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A Performance Driven Switching Control of DC-DC Converters*

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Abstract— **This paper reports the application of the switching control method based on the controller performance assessment. The switching of the controllers are done based on the current control performances. The accepted controller has the best estimated performance of all controllers. Finally, the practically and utility of this idea are evaluated by the voltage control result of the DC-DC converters.**

I. INTRODUCTION

There are a lot of applications of DC-DC converters for various fields. The suitable regulation against the load change is requested from the controller of DC-DC converters. This controller was consisted only one IC as a simple switching regulator. Advanced control theory is recently appled for DC-DC converters. Guesmi has poposed the fuzzy PID stabilizer for DC-DC converters[1]. This paper reported the possibility of PID control for the DC-DC converters.

PID control schemes based on the classical control theory, have been used for various process control systems for a long time. The main reasons are PID controllers have simple control structures and easy to understand. However, since such many industrial processes have time varying properties and uncertainties. It is difficult to find a suitable set of PID parameters that will provide optimal process performance under all conditions. One solution for dealing with such systems is to implement self-tuning(STC) or adaptive control. The algorithm of STC is following steps. First, the property of the controlled system is identified by an on-line identification method such as recursive least squares. Next, the control parameters are calculated from the estimated parameters by using any one of the several PID controller design algorithms. Finally, the control input is generated by the newly computed control parameters. This procedure is repeated. However, this scheme is based on the on-line estimation.

At the field of a process control, the switching control based on the idea of the self-tuning control is used. It is the way an operator changes the sets of the PID patrameters prepared beforehand by Driven condition. This method is very effective for a nonlinear system and/or time varying system. But, automatically switching is desired. since it is dependent on an operator's experience.

On the other hand, The control performance assessment is important in the process control area[2, 3]. Many control performance assessment methods have been proposed, and many instrument and control vendors have software that allows one to obtain a performance index. One of the first performance monitoring index was based on the minimum variance control benchmark, proposed by Harris[4]. The performance index of this method is defined as the ratio of minimum variance of the closed loop output and the current actual control output variance. This index is calculated as the number between 0 and 1. The index near 1 means good control performance, and near 0 means bad performance that may need retuning of control parameters.

This paper deal with the switching control method based on the controller performance assessment[5]. The switching of the controllers are done based on the current control performances. The accepted controller has the best estimated performance of all controllers. Finally, the practically and utility of this idea are evaluated by the voltage control result of the DC-DC converters.

II. CONTROL SYSTEM

A. System description

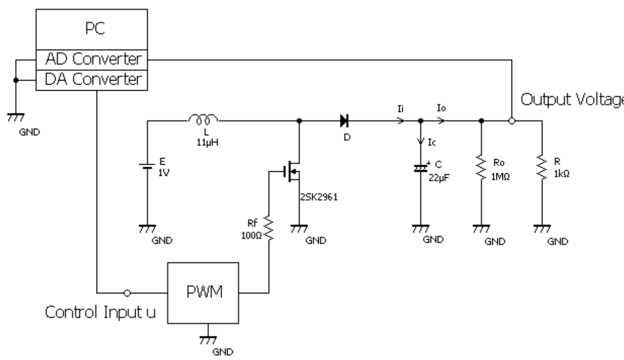

Fig. 1. Experimental system.

Figure 1 shows the experiment system. This system has the computer, AD Converter, DA Converter, boost converter and PWM circuit. Boost converter is used chopper model boost circuit. When power supply voltage is added, current flows at inductance and give a charge of electricity, If input pulse power up, currnt that flowing to L increase besides energy charge at inductance. Secondly, before charge to inductance is completed, input puls is turned off, current flowing to load increase therefore current for L decrease. And, output voltage become $V_0 = E + VL$ to start radiateing energy that inductance have obtained till now. That is to say, voltage can gain higher than input voltage E. Voltage is outputed

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here charge up. If switch turn off, $V_i + VL$ is supplied load by this capacitor. This system is ON-OFF time rate of input puls operate amount and output voltage control amount. And dynamic characteristic can be shown quadratic delay system[1]. Therefore the present study dealed in control candidate is thpught basis discrete time system is expressed in the following equation.

$$A(z^{-1})y(t) = z^{-d}B(z^{-1})u(t-1) + \xi(t) \tag{1}$$

Where $y(t)$ and d system output and minimum estimate value of dead time , respectively. $u(t)$ is control input, and $\xi(t)$ is probability noise including such as observation noise. In addition, when information about dead time can't obtain nothing, d is set as 0.

