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Digital PI control for interleave PFC boost converter

Yuto Adachi[1], Kohji Higuchi[1], Tatsuyoshi Kajikawa[1], Tomoaki Sato[2], and Kosin Chamnongthai[3]

[1] The University of Electro-Communications 1-5-1, Chofu-ga-oka,Chofu-shi, Tokyo 182-8585, Japan
[2] C&C SYSTEMS CENTER Hirosaki University, Bunkyo-Cho 3, Hirosaki-shi, Aomori 036-8561, Japan
[3] King Mongkut's University of Technology Thonburi, 126 Pracha-uthit Rd., Bangmond, Tungkru, Bangkok 10140, Thailand
(Tel: 81-42-443-5182, Fax: 81-42-443-5183)

Abstract: In recent years, improving of power factor and reducing harmonic distortion in electrical instruments are needed. In general, a current conduction mode boost converter is used for active PFC (Power Factor Correction). Especially, an interleave PFC boost converter is used in order to make a size compact, make an efficiency high and make noise low. In this paper, a PI digital controller for suppressing the change of step response characteristics and variation of output voltage at a load sudden change with high power factor and low harmonic is proposed. Experimental studies using a micro-processor for controller demonstrate that the PI digital controller is effective to improve power factor and to suppress output voltage variation and is more advantageous to control the current of the sum of each phase in hardware.

Keywords: interleave PFC, boost converter, digital PI control, micro-processor

1 INTRODUCTION

In recent years, improving of power factor and reducing harmonic of power supply using nonlinear electrical instruments are needed. A passive filter and an active filter in AC lines are used for improving of the power factor and reducing the harmonic. Generally a current conduction mode boost converter is used for an active PFC (Power Factor Correction) in electrical instruments. Especially, an interleave PFC boost converter is used in order to make a size compact, make an efficiency high and make noise low. In the interleave PFC boost converter, if a duty ratio, a load resistance and an input voltage are changed, the dynamic characteristics are varied greatly, that is, the interleave PFC converter has non-linear characteristics. In many applications of the interleave PFC converters, loads cannot be specified in advance, i.e., their amplitudes are suddenly changed from the zero to the maximum rating. This is the prime reason of difficulty of controlling the interleave PFC boost converter.

Usually, a conventional analog phase lead-lag compensation controller or an analog IC controller designed to the approximated linear controlled object at one operating point is used for the PFC converter. The interleave PFC converter is difficult to control because of the nonlinearity and the complicated configuration. In the nonlinear interleave PFC boost converter system, those conventional controllers are not enough for attaining good performance. So the gain scheduling control using many controllers for many operating points is applied to PFC boost converter. This control method is very complicated and not easy to implement because of many switching of controllers. In this paper, a PI digital controller for suppressing the change of step response characteristics and variation of output voltage at a load sudden change with high power factor and low harmonic is proposed. The PFC converter is a nonlinear system and the models are changed at each operation point. When controlling the current for every phase, the interleave PFC boost converter needs three controllers, two for interleave current control and one for voltage control, When controlling the current of the sum of each phase, it needs two controller, one for interleave current control and one for voltage control. The digital PI controllers are used for these controllers. The design and combining methods of these PI digital controllers which can cope with nonlinear system or changing of the models are proposed. These controller are actually implemented on a micro processor and is connected to the PFC converter. That is, three or two digital PI controllers are equipped with one micro processor. Simulations and experimental studies demonstrate that the PI digital controllers designed suitably satisfy the desired performances and is more advantageous practically to control the current of the sum of each phase.

2 INERLEAVE PFC BOOST CONVERTER

2.1 State-space model of interleave boost converter

The interleave boost converter shown in Fig. 1 is manufactured. When controlling the current for every phase, i_{s1} and i_{s2} are measured and used. And when controlling the current of the sum of each phase, i_l is measured and used. When controlling the current for every phase, two current controllers are required. But when controlling the current of the sum of each phase, what is necessary is to shift a phase for the output of one controller 180 degrees, and just to build two outputs

