Redused Rules Fuzzy Logic Based Control of Boost DC/DC Converter

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Abstract

This paper proposes a boost DC/DC converter control in which the fuzzy logic has been implemented with reduced number of rules. The reduction of rules has been done through the elimination of those belong to the far from the set point area and directly feeding the membership values of the corresponding fuzzy labels into the defuzzification stage.

The proposed controller generates a duty ratio control signal through the addition of weighted part of the input voltage and of the low pass filtered signal of the inductor current to that of the fuzzy which has been fed by voltage error signal and a one represents the differences of the output voltage from its low pass filtered version.

The simulation results proved that this controller has added significant improvements to the dynamic performances of the well known PI like fuzzy controller which uses the output voltage error and its rate of change as an inputs.

The controlled boost DC/DC converter exhibited excellent performances under small and large disturbances of the input voltage and output load resistance and also showed good reference tracking ability.

الخلاصة

يقترح هذا البحث مسيطر لمحول تيار مستمر من النوع الرافع يعتمد منطقا مضببا بعدد مخفض من قواعد التحكم . تم تخفيض القواعد من خلال الغاء القواعد التي تحكم حالة الفرق الكبير واستبدالها بالتغذية المباشرة لقيم انتماء اللافتات الخاصة بهذه المناطق الى مرحلة التحويل من قيم مضببة الى قيم حدية.

يولد المسيطر المقترح اشارة تحكم من خلال اضافة جزء من فولتية المصدر وجزء من تيار المحاثة بعد ترشيحه الى اخراج المسيطر المضبب بعد تغذيته باشارة خطأ الفولتية و اشاره تمثل الفرق ما بين فولتية المحول و صورتها بعد عرضها على مرشح ترددات واطئة.

برهنت نتائج المحاكات على ان المسيطر المقترح يضيف كثير الى الاداء الحركي للمسيطر المضبب المشابه لمسيطرمن نوع PI والذي تكون ادخالاته متمثلة بفولتية الخطأ ومعدل الخطأ.

ابدى محول التيار المستمر(المسيطر عليه بالمسيطر المقترح) اداء عال تحت ضروف تغيرات كبيرة و صغيرة في كل من فولتية المصدر و مقاومة الحمل اضافة الى سرعة استجابة لمتطلبات مرجع الاخراج.

Introduction

It is well known that DC/DC converters are widely used in a variety of industrial and commercial environments. For example, they are used to drive dc motors, power personal computer, and power telecommunication equipments. In fact these applications need some form of energy flow control between two DC systems.

Definitely, these applications ask DC/DC converters to achieve one of the following functions:

1. Map unregulated DC input voltage into highly regulated one.
2. Change an input DC voltage level into another output DC voltage level (as example: boost converter can step up 28V input voltage into 50V output voltage).
3. Maintain constant output voltage irrespective of load resistance variations.
4. Follows a given reference pattern.

Inherent Nonlinear Nature of Boost DC/DC Converters

Boost DC/DC converter forms one of the important circuits within the family of DC/DC converters. It is intended to mimic step up ac transformer but in the DC domain. Structurally as shown in Fig.(1), it consists of linear elements represented by the resistor, inductor, capacitor, and nonlinear ones represented by the switching transistor and diode.

The cyclic and complementary switching of these nonlinear elements under the control of pulse width modulation, give rise to cyclic switching of circuit topologies (Fig.(2)) which intern leads to nonlinear dynamics[1]. This inherent nonlinearity restricts the validity of the driving controller based on small signal linearized models[2] and recommends the adopting of nonlinear approaches.

Fuzzy Logic Control Techniques in Boost Converter Environment

Fuzzy logic controller has been developed from the fuzzy set theory introduced by Lotfi Zadae. This set theory has the ability of processing nonlinear systems a situation which gained the fuzzy controller a nonlinear regulating ability.

Briefly, fuzzy controller is a nonlinear regulating system capable of coping with time varying nonlinear problems such that introduced by the boost converter cyclic topologies.

The fuzzy controller does not require an accurate mathematical model[3]. It is based on expert knowledge that convert human linguistic concept into an automatic control strategy [4]. Its performance depends on the proper choice of its membership functions and control rule set. Functionally, it consists of the following processing units (Fig.(3)):

a. **Fuzzification stage:**

This stage maps the actual measured values into membership function or functions. For each fuzzy variable, there is a set of membership functions which do the mapping for the related actual input. The most popular type of these functions are the triangular_ shaped and trapezoidal_ shaped functions.

b. **Inference process:**

Here, the list of rules that represents the control actions of the fuzzy controller are evaluated. It is the decision making stage. It is the expert in the loop.

c. **Defuzzification process:**

Defuzzification process forms the final stage in the fuzzy controller and its function is to transform the fuzzy output of the inference stage into a crisp control action. The transformation can be done by a number of defuzzification strategies. The most commonly used one is that of “Center of Gravity”.

The Proposed Controller Design and Implementation

Power Circuit Operating Distinct Topologies (Operating States)

The boost converter circuit under examination is shown in Fig.(1). It comprises an inductor, transistor switch, diode switch, filtering capacitor, and load resistance. It is powered from DC voltage source. This circuit is assumed to operate under continuous conduction mode. Under such assumption, the circuit will cyclically loops through two topologies. The first one is characterized by closed transistor and open diode switches. The second is characterized by open transistor switch and close diode switch.

