FUZZY LOGIC CONTROLLED MONOLITHIC SWITCHING REGULATOR IN BCD TECHNOLOGY

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ABSTRACT

In this work a monolithic architecture to realize a high-performance switching regulator with non-linear fuzzy logic control is introduced. An overview of the main issues related to PWM DC/DC conversion in continuous mode is reported and an introduction to nonlinear fuzzy logic control is given. The main analog Fuzzy Logic blocks are illustrated and the overall architecture presented with the main results obtained.

1. INTRODUCTION

An intense research activity exists today related to the power conversion techniques based on monolithic integrated DC/DC converters with high performances in terms of bandwidth and load transient recovery speed in high current fast applications, like high-speed processors.

In the last years the microelectronic factory has produced and commercialised several integrated devices based on linear control in current mode PWM architectures [1].

This approach shows its limitations when the application requires high-speed capability in abrupt load transient response. This is due to the finite response time of the control loop required by stability issues in PWM continuous mode controllers.

This work aims to introduce a novel approach based on nonlinear fuzzy logic control to overcome the limits of existing architectures. Some preliminary analysis and problem introduction has been already reported in [2].

The present work will focus on technical aspects related to the design of such dedicated monolithic controllers by using suitable mixed technology. In fact, this architecture has been implemented in high performance ST proprietary 1.2um BCD technology [3].

The target application is the most critical in terms of stability, known in literature as step-up (boost) converter at fixed frequency with duty cycle control in continuous mode (PWM controller).

The flexibility of the approach proposed can be a key aspect in the development of new products and power conversion applications.

2. STEP-UP DC/DC CONVERTERS AND CONVENTIONAL CONTROL

The voltage regulators are circuits that, absorbing input power from a generator of not regulated voltage, make it available to the output with a stable value, independently from any variation of the input and the load. There are two main classes of regulators: the series linear regulators and the switching regulators. The switching regulator has a wide control possibility, reaching high performances (85%—98%) and allow the over-voltage (step-up configuration) of the input voltage.

The main drawback is the noise level produced by the switching un-stability due to the difficulty to compensate properly a high-order control loop affected by load variations.

![Figure 1: Energy Flow "power-load" regulated by a DC/DC converter](image1)

In single-ended DC/DC converters the power conversion is achieved through a magnetic field storage in an inductor and its transfer in the electric field of a tank capacitor put in parallel to the load, as shown in Figure 1. In Figure 2 the basic Step-Up DC/DC converter topology is shown.

![Figure 2: Circuit scheme of the Step-Up topology](image2)
The two power storing elements are an inductor and a capacitor, while two power switches are a bipolar transistor (SW1) and a diode (SW2). A control circuit provides the proper timing to the energy transfer in order to keep as stable as possible the output voltage.

For each switching cycle with period T it can be found a set of 3 time intervals:

(Ton time): the transistor SW1 is ON and the diode SW2 is OFF. In this interval energy is stored in the magnetic field of the inductor;

(Toff time): the transistor SW1 is switched off by the control signal while the diode SW2 is ON; in this phase the energy stored in the inductor decreases, due to the transfer of energy from the magnetic field to the electric field of the capacitor;

(Tfw, free-wheeling time): both SW1 and SW2 are OFF, the magnetic field of the inductor is exhausted, and all the energy required by the load is supplied by the output tank capacitor.

The presence of Tfw determines the two possible operation mode for the DC/DC converters:

- Continuous mode (CCM): current in the inductor, never null.
- Discontinuous mode (DCM): current in the inductor cross the zero value, within the time period T.

Figure 3 shows the main switching waveforms characterising a step-up conversion.

Therefore a novel non-linear control technique, based on fuzzy logic, is applied to this topology.

