Digital Control of a Zero-Current Switching Quasi-Resonant Boost Converter

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***Abstract*—The most important component of a closed-loop industrial control system is a communication unit between digital controller and controlled object. A pulse converter is usually used for this purpose in the systems operating under pulse width modulation. However the dynamic characteristics of the converter bring a significant impact on the quality of the system regulation. The article discusses the design and implementation a closed -loop digital automatic control system for a zero-current switching quasi-resonant boost converter. It enables a high-speed transient process of the controlled object voltage having the advantages provided by pulse methods of electrical energy conversion. The paper also presents simulation and experimental verification of the proposed approach.**

Keywords-digital control system; switching-mode power supply; boost converter

I. INTRODUCTION

Quality of control in a conventional closed-loop digital control system comprising reference block, digital controller and plant depends on deviation between a reference signal and state of a plant usually referred to as an error. The digital controller responsible for processing an error signal plays a key role in minimising of the deviation and improving the quality of control [1].

The requirements to regulation of a system in context of quality control are often defined in terms of transient process dynamics by final and minimum time of the transient process and absence of overshoot. [2] provides an overview on various approaches to the voltage regulation of power systems adopted these requirements. The range of application for such systems is extremely wide: from home appliances to industrial complexes [3]. The role of a plant may play electric motors [4], [5], electric heaters, renewable energy applications including modern devices for solar energy [6] or wind energy applications [7], electrotechnological installations [8] or even a human body model [9].

Digital controller as a component of analogue control system has a relatively complicate structure due to presence of interface blocks (or communication units). These blocks include, for example, analogue-to-digital converters (ADC) generating digital valid samples of either reference or feedback signal from a controlled parameter sensor.

Another communication element which brings a significant impact on quality of control is a digital-to-analogue converter (DAC) providing interface between the digital controller and the plant. The converter generates amplitude modulated (AM) analogue control signal into the plant input. However, the practical use of such analogue signal is not possible in power electronic applications based on switching techniques. For these applications AM is replaced by pulse-width modulation (PWM) or frequency modulation (FM). To smooth piecewise-step voltage waveform at the output of the plan both modulation methods require installation of filters whose weight and size are strongly dependent on the switching frequency. Increase in the switching frequency improves the mass-dimensional characteristics of the system and reduces the duration of transient processes due to the filters with smaller time constants. [11]-[14].

II. QUASI-RESONANT BOOST CONVERTER

Zero-current switching quasi-resonant boost converter (ZCS-QRBC) is promising for variety application due to high efficiency at high switching frequency [10] comparing to classical pulse-width modulated (PWM) boost converter. A simplified functional diagram of the investigated ZCS-QRBC is shown in Fig. 1 [15].

The main elements defining a resonant process are capacitor C_r and inductor L_r. The switch *S1* in the full-wave circuit is a MOSFET having a reverse protective diode between the drain and the source (not shown in Fig. 1). The full period of the switching frequency in steady state can be divided into four intervals starting from the time of closure of the switch *S1*.

Since the equivalent circuit of ZCS-QRBC for each interval is a linear stationary system it can be described by a set of

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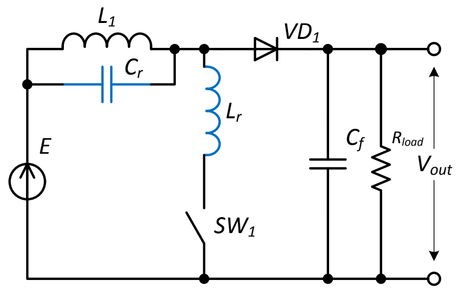

Figure 1. A simplified electrical scheme of a zero-current switching quasi-resonant boost converter.

linear first-order differential equations with constant coefficients. This can be represented in the following vector-matrix form [16]:

$$\frac{d\mathbf{v}(t)}{dt} = \mathbf{A}\mathbf{v}(t) \tag{1}$$

where $\mathbf{A}$ is the matrix of coefficients; $\mathbf{v}(t)$ is a column vector of system states.

