An Adaptive Current Mode Fuzzy Logic Controller for DC-to-DC Converters

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Abstract — **This paper introduces a new fuzzy logic controller (FLC) using inductor current feedback for significantly improving the dynamic performance of DC-to-DC converters. Inductor current plays an important role in high performance DC-to-DC converter control and FLC is suitable to deal with time-varying nonlinear nature of power converters. Based on the feedback of the inductor current, the new control method combines the merits of both the conventional FLC and current mode control. The dynamic performance of power converter system is improved. Furthermore, in order to enhance system robustness and adaptability, a new nonlinear configuration called extended state observer (ESO) is developed. By using ESO, the influence of load disturbances and parameter changes are precisely estimated and compensated without accurate knowledge of converter parameters. Simulation results have demonstrated that the proposed methods ensure good robustness and adaptability under modeling uncertainty and external disturbance, such as load current variation, supply voltage changes and converter parameter changes. It is concluded that the proposed topology produces substantial improvement of dynamic performances such as small overshoot, more damping and fast transient time under different operating conditions. In addition, small signal frequency response analysis demonstrates that by using the proposed FLC, the bandwidth and phase margin of the closed loop system have been significantly increased.**

Keywords – current mode; fuzzy logic controller; extended state observer; adaptive; robustness; digital control

I. INTRODUCTION

DC-to-DC converters have been predominately controlled by analog integrated circuit technology and linear system design techniques. In recent years, with the rapid development of advanced high-speed digital circuits, digital control will gradually replace the currently used analog controller in high frequency switching converters. Under this trend, the intelligent power supplies are expected to play an important role in communication, automobile, computer and aerospace industries in the near future. Among many available digital control methods, fuzzy logic controller (FLC) has emerged as one of the most active and promising control method in the power electronics due to its capability to compute very fast and with high precision. The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical modeling [1]. Fuzzy logic controller has been proven to be superior to the conventional PID controller in that it naturally provides the ability to deal with highly nonlinear, time-variant and ill-defined systems where the mathematical models are difficult to be obtained or the control variables are too hard to measure. Thus, it is well suited in resolving the time-varying nonlinear nature of switches in DC-to-DC converters [2,3]. Much research has been done to improve the global robustness of FLC to nonlinearities of power converter systems, such as parasitic elements, parameter variations, time-varying loads, and variable supply voltages.

Conventional FLC, which utilizes the output voltage error and the change of error as its inputs, has been widely used in the past few years, but its dynamic performance is not satisfactory. In order to further improve the dynamic characteristics of switching mode power converters including wide bandwidth, high rejection of input voltage variations and load transients, additional information on the energy stored in the converter such as inductor current can be used [4].

In this paper, a new current mode fuzzy logic control method is proposed and demonstrated. This new control law is based on the introduction of inductor current feedback into the inner control loop of converter system, where FLC serves as the outer control loop. The proposed topology combines the merits of both the conventional FLC and current mode control in digital implementation. Therefore, instantaneous correction actions against input voltage changes and load current variation are achieved. By carefully designing the gains and rule bases, the proposed FLC can quickly generate the appropriate command duty cycle in case of any large or small output voltage discrepancy. This methodology can be easily applied to many converter topologies such as Buck, Boost or Buck-Boost converters.

In order to guarantee the robustness to the load variation and parameter changes, a new nonlinear configuration called extended state observer (ESO) is developed for further improving the dynamic performance of the proposed FLC. The theory of ESO is inherently aimed at dealing with system uncertainties and unknown disturbance. Based on the concept of generalized derivative, extended state observer can realize the accurate estimation and compensation of external disturbances and parameter variations. Furthermore, the configuration of ESO is inherently independent of the system under control and its parameters. By using ESO, the proposed fuzzy logic controller has the advantage of good adaptability and robustness, which leads to very good steady state and dynamic performance even in presence of strong and fast variation of converter parameters and load disturbance.

Simulation is performed in Boost converter to verify the proposed fuzzy logic controllers. The results confirm that the proposed methods achieve much better robustness and adaptability in terms of load change, input voltage and output voltage variation. Better dynamic performance, such as small overshoot, more damping and fast transient time, has been achieved. In addition, small signal loop response analysis demonstrates that, by using the proposed FLC, the bandwidth and phase margin of the closed loop system have been significantly increased.