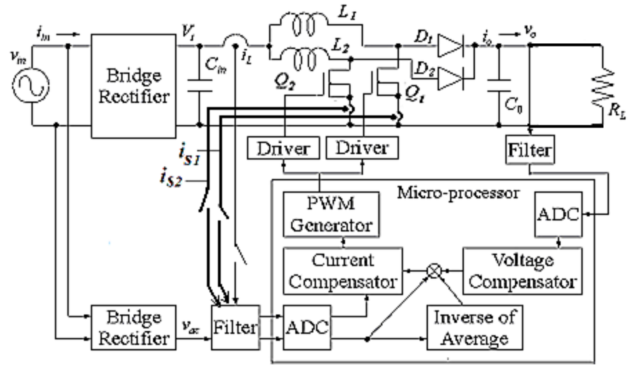


Fig.1 Interleave PFC boost converter

Fig.1, v_{in} is an input AC voltage, i_{in} is an input AC current, C_{in} is a smoothing capacitor, V_i is a rectifying and smoothing input voltage, Q_1 and Q_2 are MOSFETs or IGBTs, L_1 and L_2 are interleave boost inductances, D_1 and D_2 are interleave boost diodes, C_0 is an output capacitor, R_L is an output load resistance, i_{s1} and i_{s2} are inductor currents of inductance L_1 and L_2, respectively, i_L is the sum of inductor current, v_{ac} is an absolute value of the input AC voltage and v_o is an output voltage. The inductor currents i_{s1} and i_{s2} or i_L is controlled to follow the rectified input voltage v_{ac} for improved power factor, reduced harmonics and stable the output voltage. Using the state-space averaging method, the state equation of the inter leave boost converter becomes as follows [11]:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} -\frac{R_0}{L_0} & -\frac{1}{L_0} \\ \frac{1}{C_0} & -\frac{1}{R_L C_0} \end{bmatrix}\begin{bmatrix} i_o \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{V_i}{L_0} \\ 0 \end{bmatrix} + \left\{ v_o \begin{bmatrix} \frac{1}{L_0} \\ 0 \end{bmatrix} + i_o \begin{bmatrix} 0 \\ -\frac{1}{C_0} \end{bmatrix} \right\}\mu \tag{1}$$

Here μ is duty ratio. When controlling the current for every phase, i_o is i_{s1} or i_{s2}, R_0 (equivalent resistance of inductor) is R_1 or R_2 and L_0 is L_1 or L_2. When controlling the current of the sum of each phase, i_o is i_L R_0 is $R_1R_2/(R_1+R_2)$ and L_0 is $L_1L_2/(L_1+L_2)$. The boost converter has non-linear characteristics because this equation has the product of state variable v_o, i_o and duty ratio μ.

2.2 Static characteristics of boost converter

At some operating point of eq. (1), let v_o, i_o and μ, be V_s, I_s and μ_s, respectively. Then average of output voltage V_s and inductor current I_s at the operating points becomes as follows:

$$V_s = \frac{1}{1 + \frac{1}{(1-\mu_s)^2}\frac{R_0}{R_L}}\frac{1}{1-\mu_s}V_i \qquad I_s = \frac{1}{R_L}\frac{V_s}{1-\mu_s} \tag{2}$$

The actual measurement results of the static characteristics of μ_s to V_s are shown in Fig.2. In Fig.2, it turns out that the boost converter is a non-linear system.

The static characteristic of the boost converter is changed greatly with load resistances, and it influences the dynamic characteristics of converter. In addition, the static characteristics will be changed with input voltage variation Sasaki [1].

2.3 Dynamic characteristics of boost converter

The linear approximate state equation of the interleave boost converter using small perturbations $\Delta i_o = i_o - I_s$, $\Delta v_o = v_o - V_s$ and $\Delta\mu = \mu - \mu_s$ is as follows:

$$\dot{x}(t) = A_c x(t) + B_c u(t) \qquad y(t) = C_c x(t) \tag{3}$$

where

$$A_c = \begin{bmatrix} -\frac{R_0}{L_0} & -\frac{1-\mu_s}{L_0} \\ \frac{1-\mu_s}{C_0} & -\frac{1}{R_{LDC}C_0} \end{bmatrix}, B_c = \begin{bmatrix} \frac{V_s}{L_0} \\ -\frac{I_s}{C_0} \end{bmatrix}$$

$$x(t) = \begin{bmatrix} \Delta i_o(t) \\ \Delta v_o(t) \end{bmatrix}, u(t) = \Delta\mu(t), y = \begin{bmatrix} y_i \\ y_v \end{bmatrix}, C_c = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Here, Δi_o, Δv_o, $\Delta\mu$ are small-signal variables. And $y_i = \Delta i_o$ is a small signal inductor current and $y_v = \Delta v_o$ is a small signal output voltage.

From this equation, matrix A and B of the interleave boost converter depends on duty ratio μ_s. Therefore, the converter response will be changed depending on the operating point and other parameter variations. The changes of the load R_L, the duty ratio μ_s, the output voltage V_s and the inductor current I_s in the controlled object are considered as parameter changes in eq. (1). Such parameter changes can be replaced with the equivalent disturbances inputted to the input and the output of the controlled object. Therefore, what is necessary is just to constitute the control systems whose pulse transfer functions from equivalent disturbances to the output y become as small as possible in their amplitudes, in order to robustize or suppress the influence of these parameter changes.