These operating topologies whose configurations are previously shown in Fig.(2) (part a and b) are defined by the following derived differential equations system:

First topology : (S1 is ON and D1 is OFF)

$V_S = r_L i_L + L di_L/dt$ ….(1)

$di_L/dt = -r_L i_L/L + V_S/L$ ….(2)

$i_C = -i_R$ ….(3)

$V_O = V_C + r_C i_C$

$i_C = C dV_C/dt$

$i_R = V_O/R$

$C dV_C/d t = -(V_C + r_C C dV_C/dt)/R$

$dV_C/dt = -V_C/\{C(R + r_C)\}$ ….(4)

Second topology: (S1 is OFF and D1 is ON)

$i_L = i_C + i_R$

$i_L = CdV_C/d\,t + (V_C + r_C C dV_C/dt)/R$

$dV_C/dt = [\,R/\{C(R + r_C)\}.]i_L - [\,1/\{C(R + r_C)\}]V_C$ ….(5)

$V_S = r_L i_L + Ldi_L/dt + V_O$

$V_S = r_L i_L + Ldi_L/dt + r_C C dV_C/dt + V_C$ …. (6)

Substitute (4) in (6)

$di_L/dt = V_S/L - [\{r_C R(R+r_C) + r_L\}/L]i_L + [R/\{L(R + r_C)\}]V_C$ ….(7)

Calculation of Energy Storage Elements

These elements are represented by the inductance L and the capacitor C. The value of the inductance determines the mode of operation (continuous or discontinuous current conduction mode) and the input current ripple (inductor current ripple). That of the capacitor determines the output voltage ripple. So, proper selection of these two components keeps the converter out of discontinuous mode and the ripple of the input current and output voltage within the allowable range.

Inductance Calculation Criteria:

Referring to Eq.(1), one can see that the inductor voltage is slightly less than V_S. Knowing that r_L which stands for the series resistance of the inductor wire is small, V_S can be approximated by:

$V_S = L\Delta i_L/\Delta t$ ….(8)

Where Δi_L represents the peak to peak of the input current ripple and $\Delta t = D_1 T_S$ represents the ON period of the transistor switch S1.

From Eq.(8), the required inductance should be :

$L > V_S D_1 T_S / \Delta i_L$ …..(9)

To get the highest value of the inductance:

1. The maximum value of $V_S D_1$ should be taken. This can be obtained by substituting the expected input voltage range in $V_S D_1 = VS(1 - V_S/V_{ref})$ and taking the highest.

2. Δi_L is taken in term of the required input current's ripple (Δi_L = twice the input current change during the ON time of the transistor).

Capacitance Calculation Criteria

The capacitor should be assigned a value that ensure a pre specified output voltage ripple range. Eq.(3) states that the capacitor carries the load current during the turn on period of the transistor switch.

The maximum discharge occurs during this period. The worst case belong to that with the lowest input voltage and highest output drawn power. So the capacitor is:

$C > I_{OMAX} D_{1MAX} /(\Delta V.F_S)$

Where I_{OMAX} represents the output current maximum loading, D_{1MAX} represents the duty ratio under minimum input voltage, ΔV represents the required output voltage ripple, and F_S is the switching frequency.

System Requirements

Input voltage = 28 ± 25% (V)
Output voltage = 50 (V)
Nominal load resistance = 10Ω
Max. input current ripple≤ 10% of the nominal load current
Max. output voltage ripple ≤ 0.5% of the rated output voltage.

Selected Component

$L = 135\ \mu H$
$C = 360\ \mu F$
$r_L = 0.005$ (assumed)
$r_C = 0$ (assumed)

Architecture of the Proposed Controller

The controller is responsible to keep the converter output voltage equal to that specified with the reference input. This is the sound function of the controller, but it must be achieved along with keeping the input current ripple and the output voltage ripple with in the range of ±10% of the rated current for the input current ripple and ±0.5% of the nominal voltage for the output voltage ripple.

The proposed controller solved these requirements by generating switching command composed of three parts. These are:

1. The output of the PI like fuzzy controller: the fuzzy controller has been supplied with the output voltage error signal and a signal derived from subtraction of the output voltage from its low pass filtered version. The main target of this part is to keep the converter output voltage equal to that of the reference.

The control mechanism rule set of this part are shown in table(1).

2. Weighted part of the low pass filtered inductor current: it acts as dumper during the sudden changes of the load resistance and input voltage level.
3. Weighted part of the input voltage: this is aimed to add an extra damping during the changes of the input voltage.

The integrated structure of the converter along with its controller is shown in Fig.(4).

Simulation Results and Discussion

To test the performance of the proposed controller. The controller has been used to drive DC/DC boost converter with the specification tabulated in table(2).

The validity examination has been done through :

1. Driving the power circuit with different values of input supply voltage.
2. Loading power circuit with different values of load resistances.
3. Applying different output voltage setting.

The results of these tests have been plotted in Fig.(5) to Fig.(15), where :

Fig.(5) :Displays the transient response of the converter output voltage and its inductor current under nominal load (10Ω) and ±25% step changes relative to the nominal value of the input voltage.

The responses ensure the ability of the proposed controller in keeping the output voltage equal to that defined by the reference value and at the time of change occurrence, the current and voltage overshoots and settling times are limited to an acceptance levels.

From the figure, one can say that under the load for which the converter has been designed, the system gives an excellent response irrespective of the step down and up of the input voltage in the range of the nominal ±25%.

Fig.(6) and Fig.(7) : As it is clear from the figures, the attached drawings register the performance from the starting instant to the steady state one under an input voltage of 28V and a given loading resistance ranging from 5Ω to 100Ω.

Fig.(6) and Fig.(7) pinpoint the following points:

1. The proposed system can start and settled within a time of 5ms for loading ranges from 50W to 250W (load resistance of 50Ω to 10 Ω).
2. For heavy load (5 Ω) and light load(100 Ω), the system settled after 7ms.
3. The maximum voltage deviation occurs at the overload condition and it is less than 0.5% of the nominal output voltage.
4. The current deviation is within the range of ±10% of the output current.

Fig.(8) and Fig.(9): These figures do the same as that of Fig.(6) and Fig.(7) but under an input voltage (35V) greater than the nominal one (28V) by 25%.