II. BASIC OPERATION PRINCIPLE OF THE PROPOSED FUZZY LOGIC CONTROLLER USING INDUCTOR CURRENT FEEDBACK

The inductor current plays a very important role in high performance DC-to-DC converter control. It can provide additional information on the energy stored in the converter. In this paper, the proposed fuzzy logic control using inductor current feedback is implemented with two control loops (shown in Fig. 1). The outer loop is the voltage loop, and the inner loop is the current loop. The output of voltage loop serves as the reference of the inductor current.

As shown in Fig. 1, Boost converter is used as an example, from the equivalent circuit model presented in [5], its average value model can be described as:

$$\frac{di_L}{dt} = -\frac{R_L}{L}\cdot i_L - \frac{1-d}{L}\cdot v_o + \frac{1}{L}v_{in} \tag{1}$$

$$\frac{dv_o}{dt} = \frac{1-d}{C}\cdot i_L - \frac{1}{C}\cdot\frac{v_o}{R_o} \tag{2}$$

where i_L, v_o, v_{in} are the inductor current, output voltage and supply voltage. d is the duty cycle, R_o is the load resistor and R_L is the winding resistor of the inductor.

Equation (2) can be rewritten as

$$i_L = \frac{C}{1-d}\frac{dv_o}{dt} + \frac{1}{1-d}\cdot\frac{v_o}{R_o} \tag{3}$$

It can be seen from (3) that the inductor current contains the information about the derivatives of the output voltage. By using the inductor current into FLC, the dynamic response of whole system could be significantly improved. This approach will allow substantial improvement of converter dynamic performances similarly to that obtained in analog current mode controlled converters.

The voltage control loop can be implemented by a Proportional-Differential (PD) like FLC combined with a digital integrator. The inputs of PD like FLC are defined as the error of output voltage $e_u(k)$ and the change of error $ce_u(k)$. Seven fuzzy levels are defined for e_u and ce_u. The input membership functions chosen for e_u and ce_u are triangular ones with 50% overlap. The membership functions of output variable i_{Lref_P} are 7-level triangular fuzzy-set values. The min-max method of inference engine is used. The defuzzify method used in this FLC is the Center of Area. The fuzzy control rules for the voltage loop are shown in Table I.

The output of the fuzzy logic controller i_{Lref_P} is the proportional part of reference current. Combined with the output of integrator i_{Lref_I}, it constitutes the reference current signal i_{Lref}, which can be represented as $i_{Lref} = i_{Lref\_P} + i_{Lref\_I}$. In fact, the fuzzy logic controller will play the role of a PD controller, which ensures very fast dynamic response. Digital integrator is added to cancel the steady state error and will act only around the reference value. Based on this algorithm, no steady error and fast large-signal dynamic response with small overshoot can be achieved with proper handling of the proportional and integral part.

In the inner control loop, the difference between the sensed inductor current i_L and the reference current signal i_{Lref} can be processed by a digital PID controller or another fuzzy logic

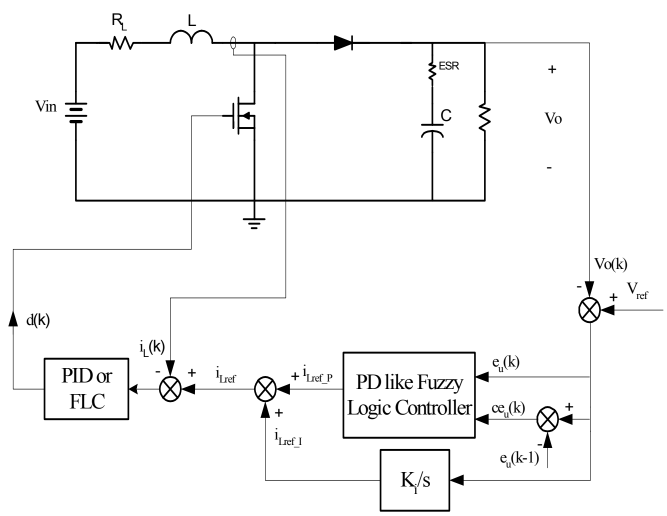

Figure 1. Block diagram of current mode fuzzy logic controller using i_L in the inner control loop

TABLE I. THE RULE BASE OF FLC IN TABULAR FORM

ce\e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

controller which will generate the duty cycle $d(k)$. Different from analog current mode control, the duty cycle d is directly calculated, so the comparator and artificial ramp are not needed any more. Therefore, the problems of susceptibility to noise and sub-harmonic oscillation for duty cycle greater than 0.5, which exist in the analog peak current control method, are eliminated inherently.

