Control Strategy for Buck DC/DC Converter Based on Two-dimensional Hybrid Cloud Model

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Abstract – In order to adapt the fast dynamic performances of Buck DC/DC converter, and reduce the influence on converter performance owing to uncertain factors such as the disturbances of parameters and load, a control strategy based on two-dimensional hybrid cloud model is proposed. Firstly, two cloud models corresponding to the specific control inputs are determined by maximum determination approach, respectively, and then a control rule decided by the two cloud models is selected by a rule selector, finally, according to the reasoning structure of the rule, the control increment is calculated out by a two-dimensional hybrid cloud decision module. Both the simulation and experiment results show that the strategy can dramatically improve the dynamic performances of the converter, and enhance the adaptive ability to resist the random disturbances, and its control effect is superior to that of the current-mode control.

Keywords: Buck DC/DC converter, Uncertainty, Two-dimensional hybrid cloud model

1. Introduction

A DC/DC converter is a kind of power electronic converter and has been extensively used in many fields. In recent years, there have been manifested a great deal of control strategies associated with such a converter. According to whether strategy designs rely on converter models or not, they can be broadly divided into two categories as follows:

1.1 Control strategies based on converter models

In [1], the notion of the N -step model is introduced to capture the hybrid nature of DC/DC converters, and an optimal control problem is formulated and solved offline. The resulting state-feedback control law is of piecewise affine form, which can be easily stored and implemented in a lookup table and used for the practical implementation of the control strategy. In [2], a discrete controller for DC/DC converter is designed based on average model. Such a digital controller combined with the load estimator provides a complete compensation, which further improves the dynamic performance of the control system. In [3] and [4], the passivity-based control strategy is applied to the control of DC/DC converter, which not only ensures the fast response of the system in different modes but also stabilizes output voltage in a wide range of operation. In addition, the differential geometry theory is used to the

modeling and control for DC/DC converter in [5] and [6]. This control strategy is based on the exact feedback linearization model of DC/DC converter, improving the robust and dynamic performances of the control system. Generally speaking, the above control strategies are all based on converter models which can be established through a variety of ways. Yet, the parameters of converter are sensitive to the disturbance of random factors, leading to the uncertainty and variability of the established model, which usually decreases the control performance and makes some control strategies too complicated to apply.

1.2 Control strategies without requirement of a model

When the construction and some parameters of a controlled object are uncertain, or its exact model cannot be established, some control strategies can also be designed by experience or field debugging, traditional PI control is one of them. Moreover, voltage-current two closed loops control [7], peak-current control [8, 9], and average-current control [10], etc., also belong to the category. Although these strategies are simple and practical, they suffer from the effect of system noise and parameter disturbance, and hard to obtain the optimal dynamic performance (By the optimal dynamic performance here is meant both the relatively small adjusting time and overshoot), thus limiting their applications in some fields where the high performance is needed. In addition, for some intelligent control strategies such as neural network control [11] and fuzzy control [12], a model is also not required. Neural network control has the capability of supporting the linear or nonlinear mapping, as well as learning rules from the raw data, but the requirement of its real-time is still hard to be satisfied for the high switching frequency DC/DC

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converter. And a fuzzy control uses language description and rules to express the intuition and experience of designers directly so that a rapid and effective control can be realized even though the model of controlled object is unknown, but the effect of randomness is ignored. Some random factors will lead to the disturbance of the DC/DC converters during steady-state operation, thus degrading the fuzzy control performance.

Cloud is a model described by linguistic values for representation of the uncertain relationships between a specific qualitative concept and its quantitative expression, which integrates the fuzziness and randomness (two important factors of uncertainty) in a unified way [13]-[18]. For the controller design of a DC/DC converter, the mapping relationship between the input and output of the controller has uncertainty in the process of the converter operation. In such a case, how to regulate the output voltage to the expected value with relatively small adjusting time and overshoot is the main problem to be dealt with. In this paper, a control strategy for Buck DC/DC converter based on two-dimensional hybrid cloud model is proposed, which is suitable to tackle the above problem. Firstly, the related concepts of the cloud model and the structure block diagram of the control strategy are illustrated briefly, subsequently, each parts of the block diagram is described in detail, finally, the effectiveness of the strategy are verified by simulation and experiment.

