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Designing fuzzy logic controllers for DC–DC converters using multi-objective particle swarm optimization

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ABSTRACT

This paper proposes a new method for designing fuzzy logic controllers for voltage-regulated DC–DC power converters. Low sensitivity to input voltage variations, fast regulation during load transients and robustness against the aging process of the converter passive components are the main features achievable through the proposed approach. The multi-objective particle swarm optimization (MO-PSO) is used to find multiple Pareto-optimal solutions in a multi-objective optimization problem for the identification of the best possible membership functions and rules of the fuzzy controller. In order to evaluate the effectiveness of the proposed technique, different cases have been tested in laboratory on a buck converter prototype, considering deep input voltage deviations and big load transients, as well as variations in the nominal values of the passive components of the system. A comparison with a classical proportional-integral (PI) controller demonstrates the high performances of the proposed technique in terms of effective output voltage regulation under different operating conditions.

1. Introduction

In recent years, considerable attention has been devoted by researchers to the study of advanced control techniques for switched-mode power supply, chiefly DC–DC converters. The observed growing interest in this research area reflects the constantly increasing use of these conversion systems in a wide range of electrical and electronic applications, like uninterruptible power supplies [1], battery chargers [2], power factor correction systems [3], maximum power point tracking in photovoltaic panels [4], fuel cells regulation [5], devices for the automotive industry [6]. In all these applications, DC–DC converters are required to deliver regulated output voltage with minimal steady-state output error, fast dynamical response, low overshoot and low sensitivity to the noise, to the input voltage deviations, to the load transients and to the variation of the characteristics of the passive components (inductors, capacitors, switches) due to their aging. All these requirements have to be satisfied both through the correct design of the circuit parameters and components and, mostly, by the implementation of appropriate control methodologies.

A first categorization between the possible usable control strategies proposed in literature is between analog and digital solutions. For many years analog controllers have dominated the market, and they carry on being the most used, especially in low cost, low power mass-produced applications. However, when very high performances are required and the cost is not the most relevant factor, as in high power applications, digital implementations are actually preferred. Taking into account their advantages in terms of increased reliability and higher control flexibility, and considering that their typical drawbacks, i.e., high costs and limited processing speed, are being constantly ameliorated, digital controllers will probably definitively replace, in a near future, the analog implementations [7,8].

In the category of linear pulse-width modulation (PWM) controllers, two main control strategies are worth being mentioned: voltage-mode control (VMC) and current mode control (CMC) [9]. These control techniques are usually implemented in analog solutions, but also digital applications are presented in literature [10,11].

In VMC the output voltage of the converter is sensed and compared with the voltage reference value: the difference between these two signals is used as the input of an error amplifier which produces a control signal, subsequently compared to a constant-amplitude triangular waveform. The PWM signal obtained by this comparison is fed to the drivers of the controllable switches used in the converter [12].

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In CMC applications both output voltage and inductor current are sensed and used for the output voltage regulation. Two control loops are implemented, namely voltage control loop (which is the outer loop) and current control loop (which is the inner loop), and higher immunity to the input voltage variations is obtained. CMC strategies are in turn divided into peak-current mode control, average current-mode control and valley current-mode control, and each of them shows superior dynamic performances with respect to VMC [13].

An alternative analog control technique presented in literature is the one referred as One-Cycle Control (OCC) [14]. OCC is basically a nonlinear large-signal PWM technique that tries to set the duty ratio, through an operation of integration, in order to have at each cycle the average of the output voltage equal to the reference value. The main drawback of this method is that it is not trivial to obtain an effective control response because all the non-ideal elements of the circuit make the integration process of the controller non-perfect.

A further technique based mostly on analog implementations is the hysteretic voltage control [15]. This technique basically uses a hysteretic relay to compare the actual output voltage with the reference and turns on/off the switches on the base of the obtained value. As a result, very fast dynamics can be achieved, but the obtained varying switching frequency can generate unpredictable noise spectrum, making the electromagnetic interference filtering very difficult.

In the category of the advanced digital control techniques, one of the most popular techniques presented in literature is the adaptive control method [16]. Adaptive control approaches entail the variation of the control parameters on the base of the actual operating conditions with the objective of achieving optimal performances in all the possible conditions. However, their implementation requires a very effective mathematical formulation modeling the system.

