A Discrete Modeling for Power Factor Correction Circuit

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***Abstract*—In this paper, a novel discrete model has been proposed to simulate the controller IC UC3854. The main contributions are as followings: 1）The power stage of the Boost converter has been modeled by using the large signal approach and the loop gain of current program has been put forward; 2) The continues-time voltage control diagram has been investigated by employing equivalent power stage which contains the main circuit and current program; 3) Based on the continues-time model, a new discrete model of PFC has been given out and the operational principle has been introduced; 4) A 4kw prototype has been built up to verify the validity of the new model; Results of the simulation and the experiment show that the power factor is 96.7% and the linear current harmonics components can completely meet the requirements of IEC 61000-3-2.**

Keywords-power factor correction circuit; discrete model

I. INTRODUCTION

The function of Power Factor Correction is to force the input current follow the input voltage by using control methods so as to achieve unity power factor. In power electronic area, the power factor will be decreased and result in the loss of the system if one of the following three conditions is satisfied:(1) the input current is not a sine wave;(2) the phase of the input current is not the same as the input voltage;(3) the input current have harmonics. By applying the power factor correction circuit, the input current can be formed to a sine wave with the same phase as the input voltage and the harmonics can be decreased at the same time. Therefore, it is of great necessity to apply the PFC to the switch mode power system.

Among power factor correction techniques, the analogy control method is now attractive in industry, but the digital control method is the trend in the future. There are many advantages of DSP controller when it is applied in power converter, such as reducing the amount of components and the cost of the converter, shortening the cycle of researching and developing, and upgrading products more conveniently. Moreover, the more DSP controllers are applied, the lower the cost will be.

The PFC circuit has been modeled firstly in section II in order to achieve the digital control method. Some Matlab simulations have been executed in section III in order to guide the experimental in section IV for the verification of the new discrete PFC model. Section V summarized the results and performances achieved.

II. MODELING FOR CONTINUOUS-TIME SYSTEM

Fig.1 shows the PFC circuit and its controller, IC UC3854. The C in fig.1 represents a capacitance, whose capacity is very small so as not to influence the output waveform of the rectifier. The resistance R is a sample resistor. IC UC3854 is an active PFC controller providing average current control method and can force the input current to follow the input voltage. It has excellent performances such as stability and low distortion.

When the output voltage goes up, the difference between the sampled output voltage and the reference one will increase and the output voltage of the regulator will decrease. Consequently, the reference value of the input current will decrease and the difference between the reference current and the sampled current will increase. This will result in the reduction of the output current of the regulator, which will finally lead to the decrease of the duty ratio and the output voltage.

When the input voltage goes up, the output of the multiplier will increase, which can also result in the reduction of the output current of the regulator and cause the same results as mentioned above.

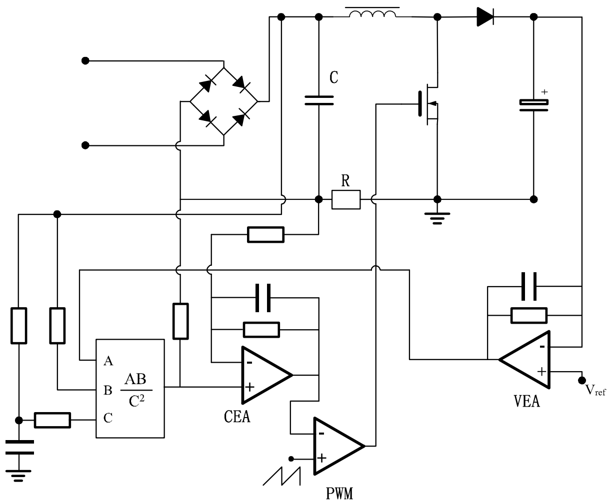

Fig.1 PFC circuit and control IC UC3854

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A. Transfer Function of the Main Circuit G(s)

When the frequency of the input voltage is less than the switching frequency, the transfer function of the main circuit G(s) can be expressed as follow:

$$G(s)=\frac{V_{OUT}(s)}{V_s(s)}=\frac{I_O R_{LOAD}}{I_{in}R_s}=\frac{R_{LOAD}}{R_s}\cdot\frac{I_O}{I_{in}}=\frac{R_{LOAD}}{R_s}\cdot D_{off}$$

B. Transfer Function of the Current Part $G_i(s)$

Fig.2 shows the equivalent big-signal continuous-time model of $\frac{\hat{v}_{Rs}}{\hat{v}_{CA}}$. The equivalent inductance is L_e In order to deduce the transfer function of the big-signal continuous-time model $\frac{\hat{v}_{Rs}}{\hat{v}_{CA}}$, two assumptions are supposed for the CCM DC-DC converter:

(1) The disturbance of the output voltage $\hat{v}=0$;

(2) The value of resistance R_s is small, i.e. $|\omega L_e|\gg R_s$, so $\omega L_e+R_s\approx\omega L_e$.