The results state that under such driving voltage:

1. The system can start up satisfactorily for loads of 5 Ω and 10Ω. The settling time is ≤7ms.
2. The settling time increases for load resistance greater than that of the nominal load, for 50Ω, it takes about 20ms.and for 100Ω , it requires 45ms.
3. The system can not drives loads with power less than 25W.
4. Under the allowed loading, the voltage and current deviations are within the standard.

Fig(10) and Fig.(11): They belong to a driving voltage of 21Vwhich is 25% less than the design value(28V). Under such driving voltage:

1. The minimum settling times occurs at the design input voltage. It takes about 14ms.
2. For 5Ω and 50Ω , the settling time is about 24ms.
3. For 100Ω, the converter settling time exceeds 45ms.
4. For these loading under which the converter settled after a certain time, the voltage and current deviations are within the standard.

Figures 12 to 14 display the output voltage and inductor current responses under load resistance step changes from the nominal value (10 Ω) to the one attached to the drawing and then back to the nominal under an input voltages of 28V, 35V, and 21V. The drawings indicates the followings:

1. Under an input voltages of 28V and 35V, the performances are excellent for load resistances up to 100Ω.
2. As the resistance step change increases, the recovery time increases too. That of 35V is shorter than that of 28V. This indicates that for each input voltage, there is an upper limit to the load resistance beyond which the performance become poor and unacceptable.
3. With the lower limit of the input voltage(21V), the converter returns to its steady states values but after exposing the system to slightly increased overshoots (around 5V) as compared to those under 28V and 35V input voltages(less than 4V).
4. Load step changes from 10 Ω to 50 Ω represent the best range for the three voltage levels.

Fig.(15): This one presents the ability of the system in keeping track with the sudden changes of the reference voltage. It has been subjected to ±20% step changes. The results noted down the followings:

1. Under supply voltage greater or equal the nominal one (28V,35V), the system jumps to the new setting after a maximum time of 5ms.
2. Poor tracking ability is obtained if the system continue to be driven by the low voltage levels (21V).

Conclusions

Fifteen rules fuzzy logic based controller supported with a low pass filtered inductor current and an input voltage weighted signals has been proposed. The fuzzy controller has been driven by voltage error signal and a one derived by subtraction of the output voltage from its low pass filtered version.

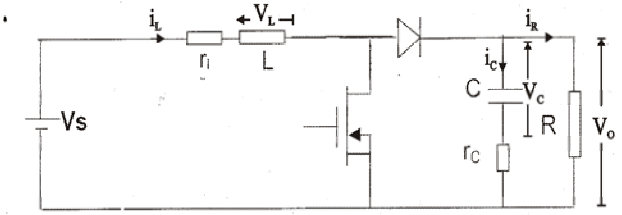
The simulated results recited the following remarks:

1. For the design specifications, the system do well from the point of view of steady state error, voltage ripple, input current ripple, settling time, and overshoots.

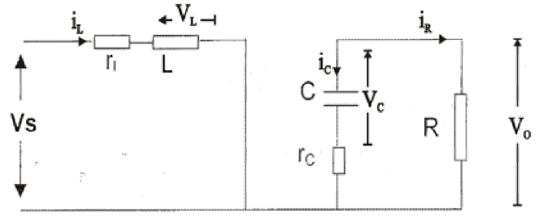
2. Under ±25% variation in the input voltage, the converter exhibited acceptable recovery speed (<5ms) with max. overshoot of 7% of the rated voltage occurred at the transition of the supply voltage from 21V to 28V.

3.:For load resistance toggling, the converter exhibited excellent regulation especially in the range of 5 Ω to 50 Ω.

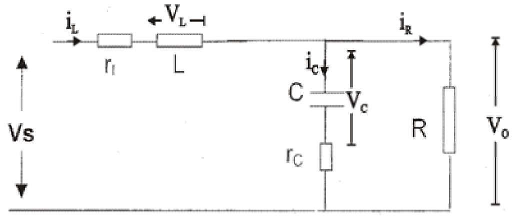
4: The converter can start under over loaded conditions (5 Ω) and light loaded condition (100 Ω).



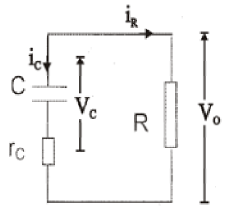
Fig(1) :Boost converter circuit elements



a : First topology : (S1 is ON and D1 is Off)



b : Second topology : (S1 is OFF and D1 is ON)



c : Third topology : (S1 is OFF and D1 is OFF)