For ZCS-QRBC the vector of system states is represented by

$$\mathbf{v} = \begin{bmatrix} E \\ i_{L1} \\ u_{Cr} \\ i_{Lr} \\ u_{Cf} \end{bmatrix} = \begin{bmatrix} E \\ x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{2}$$

where i_{L1}, i_{Lr} are currents of the inductors $L1$ and L_r, respectively; u_{Cr}, u_{Cf} are voltages of the capacitors C_r and C_f.

The solutions of (1) can be expressed in the following form:

$$\mathbf{v}(t) = \mathbf{\Phi}(t)\,\mathbf{v}(0^+) \tag{3}$$

where $\mathbf{\Phi}(t)$ is the extended transition matrix of the system; $\mathbf{v}$ (0^+) is the vector of initial conditions.

Computation of $\mathbf{\Phi}(t)$ can be performed by the following algorithm

$$\mathbf{\Phi}(t) = L^{-1}\left\{\left[p\mathbf{I} - \mathbf{A}\right]^{-1}\right\} \tag{4}$$

where $\mathbf{I}$ is the identity matrix.

The time diagrams of state variables for a ZCS-QRBC are shown in Fig. 2.

III. Control System Structure

A typical structure of a digital industrial automation system shown in Fig. 3 contains [8]:

- Reference Block. It is a digital component but it may precede an analogue reference device supplemented by the corresponding converter (ADC, interface etc.);
- Digital Controller;

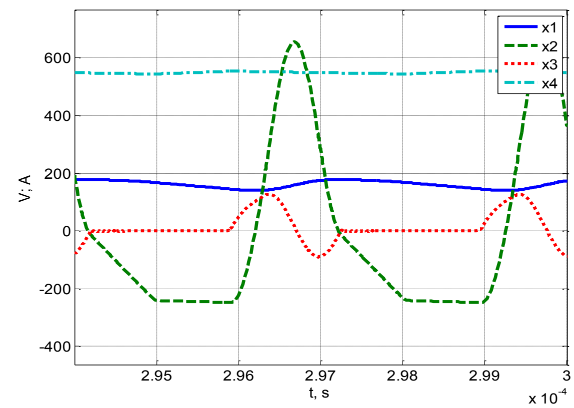

Figure 2. State variables in a zero-current switching quasi-resonant boost converter.

- Plant Interface (DAC with amplifier, pulse converter etc.);
- Plant;
- Sensor of plant's parameters;
- Sensor Interface (ADC, counter, encoder).

The adjustable output parameter $y(t)$ is usually an analogue variable. The presented structure comprises the digital reference signal $x(k)$, the feedback signal by adjustable variable $y(k)$, the error signal $\varepsilon(k)$ and the regulating signal $u(k)$. It is shown that the estimation of adjustable parameter is performed using the electrical signal of sensor $y''(t)$ which reflects the properties of a real plant imperfectly (for a general case).

The digital controller and a subtractor, at least, are built-in a microcontroller (MC). However, more functions can be embedded into advanced MC (shown in Fig. 3 by a dotted line). Thus, the modern MC comprises integrated ADCs, PWM

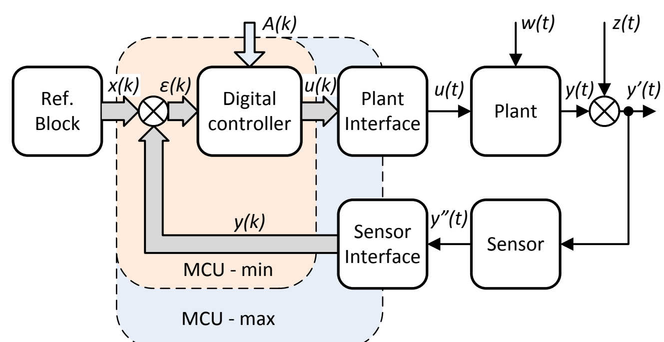

Figure 3. Structure of a digital industrial automation system.

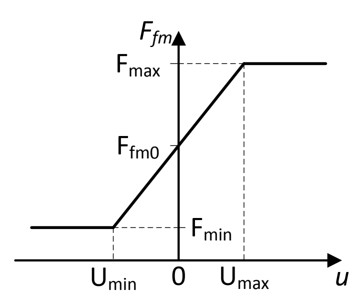

Figure 4. Pass-through characteristic of the frequency modulator.

