A New Adaptive Fuzzy Logic Control Method for DC-to-DC Converter

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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 a very 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. Furthermore, extended state observer (ESO) has been developed to ensure high dynamic performance of DC-to-DC converters. By using ESO, the influence of load disturbances and parameter changes are accurately estimated and compensated. The simulation results show that the proposed FLC with ESO ensures very good robustness and adaptability under modeling uncertainty and external disturbance, such as load current variation, supply voltage changes and converter parameter changes. 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.

I. INTRODUCTION

With the rapid development of advanced high-speed digital circuits, the application of modern control theories in real time control of DC-to-DC converters becomes more and more practical. The intelligent power supplies will play an important role in communication, automobile, computer and aerospace industries. Among many available control techniques, fuzzy logic controller (FLC) has emerged as one of the most potential and promising control areas in the power electronics. 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]. It has the advantage over 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. 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 parameter variations, time-varying loads, and variable supply voltages.

Conventional fuzzy logic controller, which utilizes the output voltage and the change of voltage as its input, has been widely used in the past few years, but its dynamic performance is not good enough. In order to improve the performance including tight output voltage regulation, high rejection of input voltage variations and load transients, a new fuzzy logic control method applied to the dynamic control of DC-to-DC converters is presented in this paper. The new control law is based on the introduction of inductor current feedback into FLC, which combines the merits of both the conventional FLC and current mode control. 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. The proposed methodology can be easily applied to many converter topologies such as Buck, Boost or Buck-Boost converters.

In addition, in order to eliminate the influence of load variation and parameter changes, a new configuration called extended state observer (ESO) is developed for improving dynamic performance of DC-to-DC converters. Based on the concept of generalized derivative, extended state observer can realize the accurate estimation and compensation of external disturbances and parameter variations. Furthermore, this configuration is inherently independent of the controlled system model and its parameters. By using ESO, the proposed fuzzy logic controller has the advantage of good adaptability and robustness, which leads to very good static 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 ensure much better robustness and dynamic performance in terms of load change, input voltage and output voltage variation. 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.

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 [4]. In this paper, a new method of introducing inductor current into fuzzy logic control 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

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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:

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

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

where i_L , v_o, v_{in} are the inductor current, output DC voltage and supply DC 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

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

It can be seen from (3) that the inductor current contains some information about the derivatives of the output voltage. By using 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-controlled converters.

The voltage control loop (outer loop) is realized by a Proportional-Differential (PD) like FLC combined with a digital integrator. The inputs of 2-input PD like fuzzy logic controller are defined as the error of output voltage $e_u(k)$ and the change of output voltage $ce_u(k)$. 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 output variable of the fuzzy 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 controller will play the role of a PD controller, which ensures a very fast 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. [4].

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 PID controller which will generate the duty cycle d . 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 analog peak current control method, are eliminated inherently.

In addition, in this method, inductor current is directly controlled by the inner control loop. Therefore, it has essentially no phase lag from control to inductor current. This also helps to achieve feedback-loop stabilization.

Fig. 2 shows the average equivalent circuit model of Boost converter [5]. 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. Therefore, the whole circuit behaves as if the output capacitor C and load resistor R_o were fed by a current source

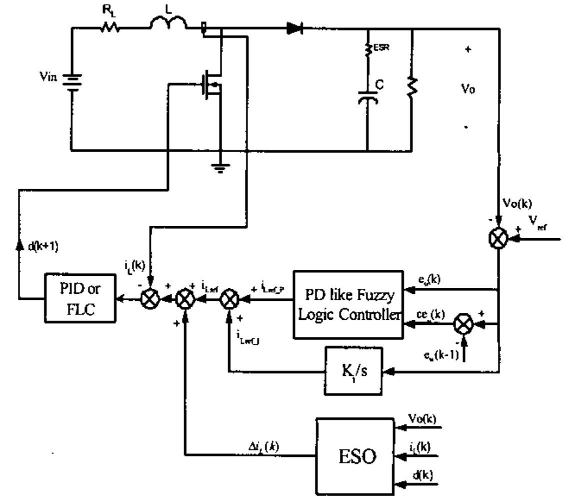

Fig. 1 Block diagram of current feedback fuzzy logic controller using i_L in the inner control loop

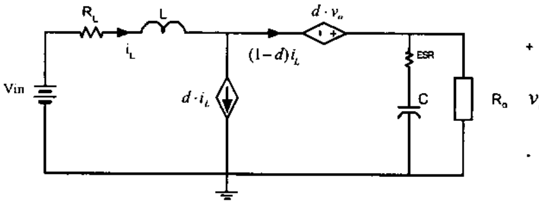

Fig. 2 Average circuit model of Boost converter

$(1-d)i_L$. 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 that uses inductor current feedback has significant advantages. First, the proposed control algorithm achieves instantaneous correction action against line voltage changes without having to wait for a sensed output voltage change to pass through the relatively long delay in a conventional FLC (without current feedback).