Fig(2) : possible cyclic topologies of boost

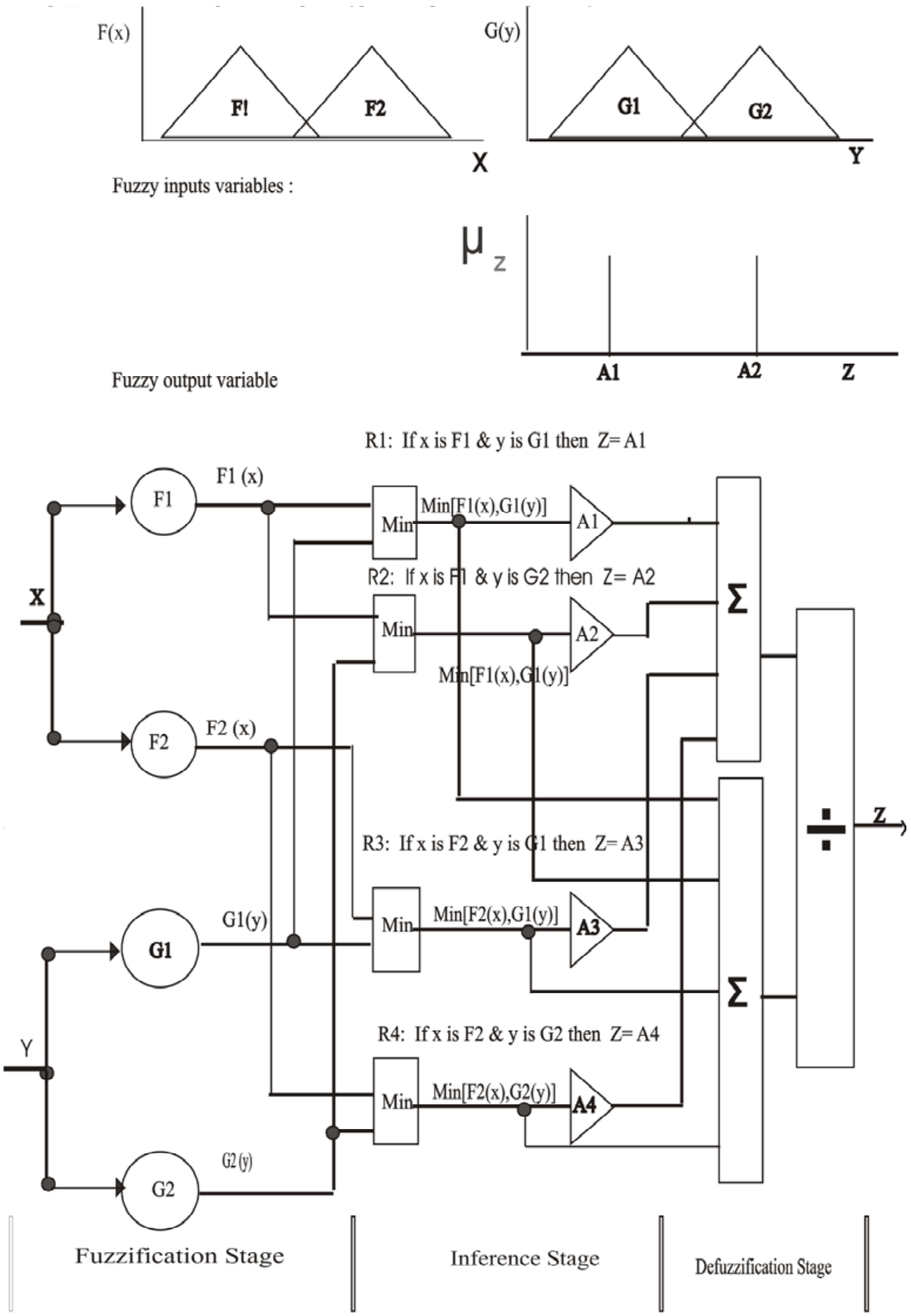


Fig.(3): Functional diagram of Sugeno type two input / one output fuzzy controller

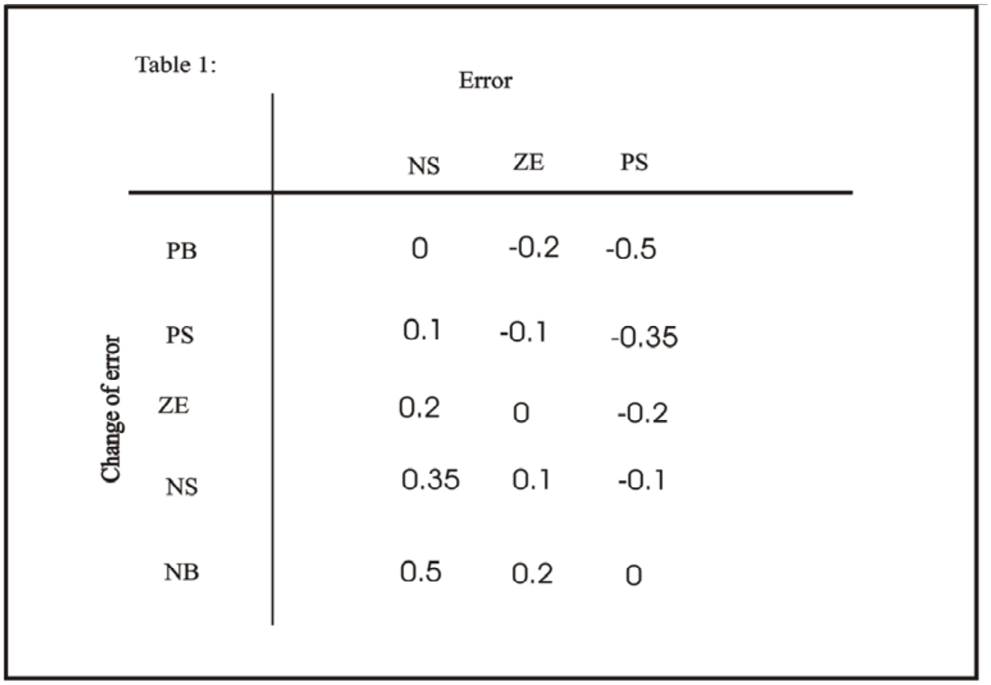


Table 1:

	Error		
Change of error	NS	ZE	PS
PB	0	-0.2	-0.5
PS	0.1	-0.1	-0.35
ZE	0.2	0	-0.2
NS	0.35	0.1	-0.1
NB	0.5	0.2	0