In addition, the inductor current is directly controlled by the inner control loop. Therefore, it has essentially no phase lag from control to inductor current and the pole related to the inductor is eliminated. This also helps to achieve feedback loop stabilization.

Fig. 2 shows the average equivalent circuit model of Boost converter. It can be seen from the model that the output voltage is fed by a current, which can be represented as $i_L - d \cdot i_L = (1-d)i_L$. If i_L is directly controlled, then $(1-d)i_L$ can be considered approximately as a current source [5]. Therefore, the whole circuit behaves as if the output capacitor C and load resistor R_o were fed by a current source $(1-d)i_L$. In small signal control-to-output transfer function, the pole of the system is mainly associated with R_o and C as if the inductor L were not there. It contains one less pole than the conventional FLC without current feedback. This configuration simplifies the mathematical model and makes the system easier to control and consequently, the dynamic performance will be improved.

The proposed FLC method using inductor current feedback has significant advantages. First, because the change in the inductor current is sensed earlier than the change in the output voltage, the proposed control algorithm achieves instantaneous correction action against line voltage changes without having to wait for the sensed output voltage change to pass through the relatively long delay in a conventional FLC (without current feedback). Therefore, the reaction of control system will begin earlier and be faster than the case when only the output voltage is sensed. Second, the proposed FLC scheme using inductor current feedback improves load transient response. By the feedforward characteristic inherent in the current feedback, the proposed control algorithm has better dynamic performance on load current regulation.

III. Introduction of Basic Principle of Extended State Observer

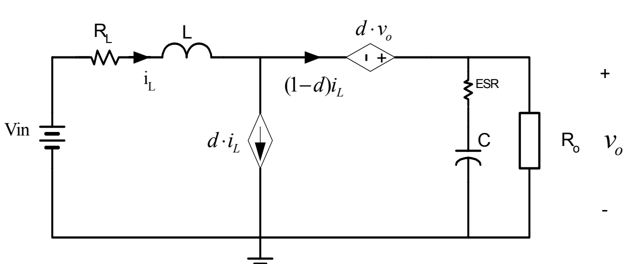

Figure 2. Average circuit model of Boost converter

In conventional digital control method, PID regulator or FLC are used to control the output voltage. The derivatives of the signals are very helpful to achieve control objectives, such as reduced response time and reduced overshoot during transient states. Unfortunately, the derivatives of signals are difficult to retrieve because of noise. Furthermore, due to nonlinearities and uncertainties existing in the controlled system, it is difficult for conventional PID or fuzzy controller to achieve good static and dynamic performance in different operating situations. As a consequence of these phenomena, a degradation of system performance occurs [6].

To overcome these problems, a great deal of research has been made into alternative control techniques. In recent years, adaptive methods and predictive control demonstrate many advantages in the improvement of the robustness and dynamic performance of control systems. However, many of them are very complicated and require some knowledge of model parameters and estimation of model states. Therefore, they have much computational intensity in the real-time implementation.

In this paper, extended state observer is introduced to achieve high dynamic performance in the overall operating range. ESO is a nonlinear configuration to observe the states and disturbances of the system under control without knowing of the exact system parameters. Given an example, for an uncertain N^{th} order nonlinear system

$$x^{(n)} = f(x, \dot{x}, \cdots, x^{(n-1)}, t) + w(t) + m \cdot u(t) \tag{4}$$

where $f(t)$ represents uncertain system function, $w(t)$ is an unknown disturbance, u(t) is the control law, $x(t)$ is the measurable state variable, m is the output gain. Its state space equation can be written as [7]:

$$\begin{cases} \dot{x}_1 = x_2 \\ \vdots \\ \dot{x}_{n-1} = x_n \\ \dot{x}_n = f(x, \dot{x}, \cdots, x^{(n-1)}, t) + w(t) + m \cdot u \\ \dot{x}_{n+1} = b(t) \end{cases} \tag{5}$$

where $x_1 = x$ and $b(t)$ is the variation rate of system uncertainty $x_{n+1}(t)$.