And $A(z^{-1})$ and $B(z^{-1})$ are polynomial given by following equation,

$$\left.\begin{array}{rl} A(z^{-1}) = & 1 + a_1 z^{-1} + a_2 z^{-2} \\ B(z^{-1}) = & b_0 + b_1 z^{-1} + \cdots + b_m z^{-m} \end{array}\right\} \tag{2}$$

Where z^{-1} shows backward shift operator and means $z^{-1}y(t) = y(t-1)$.

[Assumption A]

A.1 The degree of polynomial $B(z^{-1})$ is known.

A.2 The system parameter a_1 and b_i are unknown.

A.3 The polynomial $A(z^{-1})$ and $B(z^{-1})$ are irreducible.

A.4 The target value $r(t)$ is given as the piecewise-constant.

In addition, $\xi(t)$ is comfortable gaussian white noise order the following function.

[Assumption B]

B.1

$$\varepsilon[\xi(t)] = 0 \tag{3}$$

B.2

$$\varepsilon[\xi^2(t)] = \sigma_\xi^2 \tag{4}$$

B.3

$$\varepsilon[\xi(t)\xi(t+\tau)] = 0 (\tau \neq 0) \tag{5}$$

$\varepsilon[\cdot]$ means expectation value(spatial average).

III. Control Performance Assessment

Eqn.(1) can be written as the generalized controlled object discribed as following equation.

$$y(t) = z^{-d}G_p(z^{-1})u(t) + G_n(z^{-1})\xi(t) \tag{6}$$

Feedback control law is given as following equation for Eq.(6).

$$u(t) = G_c(z^{-1})e(t) \tag{7}$$

$$e(t) := r(t) - y(t) \tag{8}$$

The block diagram of the control system which is given as eqns. Eq.(6) and Eq.(7) is shown as fig. 2 .

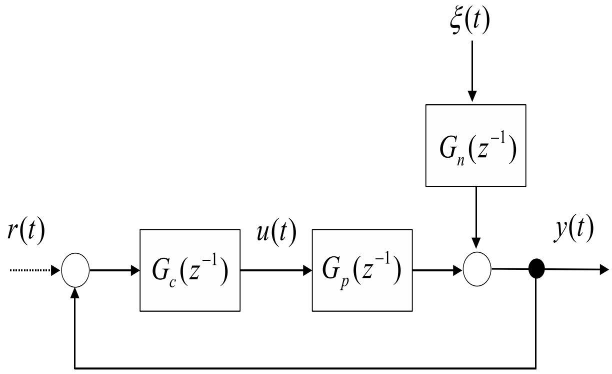

Fig. 2. Block design

$$e(t) = \frac{r(t) - G_n(z^{-1})\xi(t)}{1 + z^{-d}G_p(z^{-1})G_c(z^{-1})} \tag{9}$$

Here, by considering the steady state, control error signal can obtain as following equation.

$$e(t) = -\frac{G_n(z^{-1})}{1 + z^{-d}G_p(z^{-1})G_c(z^{-1})}\xi(t) \tag{10}$$

where, the noise transfer function $G_n(z^{-1})$ can be divided the term about the dead time before and the term about the dead time after by the following Diophantine equation

$$G_n(z^{-1}) = G_{n1}(z^{-1}) + z^{-d}G_{n2}(z^{-1}) \tag{11}$$

where, $G_{n1}(z^{-1})$ is polynomial given by following equation.

$$G_{n1}(z^{-1}) = n_0 + n_1 + \cdots + n_{d-1}. \tag{12}$$

The following equation can be obtain ed by (10) and (11).