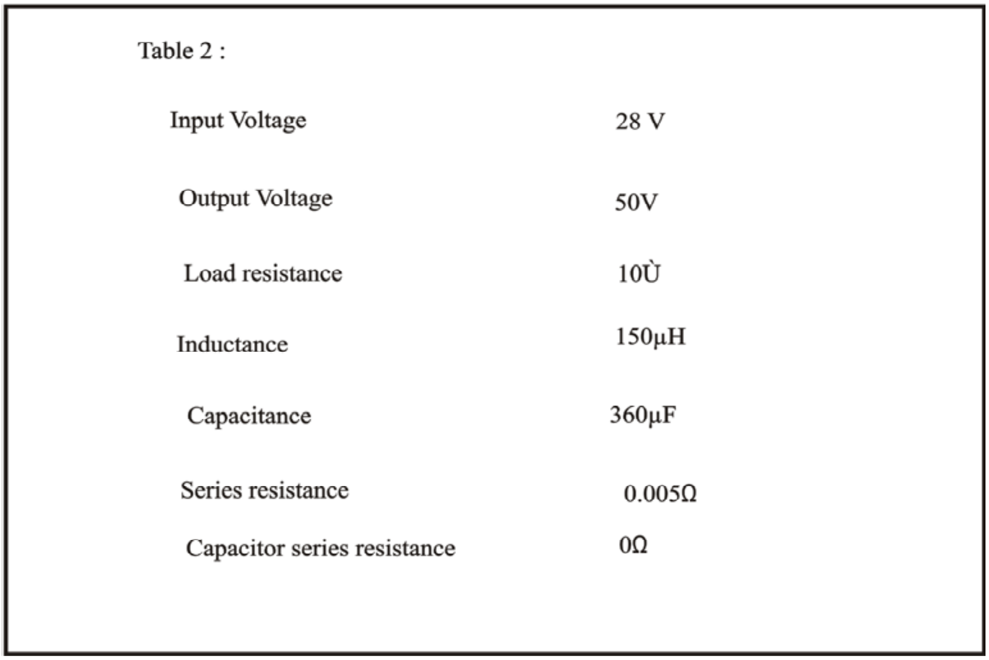
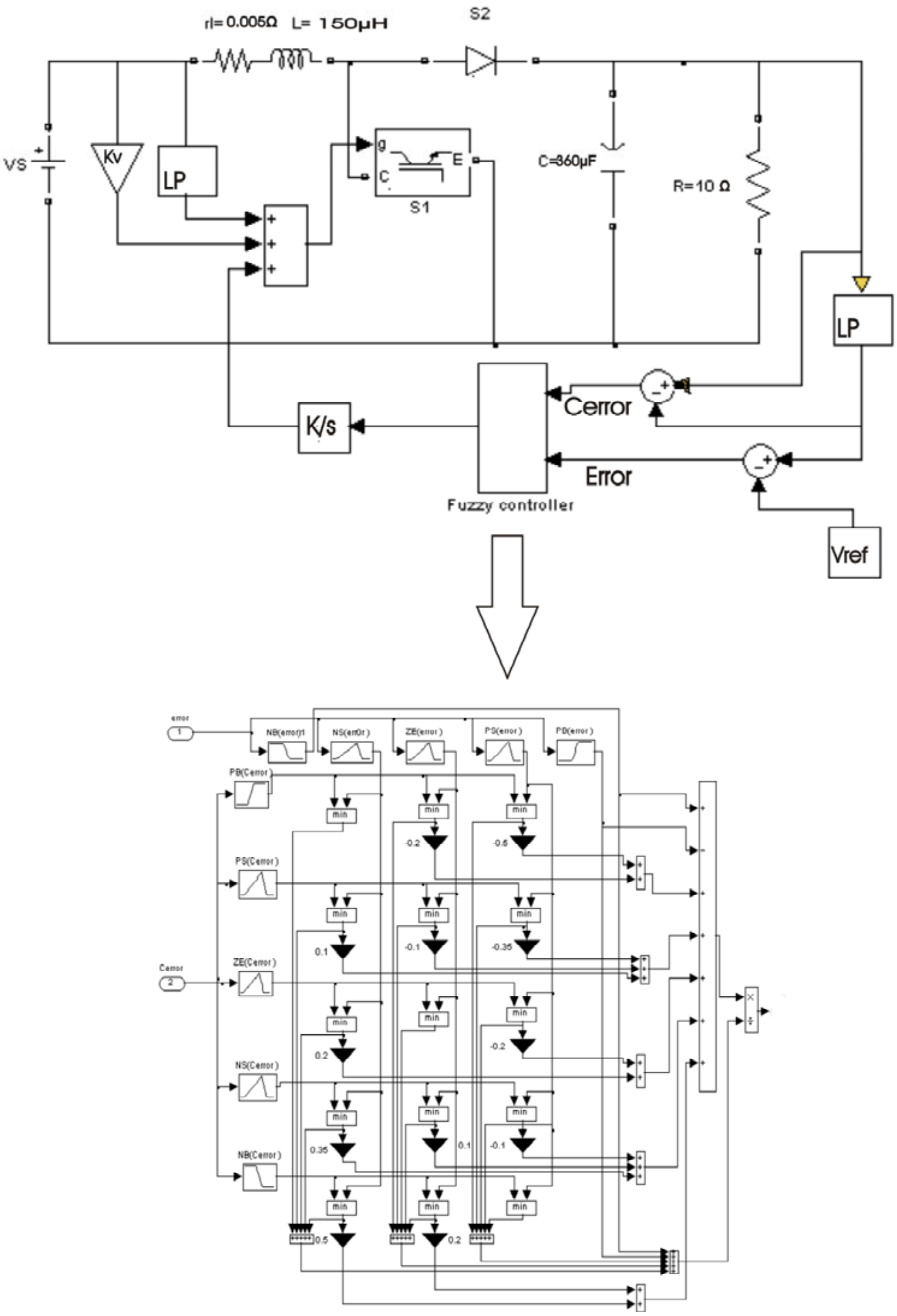
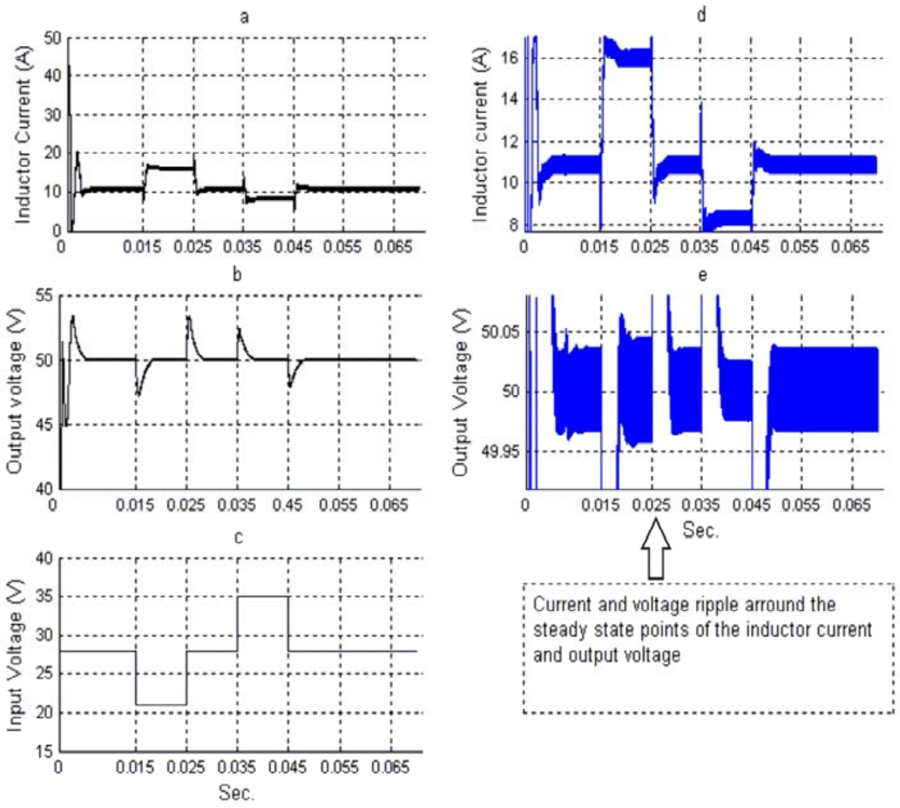