2. Continuous-time Model of Buck converter

A Buck DC/DC converter consists of voltage source v_s , switch transistor Q , diode D , inductor l , capacitor c and load r_o , of which the switch transistor Q is controlled by the manipulated variable $d(k)$ for each switch period k ; D acts as a wheel diode; the inductor l is used to store and deliver energy; the capacitor c is used to filter the ramp voltage across the load. The equivalent topology is shown in Fig. 1, where r_l and r_c are respectively representative of the internal resistor of l and c .

By taking $x(t)=[i_l(t) \ v_o(t)]^T$ as the system state vector, where $i_l(t)$ is the inductor current and $v_o(t)$ the output voltage, the system is described by the following continuous time state-space equation:

$$\dot{x}(t) = Ax(t) + Bv_s(t)s \quad (1)$$

In the above equation, if the switch Q is on, then $s=1$,

Fig. 1. Equivalent topology of the Buck DC/DC converter

otherwise $s=0$, and matrices A, B are given by

$$A = \begin{bmatrix} -\frac{r_l}{l} & -\frac{1}{l} \\ \frac{-r_o(r_c r_l - l)}{cl(r_o + r_c)} & \frac{-r_c r_o c - l}{cl(r_o + r_c)} \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{l} \\ \frac{r_o r_c}{(r_o + r_c)l} \end{bmatrix} \quad (2)$$

3. Concepts of Cloud Model

Let U be a universal set described by precise numbers, and C be the qualitative concept related to U . If there is a number $x \in U$, which randomly realizes the concept C , and the membership degree of x for C , i.e., $\mu(x) \in [0, 1]$, is a random value with stabilization tendency

$$\mu(x): U \rightarrow [0, 1], \quad \forall x \in U, \quad x \rightarrow \mu(x) \quad (3)$$

then the distribution of x on U is defined as a cloud [13]. Specially, provided that $NORM_1(E_1, S_1)$ is a one-dimensional normal distribution function, where E_1 is an expected value, S_1 is a standard deviation, then the cloud consists of cloud drops $drop(x_{1i}, \mu_i)$ ($i=1, 2, \dots$) which satisfy equation (4)

$$x_{1i} = NORM_1(Ex_{x1}, En_{x1}) \quad (4-a)$$

$$P_{1i} = NORM_1(En_{x1}, He_{x1}) \quad (4-b)$$

$$\mu_i = e^{-\frac{1}{2} \left(\frac{(x_{1i} - Ex_{x1})^2}{P_{1i}^2} \right)} \quad (4-c)$$

is called one-dimensional normal cloud [13], and denoted as $(Ex_{x1}, En_{x1}, He_{x1})$. The properties of a cloud are reflected by the three digital characteristics: expected value (Ex_{x1}), entropy (En_{x1}) and hyper-entropy (He_{x1}).

It is not difficult to extend a one-dimensional normal cloud to the two-dimensional case. Provided that $NORM_2(E_1, E_2, S_1, S_2)$ is a two-dimensional normal distribution function, where E_1, E_2 are expected values, S_1, S_2 are standard deviations, and given three digital characteristics: expected value (Ex_{x1}, Ex_{x2}), entropy (En_{x1}, En_{x2}) and hyper-entropy (He_{x1}, He_{x2}), then the cloud consists of cloud drops $drop(x_{1i}, x_{2i}, \mu_i)$ ($i=1, 2, \dots$) which satisfy equation (5):

$$(x_{1i}, x_{2i}) = NORM_2(Ex_{x1}, Ex_{x2}, En_{x1}, En_{x2}) \quad (5-a)$$

$$(P_{1i}, P_{2i}) = NORM_2(En_{x1}, En_{x2}, He_{x1}, He_{x2}) \quad (5-b)$$

$$\mu_i = e^{-\frac{1}{2} \left[\frac{(x_{1i} - Ex_{x1})^2}{P_{1i}^2} + \frac{(x_{2i} - Ex_{x2})^2}{P_{2i}^2} \right]} \quad (5-c)$$

is called two-dimensional normal cloud [13], and it can be treated as the combination of two relatively independent one-dimensional normal cloud $(Ex_{x1}, En_{x1}, He_{x1})$ and $(Ex_{x2}, En_{x2}, He_{x2})$.