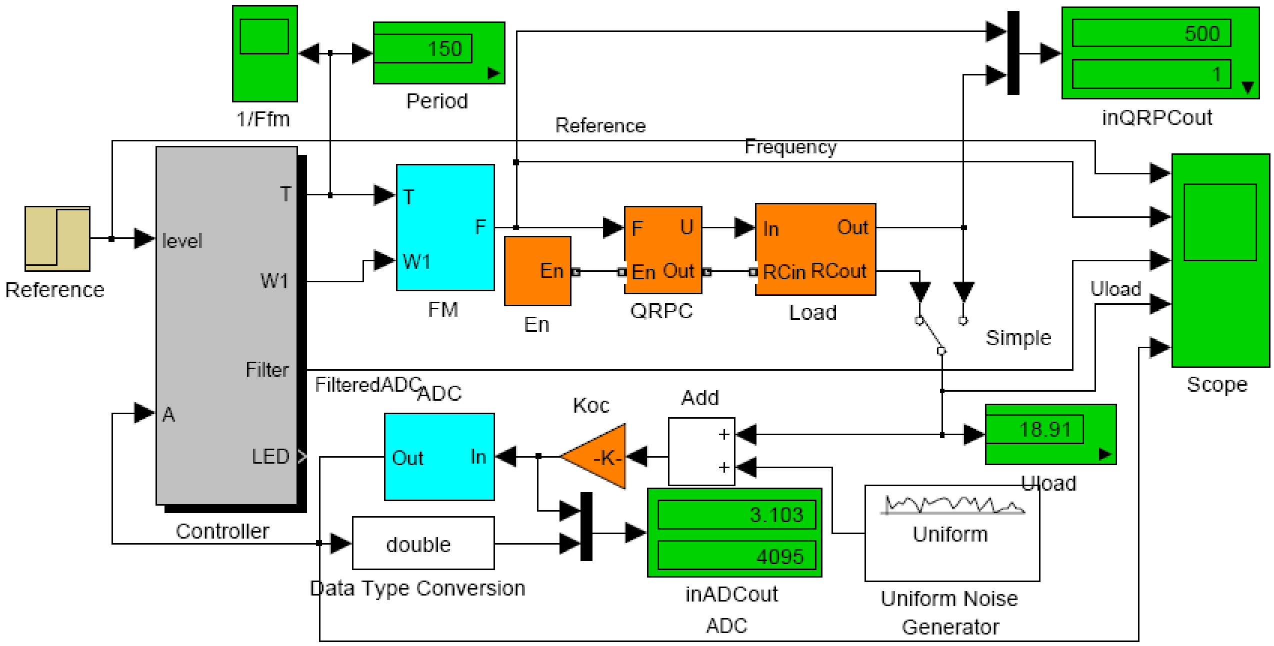

Figure 5. Simulink-model of a closed-loop control system.

blocks, encoders etc. improving the technical and economic performance of the system and increasing reliability.

The digital controller processes the code of error signal in order to produce a digital control signals transmitted through the plant interface into the plant. The aim of the control is to provide appropriate parameters of electrical energy at the output of the plant. Most often it ensures a predetermined quality of transient process and stabilisation of the output parameter (or tracking it).

A Field Programmable Gate Array (FPGA) control system is a preferable solution instead of conventional MC due to fast prototyping, reprogramming, high operating frequency, and parallel processing capabilities. An additional advantage of the programmable logic is adaptation of the controller to the external signal A(*k*) reflecting the changes of the plant properties (for example: load adaptation described in [14]).