Unlike full order (N^{th} order) state observer, ESO utilizes $(N+1)^{th}$ order (full order plus 1) state observation to achieve state and disturbance estimation (shown as follows):

$$\begin{cases} \dot{z}_1 = z_2 - g_1(z_1 - x_1(t)) \\ \vdots \\ \vdots \\ \dot{z}_n = z_{n+1} - g_n(z_1 - x_1(t)) + m \cdot u \\ \dot{z}_{n+1} = -g_{n+1}(z_1 - x_1(t)) \end{cases} \tag{6}$$

$$g_i(\varepsilon) = \begin{cases} \beta_i \cdot |\varepsilon|^{\frac{1}{2}} \operatorname{sgn}(\varepsilon), & |\varepsilon| > \delta \\ \beta_i \cdot \varepsilon / \delta^{\frac{1}{2}}, & |\varepsilon| \le \delta \end{cases} \qquad \mathrm{i} = 1, \cdots, \mathrm{n}+1$$

where $\varepsilon = z_1 - x_1$, and β_i, δ are variable parameters of ESO.

It is noted that the derivative signals are often difficult to achieve because of noises. But in ESO, lower order derivative is obtained by integrating the higher order derivatives. Differential operation is not needed anymore. Therefore, the generalized derivatives of given signals can be achieved in high accuracy. This is the first advantage of ESO.

Second, in ESO, the signal of $(N+1)^{th}$ state variable $z_{n+1}(t)$ reveals the information about external disturbances and plant uncertainties imposed on the system under control. Based on this information, compensation and elimination of disturbances and model uncertainties can be realized. Therefore, the robustness of the whole system is guaranteed.

Subtracting (6) from (5), the dynamic error equation is defined as

$$\begin{cases} \delta\dot{x}_1 = \delta x_2 - g_1(\delta x_1) \\ \vdots \\ \delta\dot{x}_n = \delta x_{n+1} - g_n(\delta x_1) \\ \delta\dot{x}_{n+1} = -b(t) - g_{n+1}(\delta x_1) \end{cases} \tag{7}$$

For any boundary $b(t)$, when the nonlinear functions $g_i(z)$ and their related parameters are properly selected to constrain the function of uncertainties and disturbances, the system (7) is ensured asymptotic stable. Under this condition, the state variables $z_i(t)$ $i = 1, \cdots, n$ of ESO will converge to the observed state variables $x(t)$ and its derivatives $\dot{x}, \cdots, x^{(n-1)}$ quickly. Furthermore, the overall effect of the external and internal disturbances imposed on the system can be observed by $(N+1)^{th}$ state of ESO $z_{n+1}(t)$ successfully, even though $f(t)$ and $w(t)$ may be still unknown. This is very important in the realization of model and disturbance compensation. From (6), (7), it is shown that the architecture of ESO is not determined by the actual expression of system under control, but only affected by the range of its variation rate. Therefore, this observer has very good robustness and adaptability. With the help of modeling uncertainty and disturbance estimation $z_{n+1}(t)$, online compensation is made by $\Delta u(t) = -z_{n+1}(t)/m$. The desired behaviors of the control system such as tracking, regulation and stability are achieved.

For the control of Boost converter, in order to improve the dynamic performance and robustness under load current disturbance and parameter changes, ESO is used in the voltage control loop (shown in Fig. 3). The inputs of ESO are the sensed inductor current, output voltage and the duty cycle calculated in the previous sampling period. The output of ESO is the dynamic compensation of the system uncertainty and disturbance $\Delta i_L(k)$.

Considering load current disturbance Δi_o and parameter changes (capacitor is changed from C to C'), The state equation (2) of Boost converter can be rewritten as follows:

$$\frac{dv_o}{dt} = \frac{1-d}{C'} \cdot i_L - \frac{1}{C'} \cdot \left(\frac{v_o}{R_o} + \Delta i_o\right) \tag{8}$$

Here, it is assumed that the derivative of output voltage exists and is continuous. Equation (8) can be rewritten as:

$$\frac{dv_o}{dt} = \frac{1-d}{C} \cdot i_L - \frac{1}{C} \cdot \frac{v_o}{R_o} + w_1(t) \tag{9}$$

where $w_1(t) = \left(\frac{1-d}{C'} - \frac{1-d}{C}\right) \cdot i_L - \left(\frac{1}{C'} - \frac{1}{C}\right)\frac{v_o}{R_o} - \frac{1}{C'}\Delta i_o$.