4. Proposed Control Strategy

4.1 Control structure based on Two-dimensional hybrid cloud model

In Fig. 2 is shown the structure block diagram of implementing the proposed control strategy for a Buck DC/DC converter based on two-dimensional hybrid cloud model, where the output-voltage error $e(k)$ and the error increment $ec(k)$ are two inputs of the controller for each switch period k , of which $e(k) = U_{ref} - v_o(k)$, $ec(k) = e(k) - e(k-1)$, and U_{ref} is the expected value of $v_o(k)$. The controller mainly consists of four parts: two maximum determination modules, a rule selector which contains a rule base, and a two-dimensional hybrid cloud decision module.

The implementation of the control strategy can be described as follows: firstly, the two one-dimensional cloud models E_i and EC_j (whose numerical representations are shown in Table 1) corresponding to $e(k)$ and $ec(k)$ are determined by the maximum determination modules, respectively, and then a control rule decided by the two clouds is selected by the rule selector from the rule base, and according to the reasoning structure of the rule and the digital characteristics of related cloud models, the control increment $\Delta d(k)$ can be calculated out by a two-dimensional hybrid cloud decision module. Finally, the

Table 1. Numerical characteristics of one-dimensional hybrid cloud model sets

Qualitative concepts	$E=[E_1, E_2, \dots, E_7]$ cloud model set	$EC=[EC_1, EC_2, \dots, EC_7]$ cloud model set
NL	$E_1=1$, if $x \in [-4.5, -40]$, otherwise $E_1=(-4.5, 0.8, 0.04)$	$EC_1=1$, if $x \in [-0.6, -0.9]$, Otherwise $EC_1=(-0.6, 0.08, 0.004)$
NM	$E_2=(-1.5, 0.2, 0.02)$	$EC_2=(-0.3, 0.03, 0.004)$
NS	$E_3=(-0.5, 0.1, 0.02)$	$EC_3=(-0.15, 0.03, 0.004)$
ZE	$E_4=(0, 0.07, 0.015)$	$EC_4=(0, 0.03, 0.004)$
PS	$E_5=(0.5, 0.1, 0.02)$	$EC_5=(0.15, 0.03, 0.004)$
PM	$E_6=(1.5, 0.2, 0.02)$	$EC_6=(0.3, 0.03, 0.004)$
PL	$E_7=1$, if $x \in [4.5, 40]$, otherwise $E_7=(4.5, 0.8, 0.04)$	$EC_7=1$, if $x \in [0.6, 0.9]$, otherwise $EC_7=(0.6, 0.08, 0.004)$

Fig. 2. Structure block diagram of implementing the proposed control strategy for a Buck DC/DC converter based on two-dimensional hybrid cloud model

manipulated variable $d(k)$ is obtained by $d(k) = \Delta d(k) + d(k-1)$, and it is converted to the PWM control signal of switch transistor Q by the PWM generator.

4.2 Determination of cloud model

First of all, two one-dimensional cloud model sets are respectively defined in the universal sets of $e(k)$ and $ec(k)$, denoted as $E=[E_1, E_2, \dots, E_7]$ and $EC=[EC_1, EC_2, \dots, EC_7]$. In E and EC , the cloud models E_1 , E_7 , EC_1 , and EC_7 are half trapezium cloud models [17], [18], while the others are normal cloud models, therefore, they are actually two one-dimensional hybrid cloud model sets. The qualitative concept sets of E and EC are defined as {Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Large (PL)}, and $(Ex_{ei}, En_{ei}, He_{ei})$, $(Ex_{ej}, En_{ej}, He_{ej})$ are utilized to denote the three digital characteristics of E_i , EC_j ($i, j=1, 2, \dots, 7$), respectively. The numerical definitions are shown in Table 1.