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From Fig.2,

$$\frac{V_s}{V_{CA}}=\frac{1}{V_M}\times e(s)\times M(D)\times\frac{R_S}{R_S+sL_e}\approx\frac{1}{V_M}\times e(s)\times M(D)\times\frac{R_S}{sL_e}$$

(1)

As to the boost converter, we have

$M(D)=\frac{1}{D'}$, $L_e=\frac{L}{D'^2}$, and $e(s)=V(1-\frac{sL_e}{R})$.

So equation (1) can be expressed as

$$\frac{V_s}{V_{CA}}=\frac{VD'R_S}{sLV_M}(1-\frac{sL}{RD'^2})$$

(2)

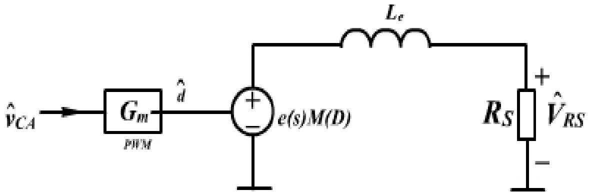


Fig.2 Equivalent Small-Signal Model of $\frac{\hat{v}_{Rs}}{\hat{v}_{CA}}$

From equation (2), it can be seen that the transfer function of the Boost converter contains a zero-point in right half-plane. In order to consider the worst situation, set $\frac{sL}{RD'^2}\to 0$, and $D'=1$.

Then equation (2) can be simplified to

$$\frac{V_s}{V_{CA}}\approx\frac{VR_S}{sLV_M}$$

The transfer function of PWM regulation $G_{PWM}(s)$ is

$$G_{PWM}(s)=\frac{1}{V_M}$$

where V_M is the peak-peak value of the sawtooth waveform. So we get

$$\frac{V_s}{D_{ON}(s)}\approx\frac{V_O R_S}{sL}$$

C. Continuous-Time Transfer Function of Current Controller $G_{ii}(s)$

The controller used for the current program is PI controller. Its transfer function is

$$G_{ii}(s)=K_{ip}+\frac{K_{ii}}{s}$$

where K_{ip} is the proportional factor, K_{ii} is the integral factor.

With respect to the voltage loop, control object is the equivalent power stage which contains the main circuit and the current control program. Its transfer function is as follow:

$$G'(s)=G(s)\times\frac{G_{ii}(s)}{1+G_{ii}(s)\times G_i(s)\times\frac{1}{R_s}}\times G_{PWM}=\frac{R_{LOAD}\cdot D_{off}}{R_s}\times\frac{K_{ip}s^2+K_{ii}s}{s^2+\frac{K_{ip}V_o}{L}s+\frac{K_{ii}V_o}{L}}$$

D. Transfer Function of Voltage Loop $G_V(s)$

PI controller is applied in the voltage loop as well, with a transfer function presented below:

$$G_V(s)=K_{vp}+\frac{K_{vi}}{s}$$

where K_{vp} is the proportional factor and K_{vi} is the integral factor.

Fig.3 below shows the elementary diagram of PFC circuit. The H in it describes the feedback loop, which is decided by sample rate. The transfer function of H is $H(s)=\frac{V_{ref}}{V_o}$. The system displayed in Fig.3 is a continuous-time system. The corresponding discrete system can be obtained by the discrimination based on it.

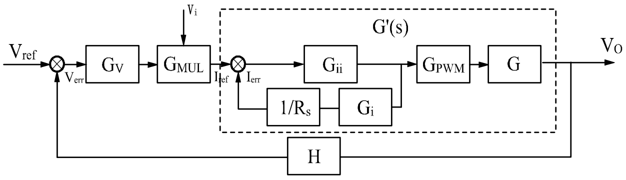


Fig.3 Elementary Diagram of PFC Circuit

For the application of the digital control method, some anti-saturating measures should be taken in order to guarantee the stability of the system. Therefore, an amplitude-limited circuit, such as the two-way zener, should be added to the regulator in order to prevent the system saturation. Fig.4 shows the PI regulator with the anti-saturation circuit.

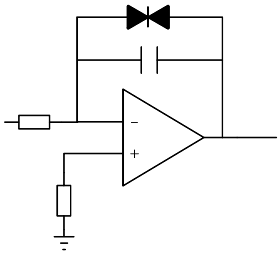


Figure.4 PI Regulator with Anti-Saturation

It can be seen that the PI controller is used in both the voltage loop and the current loop in PFC circuit. As 'I' in 'PI' represents integral, that is to say, without the anti-saturation circuit, the output of the PI regulator will be boundless if the input is boundless. This means that the system is instable. Therefore, the amplitude-limited circuit is of great necessity to the regulator that will be used in the digital control system of PFC for obtaining a boundary output and ensuring the system stability.

III. MATLAB SIMULATION

The system mentioned above has been verified using SIMULINK. The elementary diagram is shown in Fig.5. Part A in the figure describes the RMS of the input voltage, which is achieved with a second order low pass filter. Its transfer function $G_A(s)$ is:

$$G_A(s)=\frac{0.011z^7+0.067z^6+0.167z^5-0.222z^4+0.165z^3-0.66z^2+0.01z}{z^8-8z^7+27.7z^6-55.00z^5+68.55z^4-54.5z^3+27.12z^2-7.7z+0.9582}$$

Part B describes the main circuit with the transfer function $G(s)=3.3\times10^9\times\frac{z^2}{z^2-2z+1}$; Part C is the current loop, whose transfer function is $G_{ii}(s)=\frac{12.43z-3.73}{z-1}$; Part D describes the voltage loop, its $G_V(s)=\frac{2.1z-2}{z-1}$.