Second, the proposed FLC schemes using inductor current feedback improves load transient response. By the feedforward characteristic inherent in current feedback, the proposed control algorithm has better dynamic performance on load current regulation.

III. BASIC PRINCIPLE OF EXTENDED STATE OBSERVER

As we know, in conventional controller, the derivatives of the signals are very helpful to achieve control objectives, such as reduced response time and reduced overshoot during transient conditions. 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.

To overcome these problems, a great deal of research has been made into alternative control techniques. In recent years, adaptive methods and predictive control appeal much more promising 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.

Extended state observer (ESO) is a simple nonlinear configuration to observe the states and disturbances of the system under control without knowing of the exact parameters of the system [6]. Given an example, for an uncertain N^{th} order nonlinear system

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

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, c is the output gain. Its state space equation can be written as [7]:

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

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).

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

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

where $\varepsilon = z_1 - v_o$, 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 controlled system.

When the nonlinear functions $g_i(z)$ and their related parameters are properly selected, 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. In addition, 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. 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 $\Delta u(t) = -z_{n+1}(t)/c$. 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. 1). The input of ESO is the sensed inductor current, output voltage and the calculated duty cycle. The output of ESO is the dynamic compensation of the system uncertainty and disturbance $\Delta i_L(t)$.

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:

$$\frac{dv_o}{dt} = \frac{1-d}{C'} \cdot i_L - \frac{1}{C'} \cdot \left(\frac{v_o}{R_o} + \Delta i_o\right) \tag{7}$$

Equation (7) can be rewritten as:

$$\frac{dv_o}{dt} = \frac{1-d}{C} \cdot i_L - \frac{1}{C} \cdot \frac{v_o}{R_o} + w_1(t) \tag{8}$$

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 (8), 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,

$$\begin{cases} \dot{z}_1 = z_2 - g_1(z_1 - v_o) - \frac{1}{C} \cdot \frac{v_o}{R_o} + \frac{1-d}{C} i_L \\ \dot{z}_2 = -g_2(z_1 - v_o) \end{cases} \tag{9}$$

Because the variation range of 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 2nd 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 ESO does not depend on 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.

IV. RESULTS

In order to verify the proposed fuzzy logic controllers, computer simulation using simulink (Matlab) 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 in the inner control loop without ESO, (3) FLC using inductor current feedback in the inner control loop 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 V_{in}: 24V Output voltage V_o: 48V

Rated load resistor R_o=19.2Ω L = 24 uH

C = 220 uF ESR = 0.03 Ω 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.

At first, the small signal loop response is done to compare the bandwidth and phase margin. Fig. 3 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. 4 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 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. 5-6).

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 adding ESO into 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. 5).

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. 6).

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 working conditions without changing controller parameters. 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. 7). The frequency analysis in Fig. 4 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. 7. 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. 8 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 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 are changed consequently (shown in Fig. 2). This would change the poles and zeros of the whole system. The conventional FLC with original controller parameters can not cope with this operating condition very well. But the proposed FLC with ESO can still maintain good output voltage regulation in spite of input voltage change. It is demonstrated that the proposed method can achieve good dynamic performance over wider input voltage range.

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. 9-10). Comparing Fig. 7, 9 and 10, 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 applied to DC-to-DC converters has been developed and demonstrated. With the feedback of inductor current, the proposed scheme combines the advantages of both the conventional FLC and current mode control. In addition, with the help of ESO, online estimation and compensation of load variation and parameter changes are achieved. The dynamic performance of power converter system is significantly improved. Comparisons are made in details between the proposed methods and the conventional FLC. The simulation results show that the proposed control algorithms produce much better dynamic performance and adaptability than the conventional FLC in terms of input voltage changes, load current variation and output reference voltage changes. The proposed control system is robust against the modeling uncertainty and the external disturbance in various operating conditions. In addition, the bandwidth and phase margin of the closed loop system have been significantly increased. It indicates that such schemes can be attractive alternatives to the classic controller in DC-to-DC converters. All these benefits open new perspectives on utilization of intelligent control on power converters, and indicate that such scheme can be applicable to power converter application where high dynamic performance is preferred.