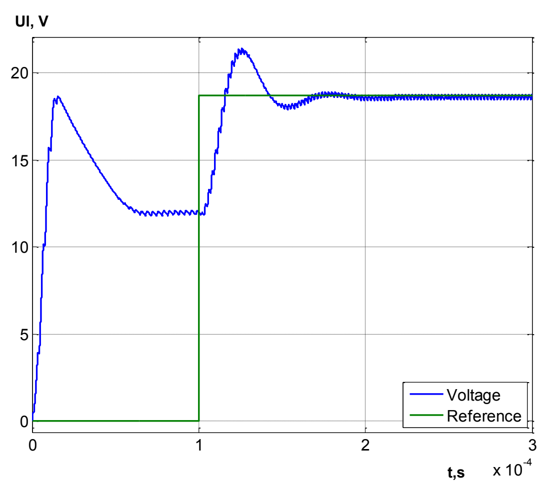

Figure 6. Transient process in the simulated system.

IV. DISCRETE FREQUENCY MODULATOR

The control of output voltage of ZCS-QRBC is provided by the switching frequency variation. Therefore, the control systems has to generate pulses of a fixed duration with a period corresponding to the input voltage. Fig. 4 shows a pass-through characteristic of the frequency modulator.

Due to the change of the input voltage u within the limits $[U_{min}, U_{max}]$ the output pulses frequency F_{fm} linearly varies within the limits $[F_{min}, F_{max}]$. The frequency of modulator should be limited outside the operating range.

Wave signal generators with a frequency depending on the applied voltage are widely used in electronics. It is so-called Voltage Controlled Generator (VCG). The frequency regulation is performed, for example, by variation of the voltage at the varicap included in the resonant circuit. .

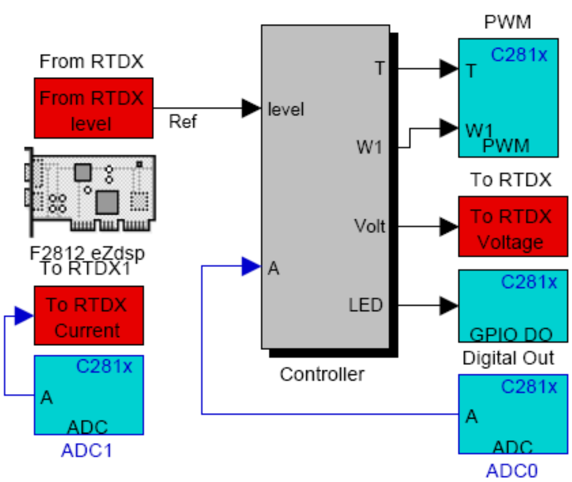

Figure 7. Structure of the control system prototype.