Fig. 3 shows the distribution of E and EC yielding from Table 1, in which each cloud model consists of many cloud drops rather than certain function curve. The uncertainty of the cloud boundary reflects the fuzziness and randomness of a cloud model, but keeps the characteristics of a qualitative concept.

On defining the cloud model sets E and EC , the following problem is to determine the two cloud models corresponding to the $e(k)$ and $ec(k)$ by maximum determination approach, respectively. The principle block diagram of the approach is shown in Fig. 4, where $CG_2 \sim CG_6$ are one-dimensional normal cloud generators, and $HTCG_1$ and $HTCG_7$ are one-dimensional half trapezium

Fig. 3. One-dimensional hybrid cloud model sets of the voltage error e and error increment ec

Fig. 4. Principle block diagram of maximum determination approach

cloud generators. When each cloud generator is activated by the specific input $x(k)$ ($e(k)$ or $ec(k)$), a corresponding membership degree μ_i ($i=1, 2, \dots, 7$) is generated randomly. The maximal membership degree $\mu_{\max}$ can be then selected from the generated 7 membership degrees, and the cloud model corresponding to $x(k)$ is determined in terms of the subscript of $\mu_{\max}$.

4.3 Rule selector

In order to design the control rules, a one-dimensional normal cloud model set is defined in the universal set of control output $\Delta d(k)$, denoted as $\Delta D=[\Delta D_1, \Delta D_2, \dots, \Delta D_7]$, whose qualitative concept set is similar to that of E and EC , and the numerical definition is in appendix.

According to the double-condition-single-rule reasoning structure: If $e(k) = E_i$ and $ec(k) = EC_j$, then $\Delta d(k) = \Delta D_m$ ($i, j, m=1, 2, \dots, 7$), and a control rule is determined. The intelligence of the control strategy is reflected by such rules. Following the expert experience, a rule base is established in Table 2, where the numbers 1~7 are used to briefly denote $E_i, EC_j, \Delta D_m$, for example, $E_i=3, EC_j=5, \Delta D_m=4$ corresponding to the control rule: If $e(k)=E_3$ ($e(k)$ is NS) and $ec(k)=EC_5$ ($ec(k)$ is PS), then $\Delta d(k)=\Delta D_4$ ($\Delta d(k)$ is ZE).

After the control rule is selected by a rule selector, the digital characteristics of the related cloud models are subsequently provided to the two-dimensional hybrid cloud decision module.

4.4 Two-dimensional hybrid cloud decision

As can be seen in Fig. 5, the two-dimensional hybrid cloud decision module consists of a two-dimensional precondition hybrid cloud generator HCG_{E_i, EC_j} and a one-dimensional postcondition cloud generator $CG_{\Delta D_m}$. It is used to realize the reasoning structure of a control rule.

The implementation of this module can be described as follows: firstly, by activating the HCG_{E_i, EC_j} n times with

the same specific inputs $e(k)$ and $ec(k)$, n membership degrees $\mu_1, \mu_2, \dots, \mu_n$ are generated randomly in terms of the two-dimensional hybrid cloud model (whose digital characteristics are decided together by that of the two one-dimensional cloud models, one of which is in E and the other one is in EC). And then these membership degrees are used for the input of the $CG_{\Delta D_m}$ to generate n cloud drops $drop(\Delta d_1, \mu_1), \dots, drop(\Delta d_n, \mu_n)$ randomly. Finally, the control increment $\Delta d(k)$ is obtained by taking the mean value of $\Delta d_1, \dots, \Delta d_n$. The two-dimensional hybrid cloud decision algorithm is illustrated below.

Algorithm 1 Two-dimensional hybrid cloud decision

Input: the numerical characteristics ($Ex_{ei}, En_{ei}, He_{ei}, Ex_{ecj}, En_{ecj}, He_{ecj}$) of the two-dimensional hybrid cloud model, the numerical characteristics ($Ex_{\Delta dm}, En_{\Delta dm}, He_{\Delta dm}$) of the normal cloud model, two specific values $e(k)$ and $ec(k)$, and the number n of cloud drops.

Output: control increment $\Delta d(k)$.