$$e(t) = -G_{n1}(z^{-1}) + z^{-d}G_d(z^{-1})\xi(t). \tag{13}$$

Where $G_d(z^{-1})$ is defined as following equation:

$$G_d(z^{-1}) =: \frac{G_{n2}(z^{-1}) - G_{n1}(z^{-1})G_p(z^{-1})G_c(z^{-1})}{1 + z^{-d}G_p(z^{-1})G_c(z^{-1})}. \tag{14}$$

And, eq.(13) is expressed as following equation including $\xi(t)$.

$$\begin{aligned} e(t) &= -\{\underbrace{n_0\xi(t) + \cdots + n_{d-1}\xi(t-d+1)}_{v(t)} \\ &\quad + \underbrace{d_0\xi(t-d) + d_1\xi(t-d-1) + \cdots\}}_{\omega(t-d)} \qquad (15) \\ &= -v(t) + \omega(t-d) \qquad (16) \end{aligned}$$

Here, $v(t)$ isn't associated with control input and if $\omega(t-d)$ is possible to be 0 by control input, let $v(t)$ minimum variance output.

$$Var\{e(t)\} = Var\{v(t)\} + Var\{\omega(t-d)\} \quad (17)$$

$$Var\{e(t)\} \geq Var\{v(t)\} \quad (18)$$

Furthermore, when it is $\sigma_{MV}^2 = Var\{v(t)\}, \sigma_e^2 = Var\{e(t)\}$, minimum-variance control performance assessment index η is shown by following equation

$$\eta = \frac{\sigma_{MV}^2}{\sigma_e^2}. \quad (19)$$

where σ_{MV}^2 and σ_e^2 mean $Var\{v(t)\}$ and $Var\{e(t)\}$, respectively. Here, σ_e^2 shows actual variance of control error and σ_{MV}^2 shows achievable minimum variance of control error at this system. This σ_{MV}^2 is calculated by the procedure which is explained later. Consequently, σ_e^2 is nearly σ_{MV}^2. in fact, η of close in value to 1 means that good control performance.

MV-index η can be calculated by eqn.(19). However, σ_{MV}^2 which is the numerator of eqn.(19) cannot be calculated directly. This term is obtained as following procedure.

$e(t-d)$ can be derived by multiplying z^{-d} for both sides:

$$e(t-d) = -\{G_{n1}(z^{-1}) + z^{-d}G_d(z^{-1})\}\xi(t-d). \quad (20)$$

$\xi(t-d)$ can be obtained from eqn.(20):

$$\xi(t-d) = -\frac{e(t-d)}{G_{n1}(z^{-1}) + z^{-d}G_d(z^{-1})}. \quad (21)$$

The following equation is derived by eqns.(20) and (21).

$$e(t) = -G_{n1}(z^{-1})\xi(t) - \frac{G_d(z^{-1})}{G_{n1}(z^{-1}) + z^{-d}G_d(z^{-1})}e(t-d) \quad (22)$$

The first term of right-hand side on eqn.(22) is defined as the following modeling error:

$$b(t) := -G_{n1}(z^{-1})\xi(t) \quad (23)$$

$e(t)$ can be rewritten from eqns.(22) and (23):

$$e(t) = b(t) - \frac{G_d(z^{-1})}{G_{n1}(z^{-1}) + z^{-d}G_d(z^{-1})}e(t-d). \quad (24)$$

On the other hand, $e(t)$ can be expressed as:

$$e(t) = b(t) - \sum_{i=1}^{\infty} \alpha_i e(t-d-i) \quad (25)$$

And, the model degree is replaced ∞ by finite value p:

$$e(t) = b(t) - \sum_{i=1}^{p} \alpha_i e(t-d-i) \quad (26)$$

Eqn. (26) on the assessment horizon n can be collected up as:

$$\mathbf{e} = \mathbf{X}\kappa + \mathbf{b} \quad (27)$$

Where, $\mathbf{e}$ and $\mathbf{X}$ are consisted of previous data. And, κ and $\mathbf{b}$ are autoregressive vector and modeling error vector, respectively. These are expressed as:

