Digitization of control systems for power electronic converters

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Abstract – **The work presents an approach for transition of an analog control system of a dc-dc power electronic converter, in particular the resonant LLC converter, to digital control system, using embedded microcontroller to perform the calculations and formation of the control pulses of the device. The study is verified using software simulations and a hardware board evaluation studies.**

Keywords –**llc resonant converter; digital control; power electronics;**

I. Introduction

Power electronic converters, in particular the switch-mode power-supply (SMPS) converters are used in a wide variety of applications, that have power requirements ranging from several watts in small appliances power management to hundreds of megawatts in industrial systems. All of these applications require efficient and cost-effective static and dynamic power regulation over a wide range of operating conditions. A controller closes the feedback loop around the switching converter and steadily controls the on/off states of the power semiconductor switches to achieve the devices' input or output regulation.

Over the past few decades, digital controllers in the form of digital-signal processors (DSPs), microcontrollers, and field-programmable gate arrays (FPGAs) have seen extensive application in power converter controllers, high-voltage and high-current power electronics. Usually in these applications the control algorithms generally due their sophistication operate at MHz frequencies, while the semiconductor devices operate at relatively low switching frequencies, e.g. at tens of kilohertz. A digital controller usually includes a standard communication block; general-purpose ADCs (ADCs); digital I/Os; memory; and a processing unit (microcontroller) that handles all the communication, diagnostics, power management, etc. The verdict is that the digital controller not only regulates the output voltage, but also performs complex sequencing and monitor of key parameters like average current and power for the host system.

The paper focuses on the implementation of a SMPS controller with the use of digital transformation and technology. First the techniques necessary to model the discrete time controller are reviewed. Then the new features and functions that digital control implement are discussed. These functions are applied to a LLC-resonant converter, first using a mathematical modelling, and after that they are verified using real hardware evaluation board, in particular the Texas Instruments TMDSHVRESLLCKIT Half-Bridge LLC Resonant DC/DC Converter with Synchronous Rectification.

978-1-7281-7426-6/20/$31.00 ©2020 IEEE

II. Converter under study

The chosen converter for the proposed study is the LLC Resonant DC/DC Converter with a classical regulation strategy, implemented with a PID controller. Mathematical modeling is done with an analog controller, the modeling of the digital equivalent controller is verified with both mathematical modeling and experimental results.

A. Resonant LLC converter

The series resonant LLC converter circuit is shown on figure #. It consists of a resonant capacitor, resonant inductor and a resonant transformer. In particular to this converter, the transformer leakage inductance can be used as the resonant inductance and in this way to element a discrete component from the PCB.

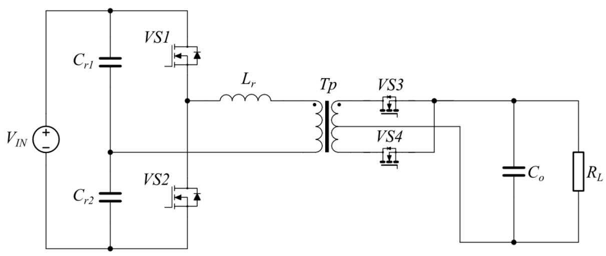

Fig. 1. Half-Bridge LLC Resonant DC/DC Converter with Synchronous Rectification

However for the modeling purpose it is invariant how the model parameters are loaded (inductance values, capacitances, resistances, etc.).

The converter mathematical model can be directly expressed with the following differential equations system:

$$\hat{L}\begin{pmatrix} \dfrac{di_1}{dt} \\ \dfrac{di_2}{dt} \end{pmatrix} + \hat{R}\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} fsw(t)\cdot U_{in} - u_{Cr} \\ -sign(i_2)u_{C0} \end{pmatrix}$$

$$C_r\frac{du_{Cr}}{dt} = i_1 \qquad (1)$$

$$C_0\frac{du_{C0}}{dt} + \frac{u_{C0}}{R} = |i_2|$$

Where the inductance and resistance matrices are:

$$\hat{L} = \begin{pmatrix} L_1 + L_r & L_m \\ L_m & L_2 \end{pmatrix}$$
$$\hat{R} = \begin{pmatrix} R_1 & R_m \\ R_m & R_2 \end{pmatrix} \quad (2)$$

The parameters in the equations are as following: $f_{sw}(t)$ – is a switching function, representing the semiconductor switching, that can be expressed mathematically as sign(sin(ωt)); i_1, L_1, R_1 – are respectively the current, inductance and resistance of the primary winding, and i_2, L_2, R_2 – are the circuit parameters of the secondary windings; L_m and R_m are the mutual inductance and mutual resistance of the resonant transformer; U_{in} is the input supply voltage; u_{Cr} is the resonant tank capacitor voltage; u_{C0} is the output voltage, C_r is the resonant capacitor, and L_r is the resonant inductance.