Step 1: If $i=1$ and $e(k) < Ex_{e1}$, then $e(k) = Ex_{e1}$; If $i=7$ and $e(k) > Ex_{e7}$, then $e(k) = Ex_{e7}$; If $j=1$ and $ec(k) < Ex_{ec1}$, then $ec(k) = Ex_{ec1}$; If $j=7$ and $ec(k) > Ex_{ec7}$, then $ec(k) = Ex_{ec7}$; /* When $e(k), ec(k)$ correspond to half trapezium cloud models: E_1, E_7, EC_1, EC_7 . */

Step 2: Generate two normal random numbers P_{ei}, P_{ecj} with expectations (En_{ei}, En_{ecj}) and standard deviations (He_{ei}, He_{ecj}), $(P_{ei}, P_{ecj}) = \text{NORM2}(En_{ei}, En_{ecj}, He_{ei}, He_{ecj})$.

Step 3: Calculate $\mu_n = e \cdot \frac{1}{2} \left[\frac{(e(k) - Ex_{ei})^2}{P_{ei}^2} + \frac{(ec(k) - Ex_{ecj})^2}{P_{ecj}^2} \right]$.

Step 4: Repeat steps 2~3 until n cloud drops are generated.

Step 5: Generate a normal random number $P_{\Delta dm}$ with expectation $En_{\Delta dm}$ and standard deviation $He_{\Delta dm}$, $P_{\Delta dm} = \text{NORM1}(En_{\Delta dm}, He_{\Delta dm})$.

Step 6: If $e(k) \leq Ex_{ei}$, $ec(k) \leq Ex_{ecj}$, then $\Delta d_n = Ex_{\Delta dm} - P_{\Delta dm} \times (-2\ln(\mu_n))^{0.5}$; elseif $e(k) > Ex_{ei}$, $ec(k) > Ex_{ecj}$, then $\Delta d_n = Ex_{\Delta dm} + P_{\Delta dm} \times (-2\ln(\mu_n))^{0.5}$;

elseif $e(k) \leq Ex_{ei}$, $ec(k) > Ex_{ecj}$, then $\mu' = e \cdot \frac{-(e(k) - Ex_{ei})^2}{2P_{ei}^2}$,

$\Delta d'_n = Ex_{\Delta dm} - P_{\Delta dm} \times (-2\ln(\mu'))^{0.5}$, $\mu'' = e \cdot \frac{-(ec(k) - Ex_{ecj})^2}{2P_{ecj}^2}$,
 $\Delta d''_n = Ex_{\Delta dm} + P_{\Delta dm} \times (-2\ln(\mu''))^{0.5}$, $\Delta d_n = (\Delta d'_n \mu' + \Delta d''_n \mu'') / (\mu' + \mu'')$;

elseif $e(k) > Ex_{ei}$, $ec(k) \leq Ex_{ecj}$, then $\mu' = e \cdot \frac{-(e(k) - Ex_{ei})^2}{2P_{ei}^2}$,

$\Delta d'_n = Ex_{\Delta dm} + P_{\Delta dm} \times (-2\ln(\mu'))^{0.5}$, $\mu'' = e \cdot \frac{-(ec(k) - Ex_{ecj})^2}{2P_{ecj}^2}$,
 $\Delta d''_n = Ex_{\Delta dm} - P_{\Delta dm} \times (-2\ln(\mu''))^{0.5}$, $\Delta d_n = (\Delta d'_n \mu' + \Delta d''_n \mu'') / (\mu' + \mu'')$.

Step 7: Repeat steps 5~6 until n cloud drops are generated.

Step 8: Calculate the mean value of $\Delta d_1, \dots, \Delta d_n$, $\Delta d(k) = \text{mean}(\Delta d_1, \dots, \Delta d_n)$.