$$\mathbf{e} = \left[\ e(n), e(n-1), \cdots, e(d+p-1)\ \right]^T \quad (28)$$

$$\mathbf{X} = \begin{bmatrix} e(n-d) & \cdots & e(n-d-p) \\ e(n-d-1) & \cdots & e(n-d-p-1) \\ \vdots & \ddots & \vdots \\ e(p) & \cdots & e(1) \end{bmatrix} \quad (29)$$

$$\kappa = \left[\ -\alpha_1, -\alpha_2, \cdots, -\alpha_p\ \right]^T \quad (30)$$

$$\mathbf{f} = \left[\ b(n), b(n-1), \cdots, b(d+p)\ \right]^T \quad (31)$$

κ in eqn. (27) is unknown. This is estimated by following equation.

$$\hat{\kappa} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{e} \quad (32)$$

Therefore, minimum variance can be obtained as:

$$\sigma_{MV}^2 = (\mathbf{e} - \mathbf{X}\hat{\kappa})^T(\mathbf{e} - \mathbf{X}\hat{\kappa}). \quad (33)$$

A. Estimated performances of PID controllers

The following PID control law is used in this paper.

$$\Delta u(t) = k_c(\Delta + \frac{T_s}{T_I} + \frac{T_D}{T_S}\Delta^2)e(t) \quad (34)$$

where, k_c, T_I and T_D mean the proportional gain, reset time and derivative time, respectively. And, T_s is the sampling intervals.

Eqn. (34) is rewritten by the following equation.

$$\Delta u(t) = C(z^{-1})e(t) = (c_0 + c_1 z^{-1} + c_2 z^{-2})e(t) \quad (35)$$

where, $C(z^{-1})$ is

$$C(z^{-1}) = k_c(1 + \frac{T_s}{T_I} + \frac{T_D}{T_s}) - k_c(1 + \frac{2T_D}{T_s})z^{-1} + \frac{k_c T_D}{T_s}z^{-2} \quad (36)$$

The following closed loop transfer function can be obtained by substituting eqn. (35) into eqn. (6).

$$y(t) = \frac{z^{-(k+1)}B(z^{-1})C(z^{-1})}{T(z^{-1})}r(t) + \frac{1}{T(z^{-1})}\xi(t) \quad (37)$$

where, $T(z^{-1})$ is the characteristic polynomial as

$$T(z^{-1}) = \Delta A(z^{-1}) + z^{-(k+1)}B(z^{-1})C(z^{-1}) \quad (38)$$

The control error signal is expressed by:

$$e(t) = \frac{1}{T(z^{-1})}\xi(t) \quad (39)$$

The variance of $e(t)$ can be calculated the following equation by using the H_2 norm$\| \cdot \|_2$.

$$\sigma_{PID}^2 = \| \frac{1}{T(z^{-1})} \|_2 \sigma_\xi^2 \quad (40)$$

The MV-index of the PID controller can be obtained by using σ_{PID}^2 in eqn.(40) and σ_{mv}^2.

$$\eta_{PID} = \frac{\sigma_{MV}^2}{\sigma_{PID}^2} \quad (41)$$

However, system parameters $A(z^{-1})$ and $B(z^{-1})$ in eqn.(40) or the noise variance σ_ξ^2 are unknown. So, in this paper, these are estimated by using the least squares method. $\hat{\theta}(t)$ is the estimates of the unknown parameters $\theta = [a_1, a_2, b_0, \ldots, b_m]^T$

$$\hat{\theta}(t) \quad = \quad [\hat{a}_1(t), \hat{a}_2(t), \hat{b}_0(t), \ldots, \hat{b}_m(t)]^T \quad (42)$$

First, the data matrix is configured as:

$$Z(t) = \begin{bmatrix} -\Delta y(t-1) & -\Delta y(t-2) & -\Delta u(t-k-1) & \cdots & -\Delta u(t-k-m-1) \\ -\Delta y(t-2) & -\Delta y(t-3) & -\Delta u(t-k-2) & \cdots & -\Delta u(t-k-m-2) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\Delta y(t-l) & -\Delta y(t-l-1) & -\Delta u(t-k-l) & \cdots & -\Delta u(t-k-m-l) \end{bmatrix}$$