![Figure 4: Blocks scheme of a PWM controller and simplified PWM control signals](image)

### 3. SYNTHESIS OF THE FUZZY LOGIC CONTROL SYSTEM

The novel approach aims to integrate the classical ramp compensation current-mode control with a fuzzy logic control that acts on the transfer function of the system with the purpose to get a non-linear regulation to compensate the negative effects of load variations.

The purpose is to join the advantages of the current mode control, with the flexibility of a fuzzy control system in the voltage loop, widening the range of stability in comparison to the traditional control. The simplified schematic of the proposed architecture is shown in Figure 5.

The error and its first derived (D_E) are assumed as input to the fuzzy algorithm.

![Figure 5: Schematic of the proposed architecture](image)

The error amplifier block of the linear regulator has been replaced with a fuzzy control block, which uses as inputs the error and its first derivative. The output of the fuzzy block is compared to the voltage ramp obtained by the sum of the switching current and a fixed slope compensation ramp, so obtaining the duty cycle control of the PWM architecture.

For the fuzzy algorithm, the linguistic rules are empirically derived based on the following criteria:

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- for a small error in absolute value, the output of the fuzzy block ('F_Out') is determined in reason of the load condition ('Derived');
- an elevated and positive value of the error forces $F_{Out}$ to its maximum value;
- an elevated and negative value of the error forces $F_{Out}$ to the least value.

The fuzzy controller has been designed using fast and reliable analog blocks and incorporated in a monolithic DC/DC converter 220KHz PWM controller built in high-speed 1.2um BCD technology.

The scheme of the employed Fuzzy Logic controller is presented in figure 6.

![Figure 6: Block scheme of the fuzzy logic controller](image)

The following figures reports some basic building blocks of the proposed fuzzy logic controller implementation.

**Figure 7:** Implementation of the ERROR Inference block

Each membership function block has been design with similar differential circuit topology as triangular (e.g. fig.9) or left-side (e.g. fig.8) and right-side trapezoidal shapes. The right position and shape of each membership function are fixed by tuning appropriately the fixed input voltage values, bias and transistor parameters. More technical aspects on design techniques for fuzzy hardware devices can be found in literature [6].

**Figure 8:** Implementation of the membership function 'ERROR is LOW'

**Figure 9:** Implementation of the membership 'ERROR is ZERO'

**Figure 10:** Implementation of the DERIVATIVE block, which computed the $\frac{dE}{dt}$ signal from the error signal $E(t)$

Simulations in ELDO environment of the full circuit are reported in fig.11-14. The external circuit parameters considered in the simulations, referring to the schematic diagram shown in fig.5, are the following: $C = 220\mu F$, $R_{ESR}=0.1\Omega$, $L=10\mu H$, $R_L=0.1\Omega$.

More in details, fig.11 and fig.12 show the obtained membership functions for the error and its derivative. Due to transistor mismatch and process parameters variations, membership position can be fixed with a maximum accuracy of about 2%. 

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Figure 11: Membership Functions for the Error

Figure 12: Membership Functions for the Error Derivative

Finally fig.13 and fig.14 report the control simulation results in the case of both load and line transients. In these charts, the circuit has been simulated with the following operative conditions for load transient \( V_{IN}=5\text{V}, \quad I_{LOAD}=100\text{mA}/300\text{mA}/100\text{mA} \) and for line transient \( V_{IN}=5/8\text{V}, \quad I_{LOAD}=100\text{mA} \), respectively.

As it is clear from simulation results the global controller is stable and its response is quite independent from any variations in terms of load current and input voltage.

Figure 13: Results for load-transient analysis

Figure 14: Simulations results for line transient analysis

4. CONCLUSIONS

The application of fuzzy logic in non-linear control systems has been widely used in the last years. In this work the problem of DC/DC power conversion and control issues have been reported as a case of study for the realization of monolithic DC/DC converters. Fuzzy Logic Control has been verified as a suitable methodology for this kind of applications, and their ability to cope with load transients and intrinsic instability issues has been reported.

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6. REFERENCES