3 DESIGN OF DIGITAL CONTROLLERS

3.1 Discretization of controlled object

The continuous system of eq. (1) is transformed into the discrete system as follows:

$$x_d(k+1) = A_d x_d(k) + B_d u(k) \quad (4)$$
$$3\; y(k) = C_d x_d(k)$$

where

$$A_d = \left[e^{A_c T}\right], B_d = \left[\int_0^T e^{A_c \tau} B_c d\tau\right], C_d = C_c$$

This dicrete-time controlled object is shown in Fig. 2. In Fig. 2, q_v, q_{yi} and q_{yv} are the equivalent disturbances with which the parameter changes of the controlled object are replaced.

3.2 Digital PI current and voltage control system

First, in order to make the input i_{in} follow the input voltage v_{ac}, the current control system is constituted by making current i_{s1} and i_{s2} or i_L into the controlled output y_i as shown in Fig. 2. The transfer function of the digital PI controller is as follows:

$$G_i(z) = k_{ri} + \frac{k_{ii}}{z-1} \quad (5)$$

Next, a voltage control system is constituted by making output voltage vo of the current control system into the controlled output yv as shown in Fig. 2. The transfer function of the digital PI controller is as follows:

$$G_v(z) = k_{rv} + \frac{k_{jv}}{z-1} \quad (6)$$

The parameters k_{ri} and k_{ii} of eq. (5) are appropriately decided from the Bode diagram of the transfer function from r_i to y_i and from q_v, q_{yi} and q_{yv} to y_i of the system of Fig. 2.

The parameters k_{rv} and k_{iv} of eq. (6) are appropriately decided from the Bode diagram of the transfer function between r_v and y_v yv and from q_v, q_{yi} and q_{yv} to y_v of the system of Fig. 2.

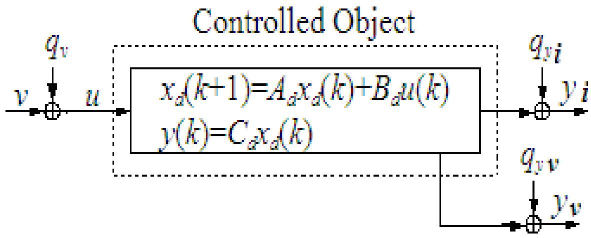


Fig.2 Discrete-time Controlled Object

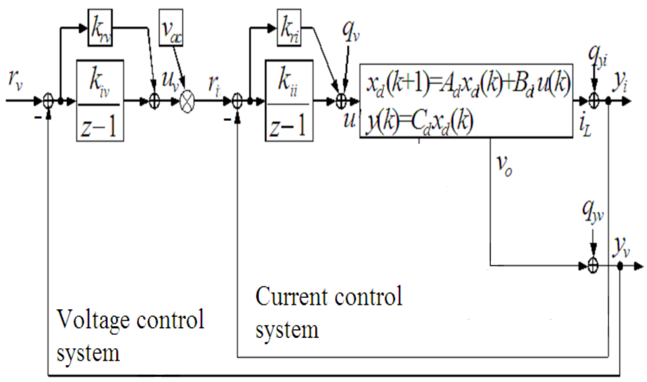


Fig.3 Interleave control system with digital PI current controller and digital PI voltage controller

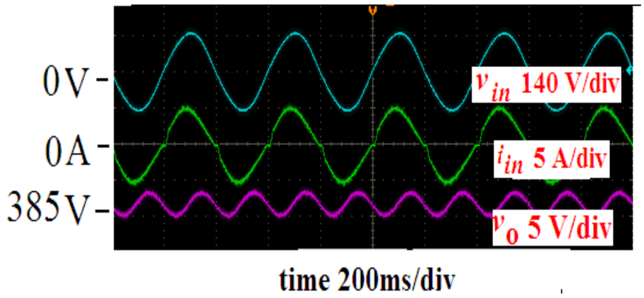
4 Expermental Studies

All experimental setup system is manufactured. A micro-controller (RX) from Renesas Electronics is used for the digital controller. The digital PI current, and voltage controllers were implemented on 1 Micro Controller.

When controlling the current for every phase, two $G_i(z)$ and $G_v(z)$ are needed. Then each PI controller parameters for each phase are determined as follow:

$$k_{ri} = 0.8 \qquad k_{ii} = 0.2$$
$$k_{ri} = 0.5 \qquad k_{iv} = 0.001$$

The experiment results of this case are shown in Fig. 4, 5, 6. The experiment result of the steady state at load RL=1kΩ and 500Ω are shown in Fig. 4 and 5. The input current waveform and the phase are the almost same as the input voltage at each load and the power factor (PFC) of converter at load RL=500Ωand 1kΩ are 0.9780 and 0.975, respectively. The experiment result of load sudden change from 1kΩ to 500Ω is shown in Fig. 6. In Fig. 6, the output voltage variation in sudden load change is less than 5V (1.30%). and.994 and 0.972