Table 2 :

Input Voltage	28 V
Output Voltage	50V
Load resistance	10Ù
Inductance	150µH
Capacitance	360µF
Series resistance	0.005Ω
Capacitor series resistance	0Ω



Fig(4):The whole circuit (power & control)



Current and voltage ripple arround the steady state points of the inductor current and output voltage

Fig.(5) : Voltage and current responses under 10Ω load resistance and an input voltage of

28 ± 25%V

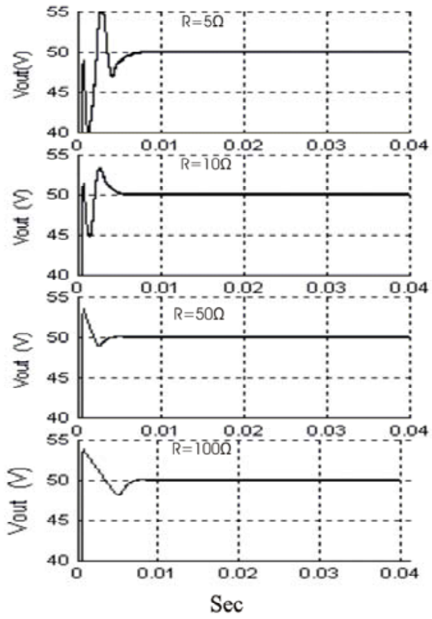


Fig.(6a) : Voltage response under different loading and an input voltage of 28V

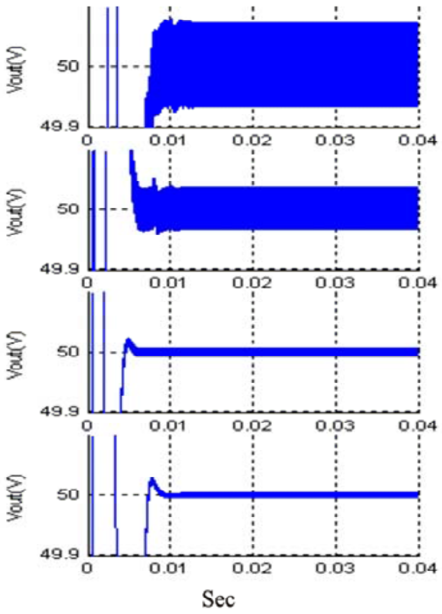


Fig.(6b) : Voltage ripple under steady state

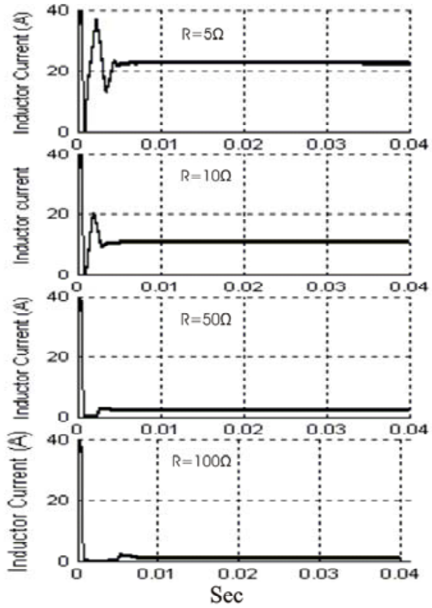