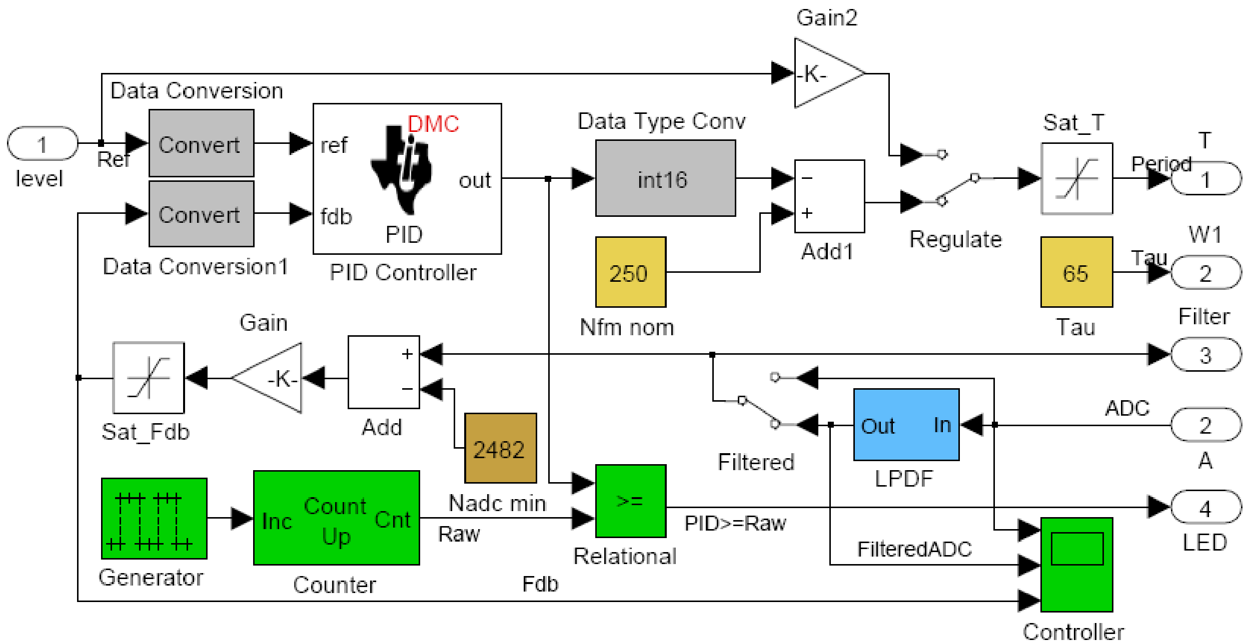

Figure 8. Functional diagram of the controller.

V. Simulation Results

Fig. 5 shows a Simulink model of a closed-loop control system comprising a reference block (Reference), a digital controller (Controller), a frequency modulator (FM), a quasi-resonant boost converter (QRBC), and auxiliary assemblies for measuring, destabilizing factors and interferences simulation, as well as signals' visualization.

Fig. 6 illustrates the transient process in the system at the initial switching on the supply voltage on QRBC. A minimum output frequency of FM is established and the minimum voltage corresponding to this frequency is generated at the output. A reference action followed a delay of 0.1 ms is performed by Controller, FM, QRBC and measuring elements.

VI. Experimental Verification of the Control System

Fig. 7 shows the result of the development of the control system prototype of the low power QRBC using the target board eZdsp TMS320F2812 (Spectrum Digital). It is based on Digital Signal Processor (DSP) from Texas Instruments and supported by Matlab.

A Simulink model contains assemblies to set the resident ADCs and PWMs modes and organise a communication between the target board and Matlab (blocks To RTDX and From RTDX). A digital regulator is implemented as a Simulink-block Controller which details are shown in Fig. 8.

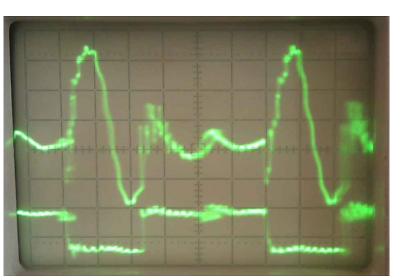

Figure 9. Experimental waveforms of the MOSFET current and its switch-on voltage.

After the model creating and debugging in simulation mode, an automated generation of the source code in C language is performed by Matlab tools. It is transferred into an integrated software development environment of DSP Code Composer. At the next step a batch file automatically runs translating the code from Matlab and loads an object module into the program memory of the target board. A further work is done in real-time.

This approach based on high-level programming by Matlab/Simulink tools significantly reduces the development time of the prototype due to integration of all low-level functions of the system into the Target Support Package.

The target board provides the real-time control from personal computer (PC) during the experiment (reference signal on regulation) and visualisation of some important parameters of QRBC (e.g. the voltage at the output or the current consumed from the power supply).

The experimental waveforms of power MOSFET current and switch-on voltage are shown in Fig. 9. It can be seen that they are in good agreement with theoretical calculations and simulation results.

The experimental results help to explore the control characteristics of QRBC and investigate the interference effect on control quality in pulse power conversion systems. It also tests different parameters of the feedback circuits and filters and clarifies the scheme of QRBC.

VII. Conclusion

The dynamic processes in a closed-loop industrial control system depend on the topology of devices connecting a digital controller to a plant. The quality of control (transient process time in particular) can be improved by high frequency pulse converters, e.g. zero-current switching quasi-resonant boost converter.

The described procedure of designing a control system for a zero-current switching quasi-resonant boost converter comprises the steps of a theoretical analysis of the processes, consideration the features of frequency control of the load voltage, modelling the feedback circuits and simulation verification, elaboration of the control system prototype and the experimental investigation.

The developed prototype based on a high-level programming of a digital signal processor by Matlab/Simulink tools identifies the most important characteristics of the system and adjust the settings of converter and control system components. The results obtained from the experimental verification of the control system demonstrated that the MOSFET current and voltage waveforms are very close to the theoretical and simulation results.

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