B. Analog compensator for the LLC converter

Although the resonant LLC converter output regulation depends on the operating frequency, which gives the need to convert the error voltage difference signal into frequency difference, which on the other hand poses some difficulties, it can be successfully operated using a simple PID-analog regulator as a controller.

On figure 2 is shown the PID-regulator in parallel form. Series and standard forms also exist, but there is no difference in between, only the coefficients are normalized due to the order of summation and multiplication of the terms.

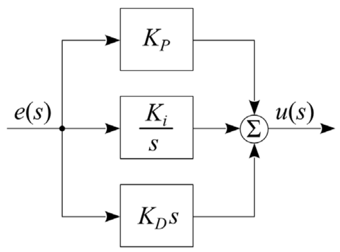

Fig. 2. Analog compensator – parallel PID regulator

However for the purpose of the digital transition the parallel PID-regulator will be reviewed. The transfer function is as follows:

$$\frac{u(s)}{e(s)} = K_p + \frac{K_i}{s} + K_d \cdot s \quad (3)$$

Using time constants for the differential and integral parts, the equation as follows:

$$\frac{u(s)}{e(s)} = K_p + \frac{1}{s \cdot T_i} + s \cdot T_d \quad (4)$$

A number of ways can be used to convert the analog compensator to a digital one [13]. Most common are the Tustin, Forward- and backward-Euler method. From practical point of view, they differ from the sampling frequency and the reaction capability of the control system.

C. Transition from analog to digital controller

There are three specific blocks that enable the digital controller to achieve the high-performance regulation requirements of an SMPS: the ADC used to sample the error voltage (and an associated reference point DAC), the digital filter that compensates the error signal, and the embedded pulse width modulator (ePWM) that converts the sampled, compensated error signal into gate-drive signals. Because most microcontrollers contain a communication interface, they can be easily configured from design software. This allows the design software to do the computation-intensive tasks in terms of modeling the system and calculating the appropriate coefficients and compensation of the converter.

From mathematical point of view the transition of the converter compensator begins with the discrete Laplace transform, using the Reverse-Euler transformation:

$$s \to \frac{1 - z^{-1}}{T_s} \quad (5)$$

Where T_s is the sampling period of the Analog to Digital Converter (ADC). Then, replacing (5) in (3) yields:

$$\frac{u(z)}{e(z)} = K_p + K_i \frac{T_s}{1 - z^{-1}} + K_d \frac{1 - z^{-1}}{T_s} \quad (6)$$

Using mathematical simplification the equation takes the form:

$$\frac{u(z)}{e(z)} = \frac{\left(K_p + \frac{K_d}{T_s} + K_i T_s\right) + z^{-1}\left(-K_p - 2\frac{K_d}{T_s}\right) + z^{-2}\left(\frac{K_d}{T_s}\right)}{\left(1 - z^{-1}\right)T_s} \quad (7)$$

The following transfer function is able to satisfy the form of the equation above:

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 - z^{-1}} \quad (8)$$

So, for the analog to digital compensator coefficients, the following relation between the analog and digital controller yields:

$$b_0 = K_p + \frac{K_d}{T_s} + K_i T_s$$

$$b_1 = -K_p - 2\frac{K_d}{T_s} \qquad (6)$$

$$b_2 = \frac{K_d}{T_s}$$

For example the following coefficients can be considered for the proportional, integrational and differential part: $K_p = 200$, $K_i = 1$ and $K_d = 5$. Using equations (6) and having a fixed sampling period $T_s = 10$ µs, this yields the following discrete coefficients $b_0 = 5 \cdot 10^7$, $b_1 = 1 \cdot 10^8$ and $b_2 = 5 \cdot 10^7$.

The evaluation of the parameters is done using these coefficients in the mathematical model.

III. Simulation Studies

The proposed LLC converter system is evaluated using simulational studies in MATLAB/Simulink. The converter principle is based on the differential equations, shown in (1) and (2). The analog compensator is a parallel PID-regulator as on figure 2, described by the transfer system on (4).

The resonant converter has the following parameters: Resonant Inductor: 55 µH; Resonant capacitor 24 nF; Output capacitor 1520 µF; Inductance of primary coil: 285 µH; Inductance of the secondary winding: 0.97 µH; Primary coil resistance: 210 mΩ; Resistance of the secondary coil: 3.5 mΩ; : A detailed description of the device's circuit elements is given in the sources [16]. On figure 2 are shown the resulting simulation waveforms. From top to bottom, the resonant inductor current (same as the primary winding current), the resonant capacitor voltage and the output voltage are plotted.