Based on (9), the external load change and internal parameter variation are all treated as disturbances $w_1(t)$ imposed on the Boost converter system. To estimate and compensate for the system uncertainties, a 2nd order ESO for the voltage control loop is used,

$$\begin{cases} \dot{z}_1 = z_2 - g_1(z_1 - v_o) - \frac{1}{C} \cdot \frac{v_o}{R_o} + \frac{1-d}{C} i_L \\ \dot{z}_2 = -g_2(z_1 - v_o) \end{cases} \tag{10}$$

$$\Delta i_L(t) = -z_2(t)/(1-d) * C \tag{11}$$

where

$$g_i(\varepsilon) = \begin{cases} \beta_i \cdot |\varepsilon|^{\frac{1}{2}} \operatorname{sgn}(\varepsilon), & |\varepsilon| > \delta \\ \beta_i \cdot \varepsilon / \delta^{\frac{1}{2}}, & |\varepsilon| \le \delta \end{cases}, \quad i = 1,2, \quad \varepsilon = z_1 - v_o,$$

and β_i, δ are variable parameters of ESO.

Because the variation range of output voltage, load and parameter change is finite, by properly selecting the functions g_1, g_2 and related parameters, the overall impact of external and internal disturbances $w_1(t)$ imposed on the power converter system can be observed by the second state of ESO $z_2(t)$. Online compensation is made by $\Delta i_L(t) = -z_2(t)/(1-d)*C$. It will greatly enhance the robustness of the control system against the system uncertainties and load disturbances. Furthermore, all these functions and parameters of ESO are all independent of Boost converter under control. Therefore, the performance of extended state observer does not depend on

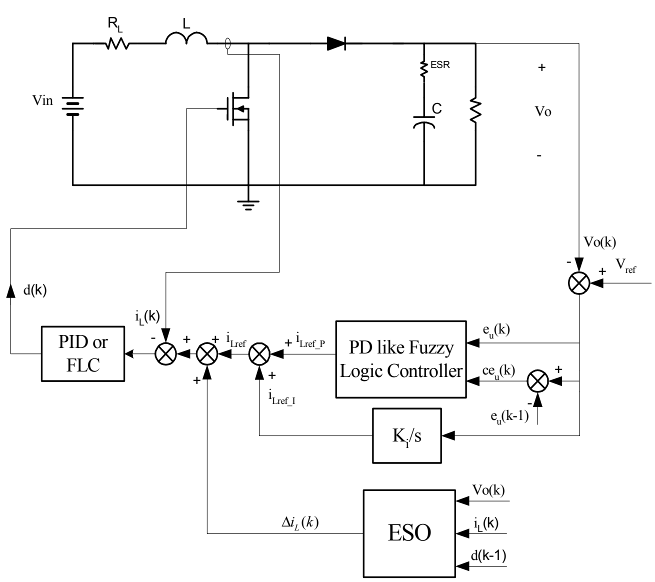

Figure 3. Block diagram of current mode fuzzy logic controller using i_L in the inner control loop combined with ESO

the accurate mathematical model of Boost converters. It has very good robustness and adaptability to parameter variation and load disturbance. This is the chief advantage of this configuration. It can be seen from (10) and (11) that, the calculation of ESO is composed of a division, a square root and several addition and multiplication. Therefore, it is easy to realized in hardware implementation.

IV. RESULTS

In order to verify the proposed fuzzy logic controllers, simulation by using Matlab and Simulink is performed to Boost converter. The dynamic performance of three types of FLC, (1) conventional FLC (without current feedback), (2) FLC using inductor current feedback without ESO, (3) FLC using inductor current feedback combined with ESO, are compared under the same operating condition. The design criterion for these 3 controllers is that the phase margins (PM) of all these controlled system are kept large enough (at least 43-45 degree).

The parameters of Boost converter are listed as follows.

Input voltage Vin: 24V Output voltage Vo: 48V

Rated load resistor R_o=19.2Ω L = 24 uH

C = 220 uF ESR = 0.03Ω R_L=0.04Ω

where ESR is the equivalent series resistor of the output capacitor and R_L is the winding resistor of the inductor.

All of the controller parameters are regulated at rated operating condition ($V_{in} = 24V$, I_{load}=2.5A , $L = 24uH$, $C = 220uF$) and then kept unchanged.