(43)

where, l is the length of the data window for estimation. And, the output vector is defined as:

$$\mathbf{y}(t) = [\Delta y(t), \Delta y(t-1), \cdots, \Delta y(t-l+1)]^T \quad (44)$$

The estimated system parameter vector is calculated by the following equation.

$$\hat{\theta}(t) = \{Z^T(t)Z(t)\}^{-1} Z(t)^T \mathbf{y}(t) \quad (45)$$

The control performance can be estimated by the above procedure. In this paper, the best controller is selected by the comparing of the performances of candidate controllers.

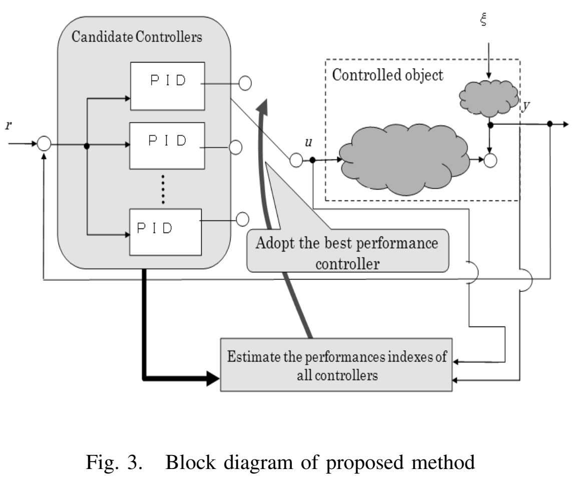

Fig. 3. Block diagram of proposed method

This schematic figure is summarized as Fig.3.

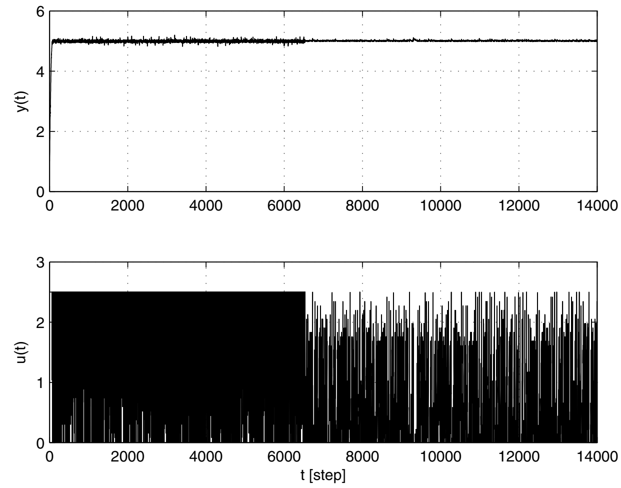

Fig. 4. Control result by fixed parameters.

IV. Experimental result

This chapter describes the experimental result in order to evaluate the effectiveness of proposed scheme. The experimental system are PC with AD-convertor and DA-convertor, chopper boost circuit and PWM circuit. The control input and the output$y(t)$ of this system are given as duty retio of input pulse and the output voltage. The actual control input$u(t)$ is given as the signal voltage of PWM circuit.

The objective of this experiment is boosting from 1.0[V] to 5.0[V]. The load is changed from 1.0[k Ω] to 1.0[M Ω] at $t = 5000[step]$.

Fig.4 and Fig.5 show the control result and the calculation result of MV-index by fixed PI controller which is set as $k_c = 30$,$T_I = 0.0001$. In Fig.5 the performance index was calculated by 1000 step date and the calculation of