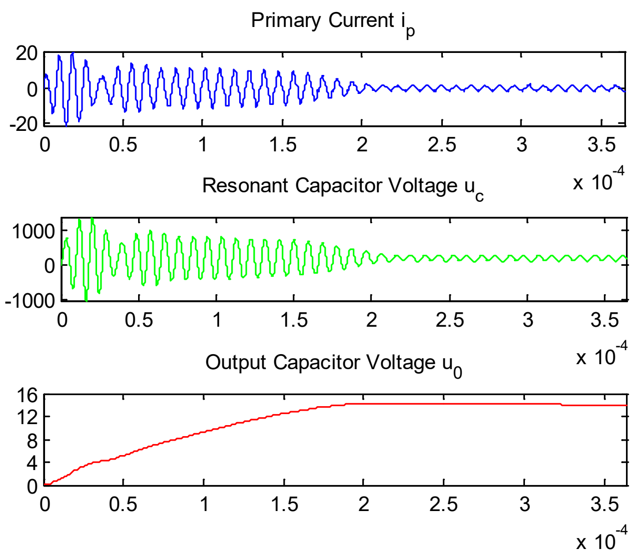

Fig. 2. Waveform of the LLC converter, simulated in MATLAB/Simulink

It can be observed, that the transient process is smooth, with minimal overshoot of 300mV in the output voltage. Compared to the desired 12V output voltage, this yields 2,5% overshoot. The regulator coefficients are as follows: $K_p = 190$, $K_i = 1$ and $K_d = 4$. The simulations are verified against a laboratory experiment.

IV. Experimental Results

The hardware verification of the simulation studies is intended to be with circuit parametrs as close as possible to the ones, used in the evaluation with the mathematical model. The laboratory test bench is composed of a high voltage power supply, four-channel DSO with two differential probes – one for the resonant capacitor voltage and one for the output voltage, along with a current probe, for the resonant current measurement. An electronic load is connected to the output for fine tuning of the output load and the device is galvanicaly split from the mains supply for more accurate and safe measurements.

The evaluation module used is the Texas Instruments' MDSHVRESLLCKIT Half-Bridge LLC Resonant DC/DC Converter with Synchronous Rectification which intentionally has the same circuit parameters, as those, loaded in the simulation model above. The regulator is realized using program software, using a microcontroller Piccolo F27038 on a controlCARD (as branded by Texas Instruments) with the developed software libraries for digital power control. The control algorithm is based on the transfer function (7), with the discrete coefficients yielding: $b_0 = 0.32$, $b_1 = -1.45$ and $b_2 = 1.3$. Please take a note, that these coefficients are in fixed point arithmetic, more precisely fixed point format Q26, which is described in detail in [16]. Those are also normalized against the analog-to-digital converter as should be done, according to [17] and [18], and then they are fed to the digital compensator programming routine. The ADC, with which the microcontroller is equipped is 12-bit with two sample and hold blocks for simultaneous sampling and up to 13-channels, which can be multiplexed.

The experimental waveforms are acquired on the figure 3, with a trigger level of the output voltage at 2V and a acquisition window of 5 µs.

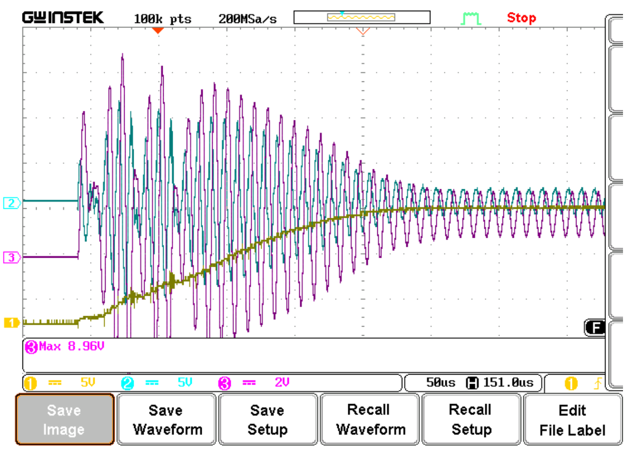

Fig. 3. Waveforms of the transient process of the LLC Resonant DC/DC Converter taken with Digital storage oscilloscope

On the figure from top to bottom are the following signals: the resonant current (2, blue), the resonant capacitor voltage (3, purple) and the output voltage (1, dark yellow).

As it can be observed the waveforms are similar to the ones produced by software simulation. The overshoot in this case is around 240 mV, according to the accuracy of the oscilloscope, which yields a 2% overshoot of the output voltage.

II. Conclusion

An approach for transition of an analog control system to digital one was presented by the work, using a dc-dc power electronic converter, in particular the resonant LLC converter. An embedded microcontroller was used to perform the calculations and formation of the control pulses of the device. A detailed procedure from transition from continuous transfer function to a discrete one was presented, alongside an example to convert from the continuous coefficients to discontinuous. The study was verified using software simulations and the tuning of the compensator yielded a smooth aperiodical transient process, with an overshoot of no more than 3%. A hardware board evaluation studies were conducted, using digital compensator with the calculated coefficient from the simulation ones. The resulting waveforms pose a good match between the simulation and hardware experiments.