At first, the small signal loop response is done to compare the bandwidth and phase margin. Fig. 4 shows the circuit diagram to simulate the small signal loop response. A small ac sinusoidal signal source $v_{ac} = V_m \sin(2\pi f_1 t)$ is added to introduce disturbance into the voltage feedback loop. The amplitude V_m is 0.1 V, which should be much smaller than the steady state value of the output voltage, and the signal frequency f_1 can be varied. The frequency component $V_o(f_1)$ of output voltage at frequency f_1 can be calculated by FFT analysis. The loop response (LR) at frequency f_1 is calculated by $LR = \frac{V_o(f_1)}{V_o(f_1) - v_{ac}}$. The gain is $Amp = |LR|$ and phase delay is $\theta = \angle LR$. While frequency f_1 is varied, the frequency analysis is obtained. In addition, similar frequency analysis system can also be applied to the conventional FLC.

Fig. 5 shows the frequency response of three controllers. It can be observed from the figure that by using the proposed FLC method, the bandwidth (BW) and phase margin (PM) of the closed loop system have been significantly increased. It is shown that the bandwidth for the system using the conventional FLC is about 5KHz, with a phase margin of 46 degree. For FLC using inductor current feedback in the inner control loop, the BW is increased to 10KHz, with the phase margin of 81 degree. If ESO is added to the proposed FLC, the BW is increased to 14KHz, with the phase margin of 46 degree. The proposed algorithm has better dynamic performance than the conventional FLC, and an earlier feedback action is achieved. Therefore, by using the proposed FLC and ESO, the frequency response has been significantly improved in Boost converter.

Considering the dynamic performance, the proposed algorithms are verified under large variation of input voltage (from 24V to 36V), and load current (from 1.25A to 2.5A) in Boost converters (as shown in Fig. 6-7).

By using inductor current feedback in the FLC, the overshoot due to input voltage change is decreased to almost 42% compared with the conventional FLC. The damping is also significantly improved and the recovery time is reduced. By using ESO in the proposed FLC, the changes in the output voltage and system states are sensed and compensated, which helps to speed up the dynamic response. Therefore, the recovery time is further reduced (shown in Fig. 6).

When the load current changes, by using inductor current feedback, the overshoot due to load change is decreased to 50% compared with conventional FLC. By adding ESO, which is aimed at dealing with external and internal disturbance, the load change are estimated and compensated instantaneously. The overshoot is further decreased to 23% compared with the conventional FLC, and the recovery time is greatly reduced (shown in Fig. 7).

In order to evaluate the dynamic performance of the system under wide operating range, the conventional FLC and proposed FLC with ESO are applied to regulate Boost converter under different input voltage without changing controller parameters (shown in Fig. 8-9). First, simulations on output reference voltage changes (from 48V to 54V) at rated input voltage (Vin=24V) and rated load resistor (R_o=19.2Ω) are performed (shown in Fig. 8). The frequency analysis in Fig. 5 shows that, by using proposed FLC with ESO, the bandwidth is enlarged. Therefore, the system response is faster than that of the conventional FLC. The same conclusion can be derived from Fig. 8. It is shown that no overshoot is achieved in the proposed FLC system and its dynamic response is faster than that of the conventional FLC algorithm.

Fig. 9 shows the simulation results of the output voltage change when the input voltage is increased to 36V. It is shown that the dynamic performance of the conventional FLC at Vin=36V deteriorates significantly. Some oscillation emerges during the output voltage change. This is because when the input voltage changes, the duty cycle d is also changed. Therefore, the parameters of the average model of Boost converter (shown in Fig. 2) are changed consequently. This would change the poles and zeros of the whole system. The conventional FLC cannot cope with this operating condition very well. But the proposed algorithm can still maintain good dynamic performance in spite of input voltage change.

In order to verify the robustness of the proposed algorithm, different values of the inductor and capacitor values are used in the simulation (shown in Fig. 10-11). As it is mentioned in section II, by using the inductor current feedback, the influence of inductor value changes on output voltage has been greatly eliminated. By using ESO, the changes in capacitor value has been observed and compensated immediately. Therefore, the system robustness to the capacitor value has been greatly improved. Comparing Fig. 8, 10 and 11, it can be seen that, the Boost converter system using the proposed FLC with ESO is less sensitive to the parameter changes than that using the conventional FLC. It could also maintain better dynamic performance, such as low overshoot, fast response time than that of the conventional FLC under different inductor and capacitor values.

From these results, it can be noted that proposed FLC with ESO can achieve good robustness and adaptability to external and internal disturbances.