Table 2. Rule base of two-dimensional cloud model

ΔD_m	1	2	3	4	5	6	7
$E_i \backslash EC_j$	1	2	3	4	5	6	7
1	1	1	1	1	2	3	4
2	1	1	1	2	3	4	5
3	1	1	2	3	4	5	6
4	1	2	3	4	5	6	7
5	2	3	4	5	6	7	7
6	3	4	5	6	7	7	7
7	4	5	6	7	7	7	7

Fig. 5. Two-dimensional hybrid cloud decision module

5. Simulation and Experiment

5.1 Converter and control parameters

In order to verify the control performance of the proposed control strategy, a simulation platform and an experiment platform of the Buck DC/DC converter are constructed, and both the simulation and experiment results are compared with that of the current-mode control. The converter parameters used are shown in Table 3.

In Fig. 6 is shown the structure block diagram of a common current-mode controlled Buck DC/DC converter. For PWM duty cycles greater than 50%, the current-mode control requires a slope compensation signal v_{ramp} to avoid sub-harmonic oscillation [19]. According to the parameters in Table 3 and related formulas in [19], the minimum compensation slope $m_{\text{cmin}}=3333.3$ can be calculated out. The control parameters are chosen as $m_c=3500$ for current-mode control and $k_p=0.8$, $T_i=0.002$ for PI control.

5.2 Random circuit parameters disturbance

In the process of the converter operation, the circuit parameters may change because of the disturbance and effect of uncertain factors such as noise and temperature. Here, the effect of random inductance parameters disturbance is mainly discussed, and the dynamic behavior of the converter during startup is investigated. In Fig. 8 is shown the simulation results under the effect of the disturbance signals shown in Fig. 7, and in Table 4 is summarized the evaluation parameters of control performance.

As can be seen in Table 4, the proposed control strategy not only improves the dynamic performances (both the

Table 3. Converter parameters

parameters	values	parameters	values
L/mH	1.5	$C/\mu\text{F}$	220
r_l/Ω	1	r_c/Ω	0.5
r_o/Ω	20	v_s/V	50
f_s/kHz	20	U_{ref}/V	30

Fig. 6. Structure block diagram of current-mode controlled Buck DC/DC converter

Fig. 7. Random inductance parameters disturbance signals

Table 4. Evaluation parameters of control performance

Control strategy	v_o , i_l adjusting time/ms	v_o overshoot/%	i_l max value /A
Cloud model control	5.5	0	2.6
Current-mode control	6	6.7	12.5

(a) Results obtained by the proposed control strategy

(b) Results obtained by the current-mode control

Fig. 8. Comparison of the results obtained by the proposed control strategy and current-mode control during startup

adjusting time and overshoot are relatively small), but also remarkably reduces the peak value of i_l compared with the current-mode control. Fig. 8(a-3) shows that the whole adjusting process of $\Delta d(k)$ is smooth. Therefore, the control strategy is suitable for dealing with the random parameters disturbance. Moreover, the advantage of using two-dimensional hybrid cloud model is obvious, that is, the step size of $\Delta d(k)$ is maximum when v_o is far from U_{ref} , and only when v_o is close to U_{ref} , will the step size of $\Delta d(k)$ reduce gradually. Therefore, the adjusting time can be decreased and the error adjusting range can be extended.

As can be seen from the waveform details during startup in the interval of 11~15 ms in Fig. 9, the random parameters disturbance has a great influence on the current-mode control so as to cause large deviations in v_o and i_l . The maximum voltage deviation reaches ± 0.5 V, while the fluctuation range of i_l is also as great as 0.6~2 A. By contrast, the proposed control strategy has strong anti-interference ability, and can make the maximum voltage

Fig. 9. Waveform details during startup

Fig. 10. Random load disturbance signal

Fig. 11. Comparison of the results obtained by the two control strategies under random load disturbance

deviation less than ± 0.2 V, and keeps i_l within 1.1~1.9 A.

5.3 Random load disturbance

In order to compare the performance of the two control strategies under random load disturbance, a random signal shown in Fig. 10 is taken as the load disturbance.

The simulation results of v_o and i_l under the random load disturbance are shown in Fig. 11. For current-mode control, it can be seen that the maximum voltage deviation reaches ± 0.3 V, and i_l has a big fluctuation. By contrast, the proposed control strategy not only keeps the voltage deviation within $-0.2 \sim 0.2$ V, but also makes i_l without obvious fluctuation. This shows that the control strategy is also suitable for dealing with the random load disturbance.