Acknowledgment

The carried out research is realized in the frames of the project № 201ПР0007-03 in the research and development sector in the Technical University of Sofia.

References

[1] Hu Qing, Liang Zhonghua, Yu Haiyan, Xia Guiwen and Yang Xia, "Application of sliding mode control in control of power electronic converters," ICEMS'2001. Proceedings of the Fifth International Conference on Electrical Machines and Systems (IEEE Cat. No.01EX501), Shenyang, China, 2001, pp. 608-611 vol.1, doi: 10.1109/ICEMS.2001.970749.

[2] W. Wei, X. Haiping, W. Xuhui and S. Wenqing, "Dynamics and Control of Electronic Cascaded Systems," 2006 CES/IEEE 5th International Power Electronics and Motion Control Conference, Shanghai, 2006, pp. 1-4, doi: 10.1109/IPEMC.2006.4778070.

[3] M. Sanz et al., "Practicing design method of regulators for cascaded converters," 2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL), Santander, 2014, pp. 1-5, doi: 10.1109/COMPEL.2014.6877197.

[4] A. Khaligh and A. Emadi, "Pulse Adjustment, a Novel Digital Control Technique, for Control of a DC-DC Buck-Boost Converter Operating in Discontinuous Conduction Mode and Driving Constant Power Loads," 2006 IEEE Vehicle Power and Propulsion Conference, Windsor, 2006, pp. 1-5, doi: 10.1109/VPPC.2006.364355.

[5] R. R. Errabelli and P. Mutschler, "A fault tolerant digital controller for power electronic applications," 2009 13th European Conference on Power Electronics and Applications, Barcelona, 2009, pp. 1-10.

[6] Fujio Kurokawa, Masashi Okamatsu, Yuichi Sumida, Yasuhiro Mimura and Masahiro Sasaki, "A novel digital control method for dc-dc converter," 2008 13th International Power Electronics and Motion Control Conference, Poznan, 2008, pp. 2434-2438, doi: 10.1109/EPEPEMC.2008.4635628.

[7] D. Maksimovic, R. Zane and R. Erickson: "Impact of digital control in power electronics", Proceedings of-2004-International Symposium on Power Semi-conductor Devices & ICs, Kitakyushu, pp. 13-22, May 2004.

[8] T. Patarau, D. Petreus, R. Duma and P. Dobra, "Comparison between analog and digital control of LLC converter," 2010 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR), Cluj-Napoca, 2010, pp. 1-6, doi: 10.1109/AQTR.2010.5520806.

[9] F. Kurokawa, H. Maruta, K. Ueno, T. Mizoguchi, A. Nakamura and H. Osuga, "A new digital control DC-DC converter with neural network predictor," 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, 2010, pp. 522-526, doi: 10.1109/ECCE.2010.5617975.

[10] D. Maksimovic, R. Zane and R. Erickson, "Impact of digital control in power electronics," Proceedings of International Symposium on Power Semiconductor Devices & ICs, pp. 13-22, May 2004.

[11] P. T. Krein, "Digital control generations digital controls for power electronics through the third generation," Proceedings of the IEEE International Conference on Power Electronics and Drive Systems, November 2007.

[12] M.Morari and E.Zafiriou, Robust Process Control. Englewood Cliffs, NJ: Prentice-Hall, Jan. 1989.

[13] L. Corradini and P. Matavelli, “Analysis of multiple sampling technique for digitally controlled DC-DC converters,” Proc. IEEE Power Electron. Specialists Conf., pp. 1–6, June 2006.

[14] D. Maksimovic and R. Zane, “Small-signal discrete-time modeling of digitally controlled PWM converters,” IEEE Trans. Power Electron., Vol. 22, No. 6, pp. 2552–2556, Nov. 2007.

[15] M. Shirazi, R. Zane, D. Maksimovic, L. Corradini, and P. Mattavelli, “Autotuning techniques for digitally-controlled point-ofload converters with wide range of capacitive loads,” Proc. IEEE Appl. Power Electron. Conf. and Exposition, pp. 14–20, 2007.

[16] HV Resonant LLC Developer’s Kit. Available online: www.ti.com/tool/TMDSHVRESLLCKIT (accessed on 20 May 2019).

[17] Application Note TIDU257: “Resonant LLC Half-Bridge DC/DC Converter Software Design Guide”, TI Designs, April 2014

[18] B. Miao, R. Zane, and D. Maksimovic, “System identification of power converters with digital control through cross-correlation methods,” IEEE Trans. Power Electron., Vol. 20, No. 5, pp. 1093–1099, Sept. 2005.