V. CONCLUSIONS

In this paper, a new fuzzy logic controller with inductor current feedback for DC-to-DC converters is proposed and demonstrated. With the feedback of inductor current, the proposed scheme combines the advantages of both the conventional FLC and current mode control. The dynamic performance of power converter system is significantly improved. In addition, with the help of ESO, online estimation and compensation of load variation and parameter changes are achieved. The robustness of control system has been greatly enhanced. Comparisons are made in details between the proposed methods and the conventional FLC. Simulation results show that the proposed control methods produce much better dynamic performance and adaptability than the conventional FLC in terms of input voltage changes, load current variation and output reference changes. The proposed FLC is robust against the modeling uncertainty and the external disturbance in various operating conditions. The bandwidth and phase margin of the closed loop system have been significantly increased. All these benefits open new perspectives on utilization of intelligent control on DC-to-DC converters, and indicate that such schemes can be an attractive alternative to the classic controller in power converter applications where high dynamic performance is preferred.

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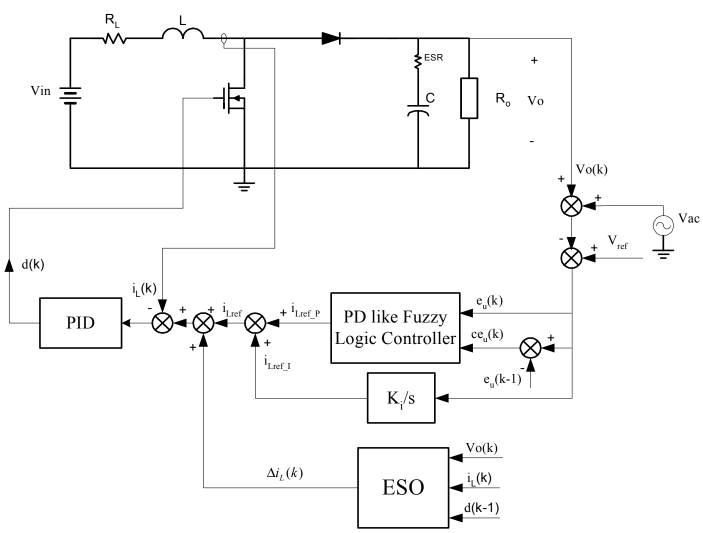

Figure 4. Block diagram of frequency analysis circuit to simulate the small signal loop response