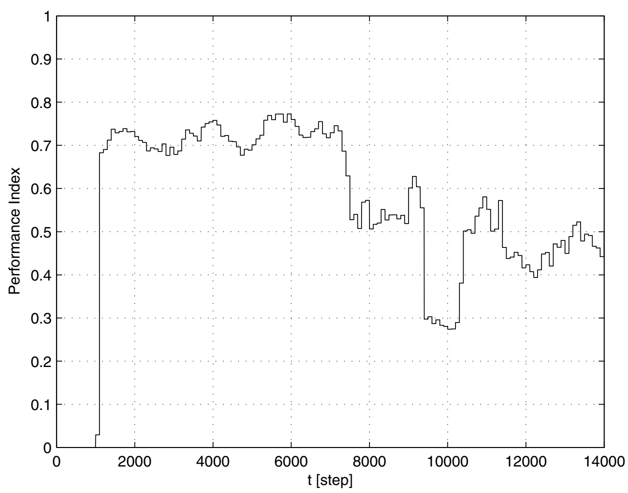

Fig. 5. Performance index by fixed parameters.

performance index was done every 100 step. Fig.5 shows the performance index is deteriorated under 0.6 after load change. The fixed PI controller can not adjust the new system properties.

On the other hand, Fig.6 and Fig.7 show the control result and the calculation result of MV-index by proposed scheme. The candidate controllers are $k_c = 30, T_I = 0.0001$ and $k_c = 10, T_I = 0.0001$ The inital controller was $k_c = 30, T_I = 0.0001$ same as the fixed controller which was shown as Fig.4 and Fig.5. Another controller $k_c = 10, T_I = 0.0001$ was adopted when the performance index was deteriorated under 0.6. Fig.7 shows the performance index return after the switching of controller. The initial controller can not adjust the new system properties. However, the other controller can adjust the new properties, so better MV-index can be obtained.

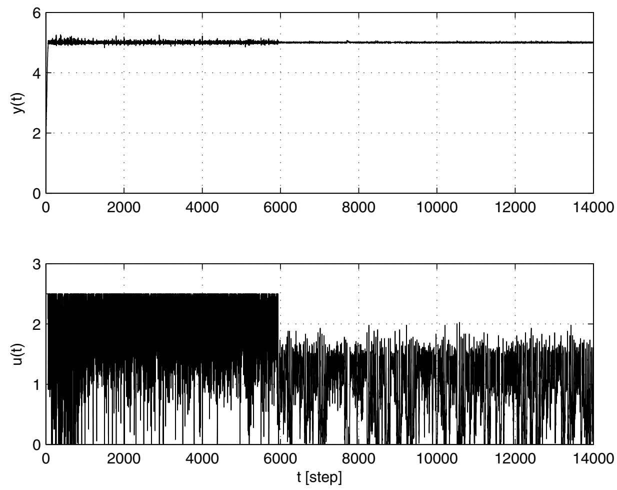

Fig. 6. Control result by propposed method.

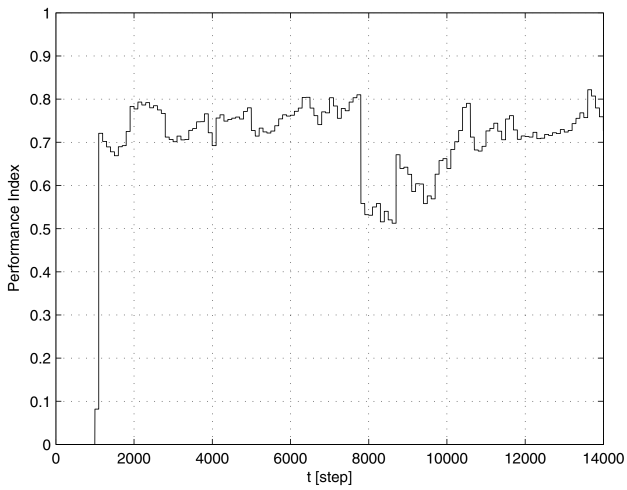

Fig. 7. Performance index by propposed method.

V. CONCLUSIONS

This paper discussed the switching method of PID parameters based on the controller performance assessment. The switching of the candidate controllers were based on the current control performances. The accepted controller has the best estimated performance of all controllers. The experimental results for DC-DC converter circuit were demonstrated the practically and utility of this idea. The experimental result used only two candidate controllers. We are now trying the another experiment with more candidate controllers.

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