Corresponding simulation results are shown in Fig.6. The value of anti-saturation in the voltage loop is between 2.2 to 2.76 and this value in the current loop is between -0.2 to 0.2

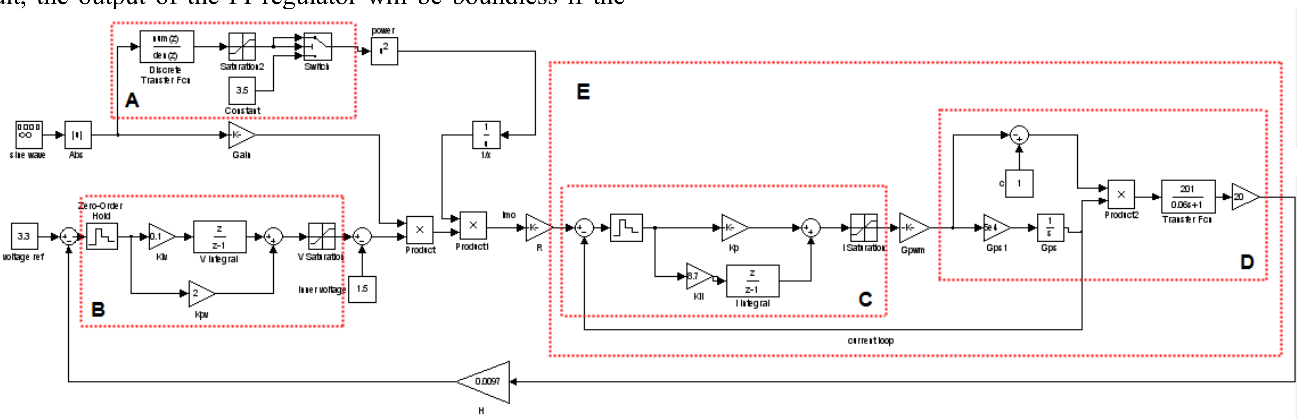
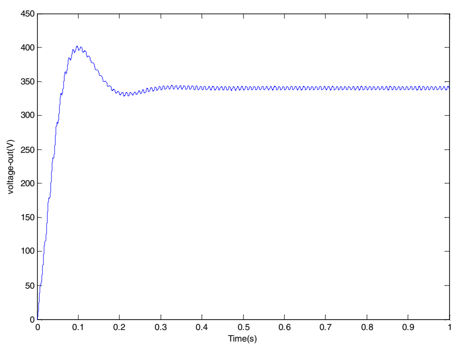
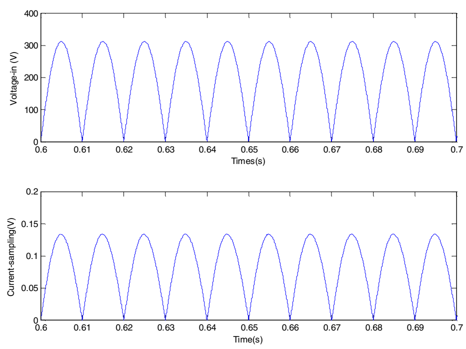


Fig.5 Elementary Diagram in MATLAB



Output Voltage



Input Voltage and Current sampling

Fig.6 Simulation Results

IV. EXPERIMENTAL VERIFICATION

Experiments are executed to verify the circuit designed above. Fig.7 shows the experimental results. It can be seen from the figure that the turn-on angle of the input current in channel 2 is widened in contrast with the current in channel 1. The power factor of the circuit is 96.7%, which indicates the validity of the PFC circuit designed above.

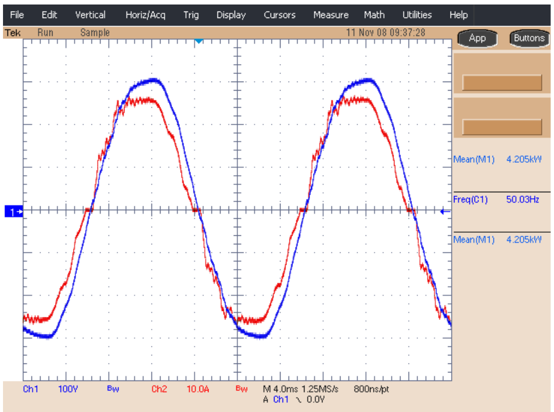


Fig.7 Experimental Result

V. CONCLUSION

In this paper, the mathematical model of PFC is built based on analyzing the controller UC3854. This model describes the object by virtue of the transfer function, which is different from the traditional way that uses switch to build the main circuit. Its advantage lies in that the causality of variables is more explicit. The corresponding simulation and experiment are implemented and the circuit power factor obtained is 96.7%, which demonstrates the model's usefulness for designing the controller of the PFC circuit.

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