Fig.(7a) : Current response under different loading and an input voltage of 28V

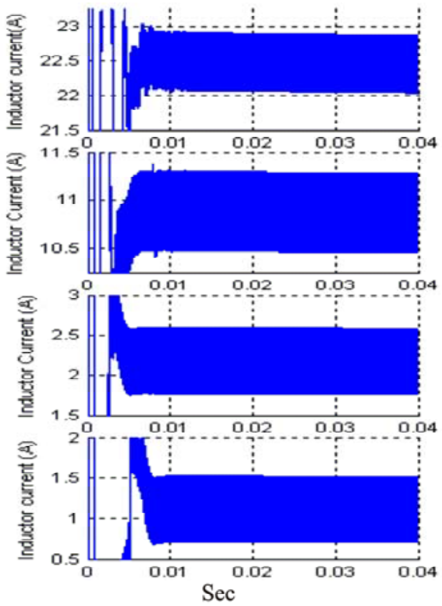


Fig.(7b) : Current ripple under steady state

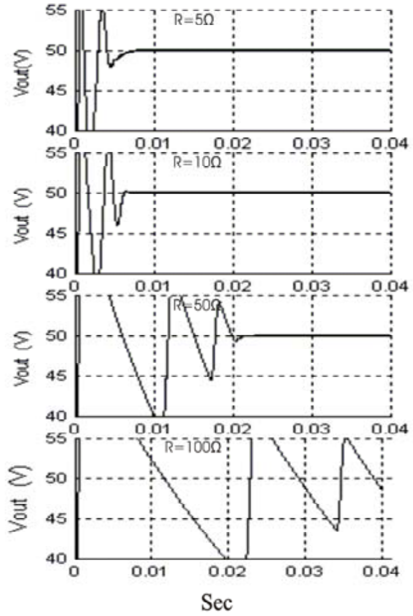


Fig.(8a) : Voltage response under different loading and an input voltage of 35V

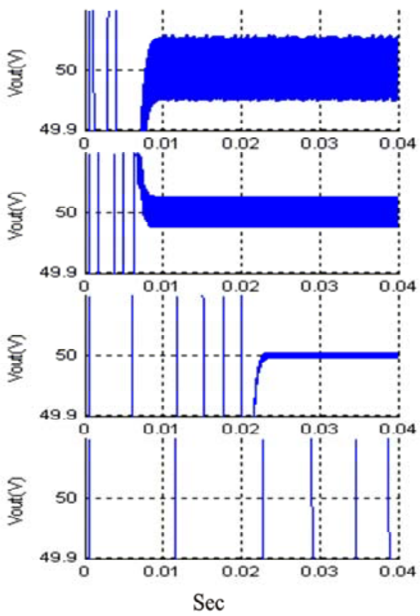


Fig.(8b) : Voltage ripple under steady state

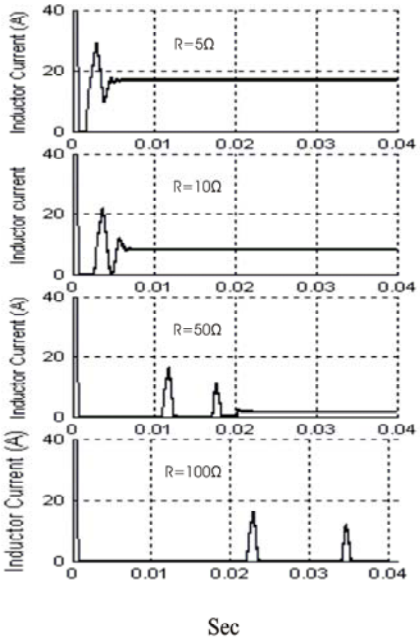


Fig.(9a) : Current response under different loading and an input voltage of 35V

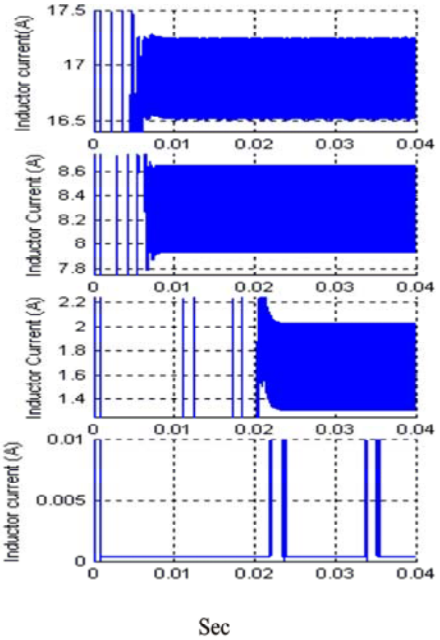


Fig.(9b) : Current ripple under steady state

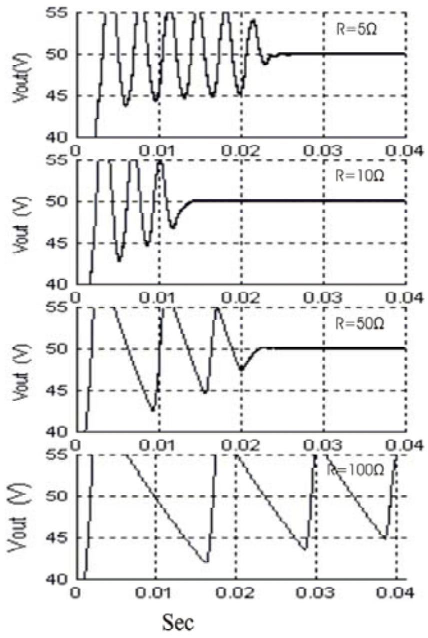


Fig.(10a) : Voltage response under different loading and an input voltage of 21V