5.4 Experimental validation

To further investigate the potential advantages of the

(a) Waveforms obtained by the proposed control strategy

(b) Waveforms obtained by the current-mode control

Fig. 12. Comparison of the startup behavior

proposed control strategy, the experimental platform of the controller is constructed on an OP5600 RT-LAB real-time system, where OP5600 allows the development of the control software in a MATLAB/SIMULINK environment. Access to the input/output (I/O) of the real-time hardware is implemented through Real Time Workshop blocks. The Buck DC/DC converter is constructed by using an MOSFET (IRFP4468) as an active switch and a diode (10SQ80) as a passive switch. The startup behavior is obtained by a DC power analyzer N6705, and the load disturbance is realized by an electronic load N3306A. The control structure is shown in Fig. 2.

Fig. 12 shows the inductance current and the output voltage of the converter during startup. As can be seen, the proposed control strategy is more efficient than the current-mode control for improving the dynamic performances of the converter, that is, unnoticeable overshoot of v_o , smaller peak of i_l , and shorter adjusting time of both v_o and i_l .

Furthermore, the waveform details during steady-state operation in Fig. 13 show that the control strategy can effectively restrain the random fluctuation of v_o and i_l . This proves the effectiveness of the proposed strategy for dealing with the random disturbance, and through observation and analysis, it can be seen that the random fluctuation in the experiment mainly results from the DC power supply.

In a last step, the control performance is investigated in the presence of step change in the load resistance. Starting from the empty-load, a step change to the full-load is applied, and the careful observation of the response is made. The condition observed is shown in Fig. 14. It can be seen that when a large load disturbance occurs, for the proposed control strategy, v_o can be quickly regulated to the expected value without steady-state error, while for the current-mode control, longer adjusting time is needed and a

(a) Waveforms obtained by the proposed control strategy

(b) Waveforms obtained by current-mode control

Fig. 13. Waveform details during steady-state operation

(a) Waveforms obtained by the proposed control strategy

(b) Waveforms obtained by current-mode control

Fig. 14. Experiment waveforms with load disturbance

small steady-state error for v_o is appeared after the load disturbance.

6. Conclusion

For the control design of a converter, the mapping relationship between the input and output of the controller has uncertainty in the process of the converter operation, while cloud models are suitable for tackling this uncertainty relationship. Therefore, a control strategy for Buck DC/DC converter based on two-dimensional hybrid cloud model is proposed, which has the following properties: the control

structure is simple, and easy to realize by digital control. In the process of the control design, the most important part is the algorithm design of the two-dimensional hybrid cloud decision module (**Algorithm 1**) which is used to realize the reasoning structure of a control rule. In the view of the computational complexity, the algorithm mainly consists of some judging syntax and index calculations, and the complex calculations are not involved so that the real-time control can be guaranteed, and the algorithm design can be easily implemented. By contrast, in the process of the current-mode control design, an appropriate slope compensation signal is needed to avoid sub-harmonic oscillation when the PWM duty cycle is greater than 50%. Either the overcompensation signal or undercompensation signal may lead to the system instability. Therefore, there is no doubt that the calculation and generation of the slope compensation signal will make the control design and implementation more complicated. In addition, both the results obtained by simulation and experiment show that the current-mode control strategy is difficult to obtain the optimal dynamic performance, while the proposed control strategy can not only improve the dynamic performances of Buck DC/DC converter, but also has obvious advantages in dealing with the uncertain disturbance factors.

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Appendix

$\Delta D = [\Delta D_1, \Delta D_2, \dots, \Delta D_7]$, where $\Delta D_1 = (-0.008, 0.002, 0.0001)$; $\Delta D_2 = (-0.002, 0.0002, 0.00005)$; $\Delta D_3 = (-0.001, 0.0002, 0.00005)$; $\Delta D_4 = (0, 0.0001, 0.00002)$; $\Delta D_5 = (0.001, 0.0002, 0.00005)$; $\Delta D_6 = (0.002, 0.0002, 0.00005)$; $\Delta D_7 = (0.008, 0.002, 0.0001)$.

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