Fig, 4 Experimental Results of Steady State Waveform, at load RL=500Ω controlling the current for every phase

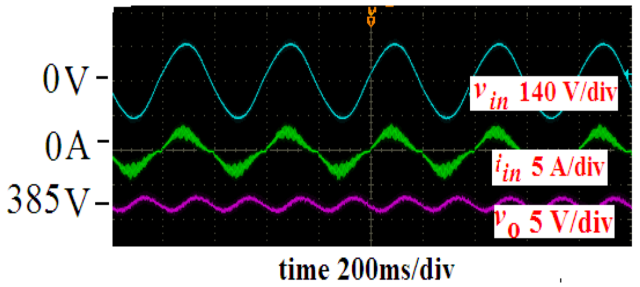


Fig.5 Experimental Results of Steady State Waveform, at load RL=1kΩ controlling the current for every phase

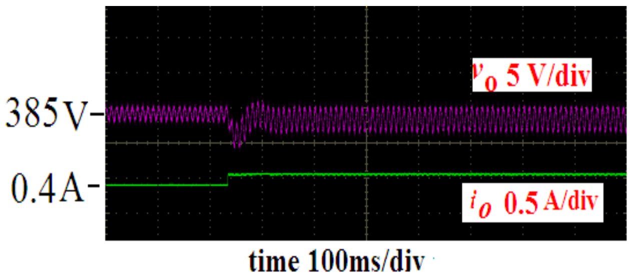


Fig.6 Experimental Results of Sudden Load Change from 1kΩ to 500Ω controlling the current for every phase

When controlling the current of the sum of each phase, one $G_i(z)$ and $G_v(z)$ are needed. Then the PI controller parameters are as follows:

$$k_{ri} = 1.0 \qquad k_{ii} = 0.2$$
$$k_{ri} = 0.28 \qquad k_{iv} = 0.001$$

The experiment results of this case are shown in Fig. 7, 8, 9. From Fig.8, at the light load the harmonic is reduced. PFC of converter at load RL=500Ωand 1kΩ are 0.994 and 0.972, respectively. So it turns out that and the PI digital controllers are more advantageous to control the current of the sum of each phase in performance and hardware.

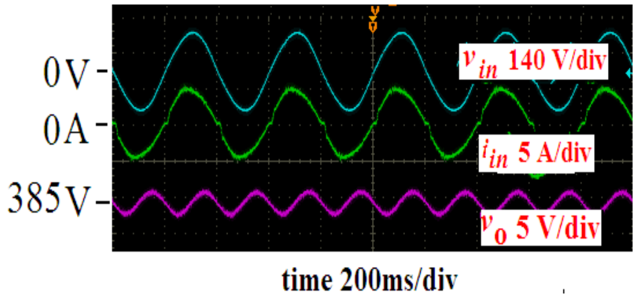


Fig.7 Experimental Results of Steady State Waveform, at load RL=500Ωcontrolling the current of the sum of each phase

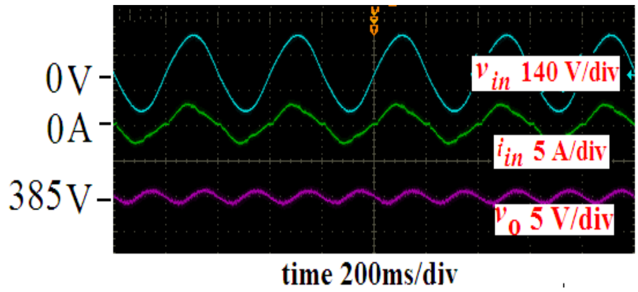


Fig.8 Experimental Results of Steady State Waveform, at load RL=1kΩ controlling the current of the sum of each phase

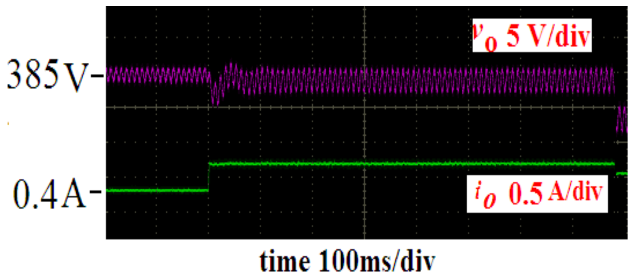


Fig.9 Experimental Results of Sudden Load Change from 1 kΩ to 500Ωcontrolling the current of the sum of each phase

4 CONCLUSION

. In this paper, the concept of controller of non-linear PFC boost converter with DC-DC converter load to attain good robustness was given. It was shown from experiments that the proposed A2DOF digital controller can attain better performance.

REFERENCES

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