Another possibility is offered by the so-called sliding mode control [17–20]. Between the nonlinear control techniques sliding mode control is the one presenting the easiest implementation. The main drawback of this technique is its intrinsic variable frequency nature and the impossibility of ensuring a null steady state error without including an integral action in the control loop.

Other approaches presented in literature are based on the application of neural networks [21–23]. The main advantage in this case is that the regulator has an intrinsic capability to learn on-line the behavior of the controlled system but, on the other side, as well for the sliding mode approach, the method cannot provide any performance guarantee in all the possible working conditions that can occur.

A basic pre-requisite for the implementation of most of the mentioned techniques is the accurate formulation of the converter mathematical model. Unfortunately, this is not a trivial task due to the inherent nonlinear and time-varying nature of these systems. This paper provides a new control approach for voltage regulated DC–DC converters. The proposed method allows to sidestep all the issues inherent in the process of modeling non-linearities and time-variant properties of the system, offering, at the same time, very high dynamic performances. The proposed solution can be classified as a current-mode-control scheme based on the application of fuzzy logic. The approach entails the use of a multi-objective particle swarm optimization (MO-PSO) to find multiple Pareto-optimal solutions in a multi-objective optimization problem for the identification of the best fuzzy logic controller.

The technique does not require any specific information about the converter model as well as the system parameters. Differently from other fuzzy logic based solutions proposed in literature, in the presented approach the controller is optimized offline by a MO-PSO that ensures the best achievable control performances.

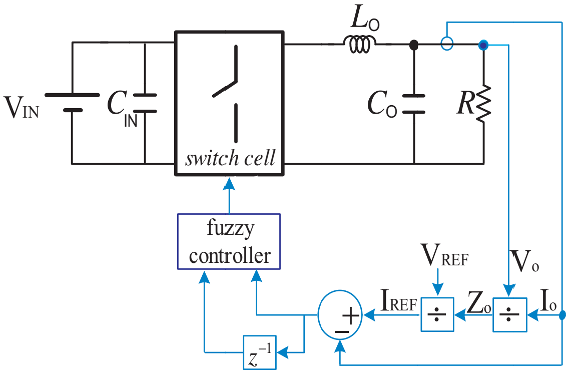

Fig. 1. Structure of the proposed control scheme.

Hereinafter, Section 2 describes the structure of the proposed scheme while the use of the optimization procedure to tune the fuzzy controller is illustrated in Section 3. Section 4 provides the results obtained with a buck converter prototype tested in laboratory under different conditions of input voltage and output load variations. A comparison with a classical proportional-integral (PI) controller demonstrates the high performances of the proposed solution in terms of fast and effective output voltage regulation under different severe operating conditions. Conclusions are drawn in Section 5.

2. Proposed control technique

2.1. Structure of the control scheme

Fig. 1 shows the structure of the proposed control scheme applied to a DC–DC buck converter. By sensing the output voltage and the output current, an estimation of the load impedance is obtained:

$$Z_O(k) = \frac{V_O(k)}{I_O(k)} \tag{1}$$

$V_O(k)$ and $I_O(k)$ are load voltage and current at kth sampling instant and $Z_O(k)$ is the corresponding computed load impedance. The estimation of the load impedance together with the desired voltage reference are used in the scheme to generate the reference for the current (2):

$$I_{REF}(k) = \frac{V_{REF}}{Z_O(k)} \tag{2}$$

where V_{REF} is the reference voltage setting.

In the inner current loop the output current is compared to the obtained reference value, generated by the voltage loop, and an error signal $e(k)$ is produced. The produced error and its rate of change $\Delta e(k)$ are fed into the fuzzy controller, whose output $y(k)$ is compared to a saw-tooth signal with pre-specified switching frequency f_s. The output of the comparator is the signal driving the mosfets. A detailed description of the fuzzy controller is provided in the next sub-section.

2.2. Fuzzy logic controller

Compared to other techniques based on the classical control theory, fuzzy logic provides the instruments to perform the design of nonlinear control systems on the base of heuristic considerations coming from the designer practical experience. The application of this technique does not require accurate models of the converter and is able to deal with its typical nonlinearities, showing less sensitivity to noise disturbances and parameters variations, with respect to other nonlinear controllers [24–26].