VI. REFERENCES

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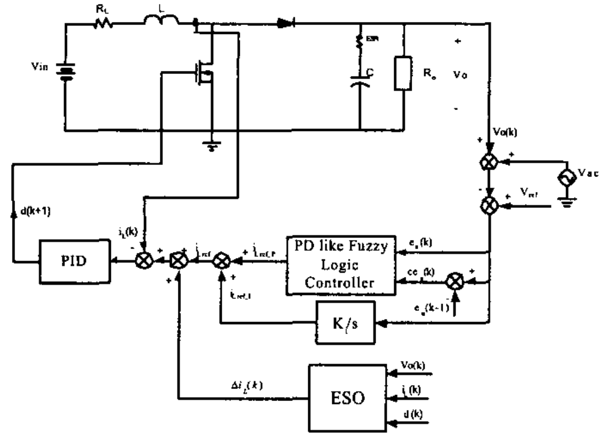


Fig. 3 Block diagram of frequency analysis circuit to simulate the small signal loop response

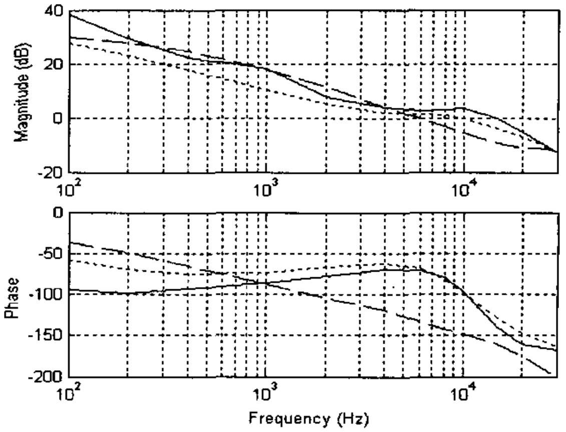


Fig. 4 Frequency analysis of fuzzy logic controllers (Dashed line: conventional FLC, Dotted line: proposed FLC, Solid line: proposed FLC with ESO)

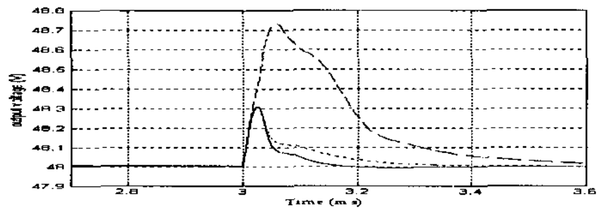


Fig. 5 Output voltage response to input voltage change from 24 to 36V

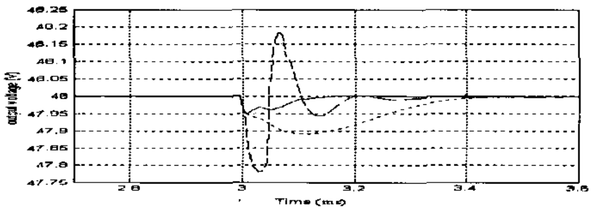


Fig. 6 Output voltage response to load current change from 1.25A to 2.5A

(Fig. 5-6: Dashed line: conventional FLC, Dotted line: the proposed FLC, Solid line: the proposed FLC with ESO)

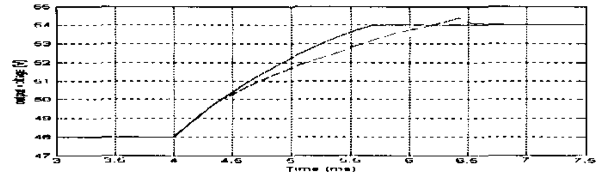


Fig. 7 Output voltage changes from 48V to 54V when Vin=24V

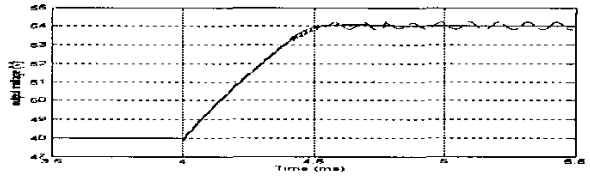
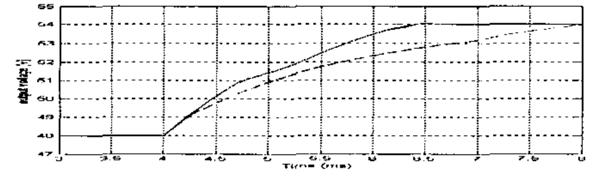


Fig. 8 Output voltage changes from 48V to 54V when Vin=36V



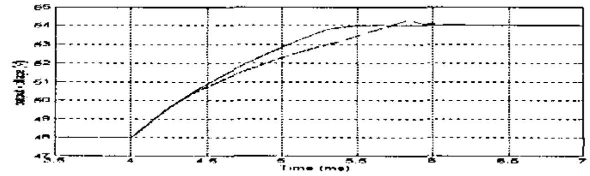


Fig. 9 Output voltage changes from 48V to 54V when inductor L is changed to 19.2uH (original value: 24uH)

Fig. 10 Output voltage changes from 48V to 54V when capacitor C is changed to 176uF (original value: 220uF)

Fig. 7-10: Dashed line: conventional FLC, Solid line: proposed FLC with ESO)