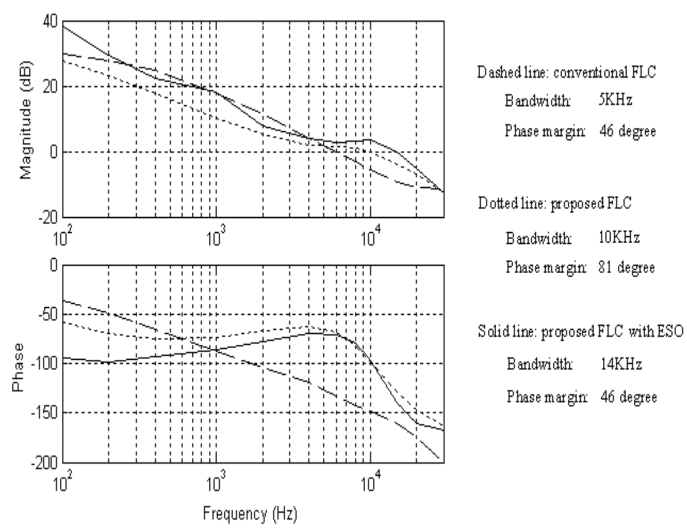

Figure 5. Frequency analysis of fuzzy logic controllers

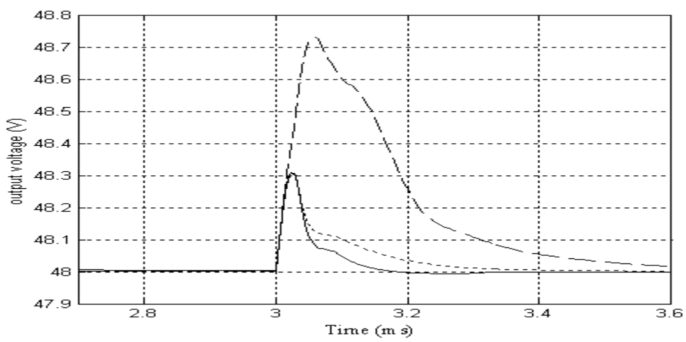

Figure 6. Output voltage response to input voltage change from 24 to 36V

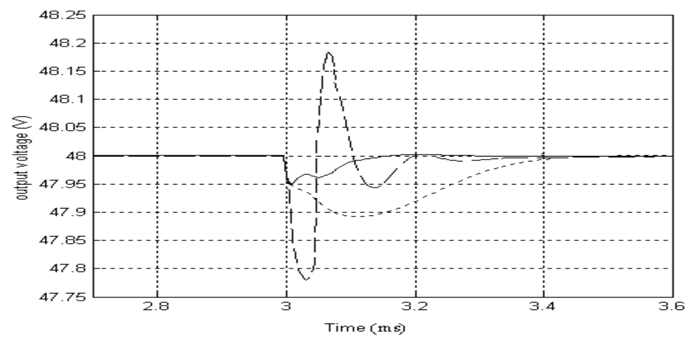

Figure 7. Output voltage response to load current change from 1.25A to 2.5A

(Figure 6-7: Dashed line: conventional FLC, Dotted line: the proposed FLC, Solid line: the proposed FLC with ESO)

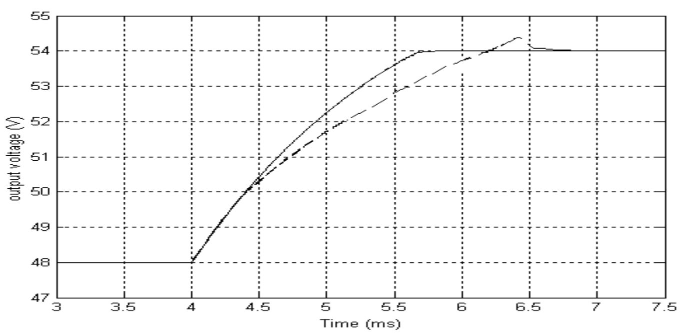

Figure 8. Output voltage changes from 48V to 54V when Vin=24V

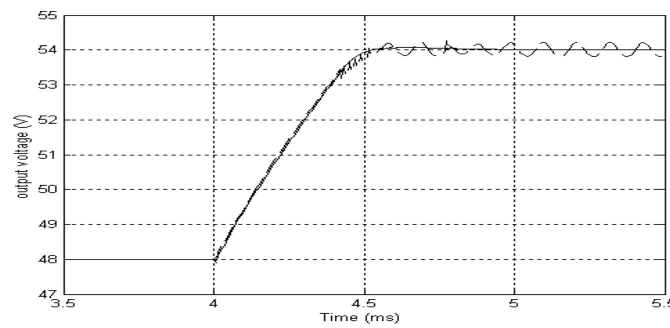

Figure 9. Output voltage changes from 48V to 54V when Vin=36V

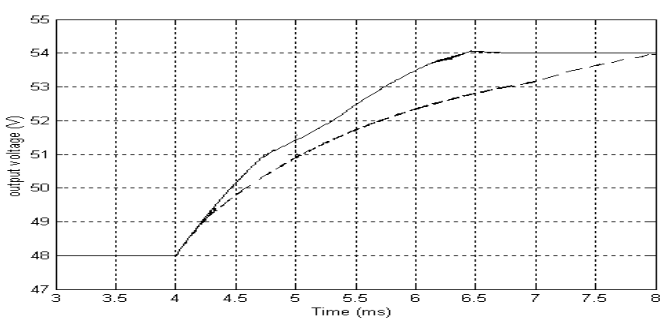

Figure 10. Output voltage changes from 48V to 54V when inductor L is changed to 19.2uH (original value: 24uH)

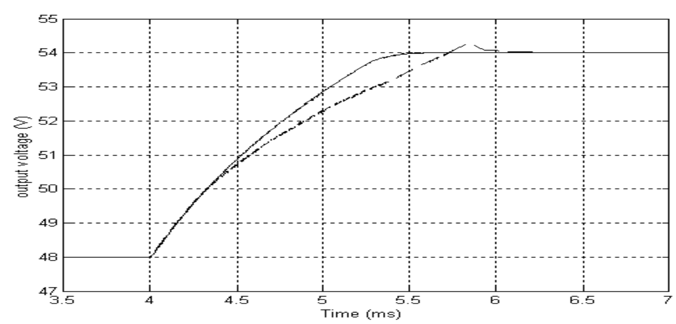

Figure 11. Output voltage changes from 48V to 54V when capacitor C is changed to 176uF (original value: 220uF)

(Figure 8-11: Dashed line: conventional FLC, Solid line: proposed FLC with ESO)