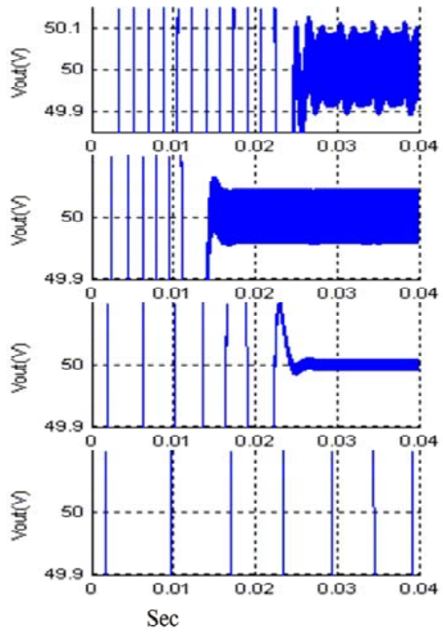


Fig.(10b) : Voltage ripple under steady state

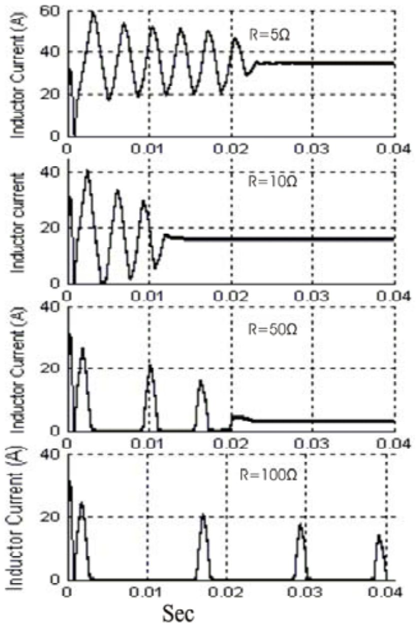


Fig.(11a) : Current response under different loading and an input voltage of 21V

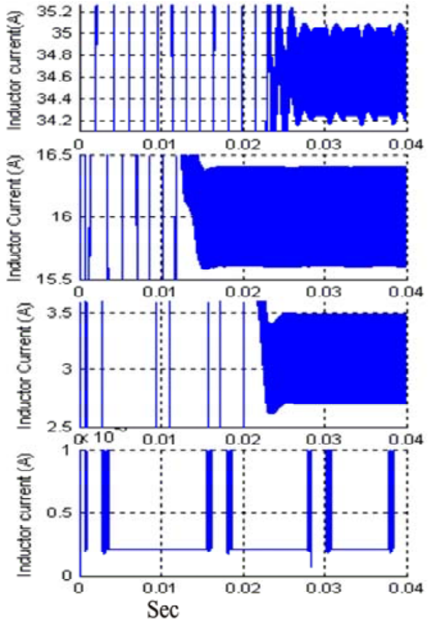


Fig.(11b) : Current ripple under steady state

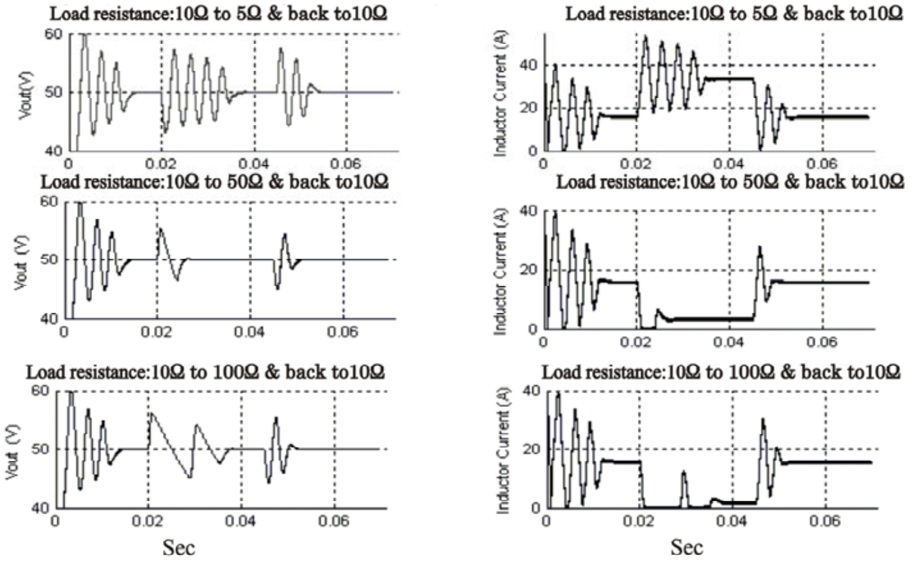


Fig.(14) : Output voltage and inductor current responses under load resistance toggling from the nominal value (10Ω) to the one attached with the drawing and then back to the nominal and an input voltage of 21V

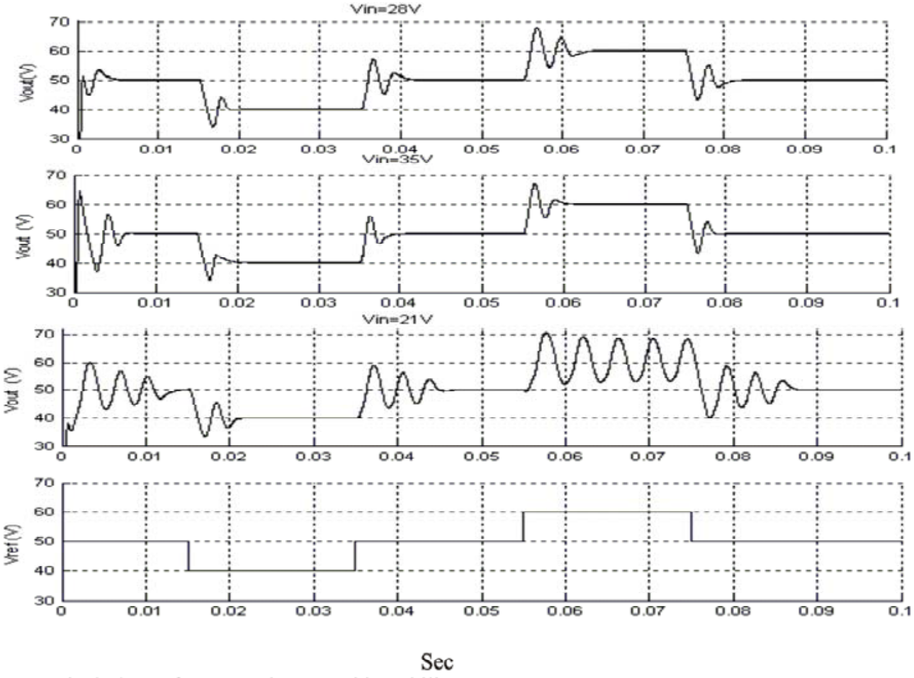


Fig.(15) : Reference voltage tracking ability

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