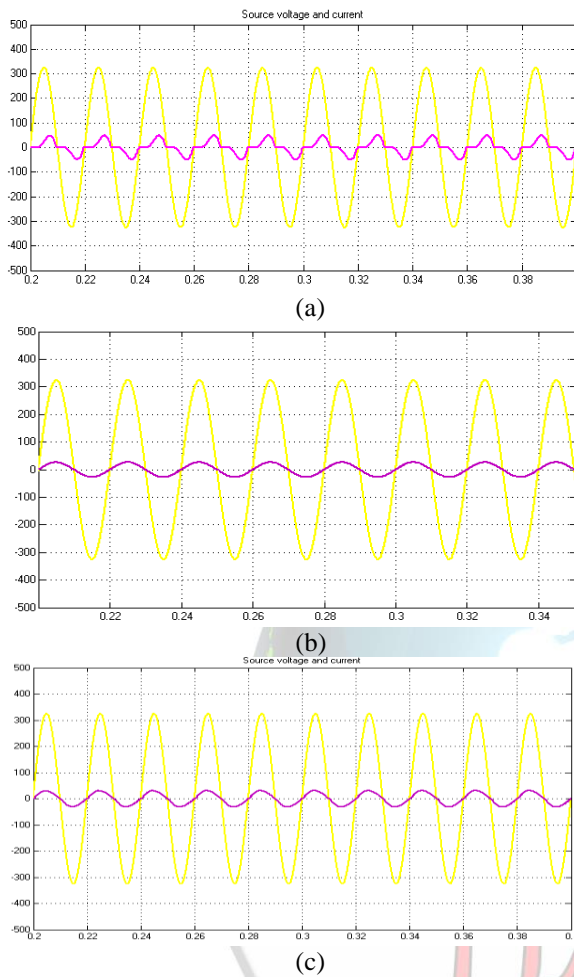| *PARAMETER*	*VALUE*
AC line voltage, frequency	*230 V(rms), 50 Hz*
DC output voltage	*500 V*
DC side inductance	*3.7 mH*
Output filter capacitance	*6600 µF*
Load resistance	*50 Ω*
Switching frequency	*70 kHz*
Output power	*5 kW*

Fig.4 Source voltage and current of (a)PCMC with PI, (b)ACMC with PI, (c)ACMC with fuzzy
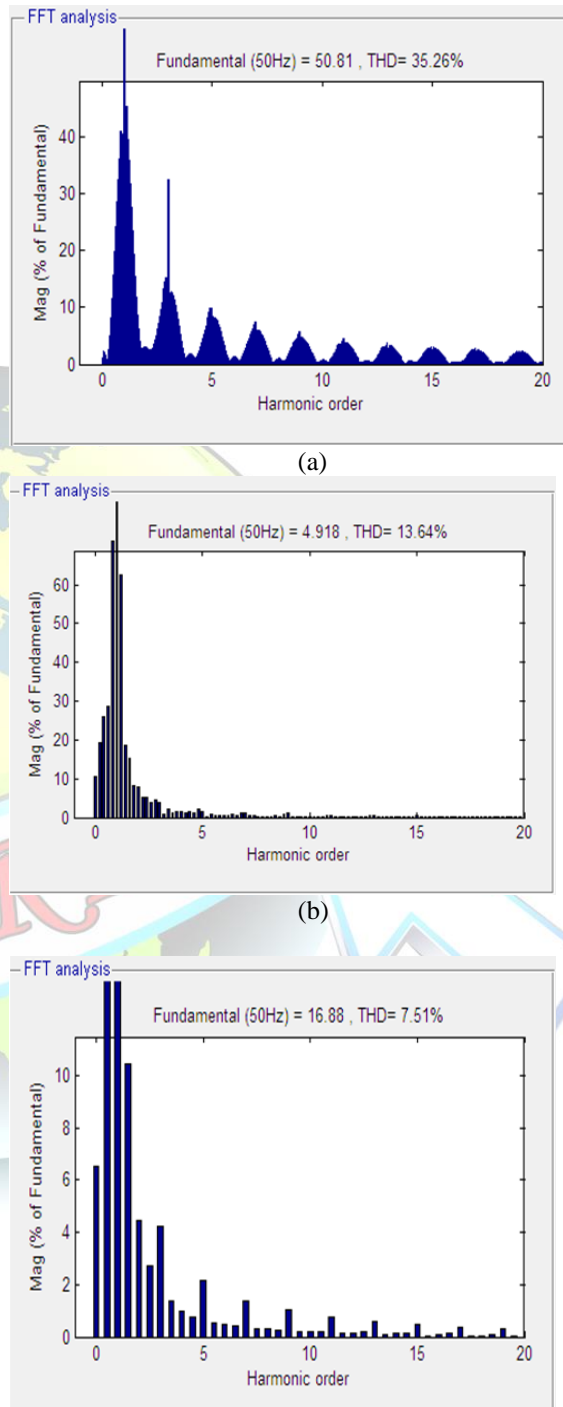

Fig.5 Total harmonic distortion of (a)PCMC with PI, (b)ACMC with PI, (c)ACMC with fuzzy

TABLE IV
PARAMETER COMPARISON

Parameter	PCMC	ACMC (PI)	ACMC (FUZZY)
THD	35.44	13.64	7.51
PF	0.9072	0.9858	0.9974
Mp %	25.4	23.2	15.4
t_s	0.3 s	0.2 s	0.06 s

VII. CONCLUSION

The operation of the PCMC is compared with the ACMC. The simulation results show that ACMC has superior performance over PCMC. The shape of the input current waveform is also improved with the average current mode control. Also the ACMC has relatively low peak overshoot, settling time and total harmonic distortion. As a result the power factor of the supply improves with the average current mode control. The operation of the fuzzy controller is compared with the linear PI regulator for ACMC. The fuzzy controller is designed to cater for the nonlinear characteristics of the switch mode power converter. The fuzzy controller is shown to adequately track the output voltage command. The ac supply current is also successfully controlled to achieve the required power factor correction, with comparable harmonic distortions in the line current.

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