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Simulation Peculiarities of High-Frequency Zero-Current Switching Quasi-Resonant Boost Converter

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***Abstract*—The article presents a comparative analysis of three approaches to the modelling of a zero-current switching quasi-resonant boost converter (ZCS-QRBC) performed in Matlab Simulink. The widely used approach based on the use of Power Electronics library components from SimPowerSystems Toolbox is found to be the most effective for an introduction at a glance to the basics of ZCS-QRBC operation as well as for educational purposes. A SPICE-model of ZCS-QRBC based on physical principles of elements operation is preferable to use to obtain the practical results quickly, elaborate ZCS-QRBC topology, select components, and establish a background for experimental investigations. In the later stages of system design the limited use of the simplified model is possible in order to comply with requirements of existing computational resources. It allows estimating the influence of a control method on the system dynamics and control accuracy or stabilization of a certain parameter.**

Keywords—high-frequency converter; Matlab Simulink; Power Electromics; power factor correction (PFC); quasi-resonant boost converter (QRBC); SimPowerSystems; SPICE models; zero-current switching (ZCS)

I. INTRODUCTION

The family of high-frequency quasi-resonant converters has been proposed and described in the late 1980s [1]. Taking into account their high energy efficiency, which is mainly provided by low power losses in power switch due to zero-current switching (ZCS) or zero-voltage switching (ZVS), these converters are still highly relevant today.

The modern studies are focused on energy consumption [2] and energy conversion [3]. There is a tendency to explore and develop new devices, which are able to deliver a significant increase of input voltage [4]. The most recent investigations are also devoted to power losses minimization [5], [6], [7] and reduction of total harmonic distortions to improve a power factor [8], [9], [10].

In particular the use of zero-current switching quasi-resonant boost converters (QRBC) in the power factor correction (PFC) devices appears as rather promising [11], [12], [13]. They represent an alternative to conventional boost converters which are usually used in PFC applications [8], [9]. The main advantage of ZCS-QRBC is primarily associated to a significantly higher switching frequency compared with conventional boost converters.

The higher switching frequency of ZCS-QRBC results into improvement in the weight and size parameters of the entire system [1], [5], [8], [9]. In addition, the dynamics of the converter could be increased [11], which not only improves the accuracy of output voltage stabilization [13], but also opens up prospects for use in high-performance industrial controllers [14], [15], [16].

The implementation of control systems for such converters is possible to perform based on modern high frequency control units: digital signal processors (DSP) [17] or field-programmable gate arrays (FPGA) [18].

One of the challenges encountered in the practical implementation of the ZCS-QRBC is to provide the precise switching at a zero current. This limits the operating range of the converter both in frequency and output voltage, leads to the need of keep track the switch current etc.

There are also many parasitic parameters of the circuit and the experimental board, which under high frequencies could significantly degrade not only the quality of the energy conversion, but also endanger the overall operation of the physical model.

Hence there is a need for a computer simulation of ZCS-QRBC, which as known can significantly reduce the time and costs for experimental prototype building and industrial design.

A considerable attention was paid to the analysis and improvement of QRBC [19], [20]. The functions offered by the computer technology, as well as a new element base of power converters [4], [7] and their control systems [17], [18] articulates the need to revise traditional approaches to the simulation of these devices.

To achieve successful research results, the accuracy of the model from the viewpoint of the correctness of the reflection of the controlled object's critical properties is crucial [15], [16]. On the other hand, the parameters of modern computers, despite significant progress, have some limitations, such as performance, memory and cost.

This work discusses several models of ZCS-QRBC built in Matlab Simulink, which are deemed the most suitable for the various stages of studying the systems with ZCS-QRBC in order to effectively achieve the experimental prototyping.

II. ZCS-QRBC MODEL BASED ON POWER ELECTRONICS LIBRARY COMPONENTS

SimPowerSystems software [21] similar to other simulation tools interacts with Matlab Simulink [22], which allows simulating different mechanical and electrical systems and their control. The first model of ZCS-QRBC (Fig. 1) is built on the elements contained in the SimPowerSystems Toolbox (Power Electronics library) from the simulation software Matlab Simulink. The oscilloscope Choke is used to display the dynamic processes in the storage inductor. The oscilloscope MosFET visualizes the switch current and voltage, and the oscilloscope Diagram shows other timing diagrams of the ZCS-QRBC operation.

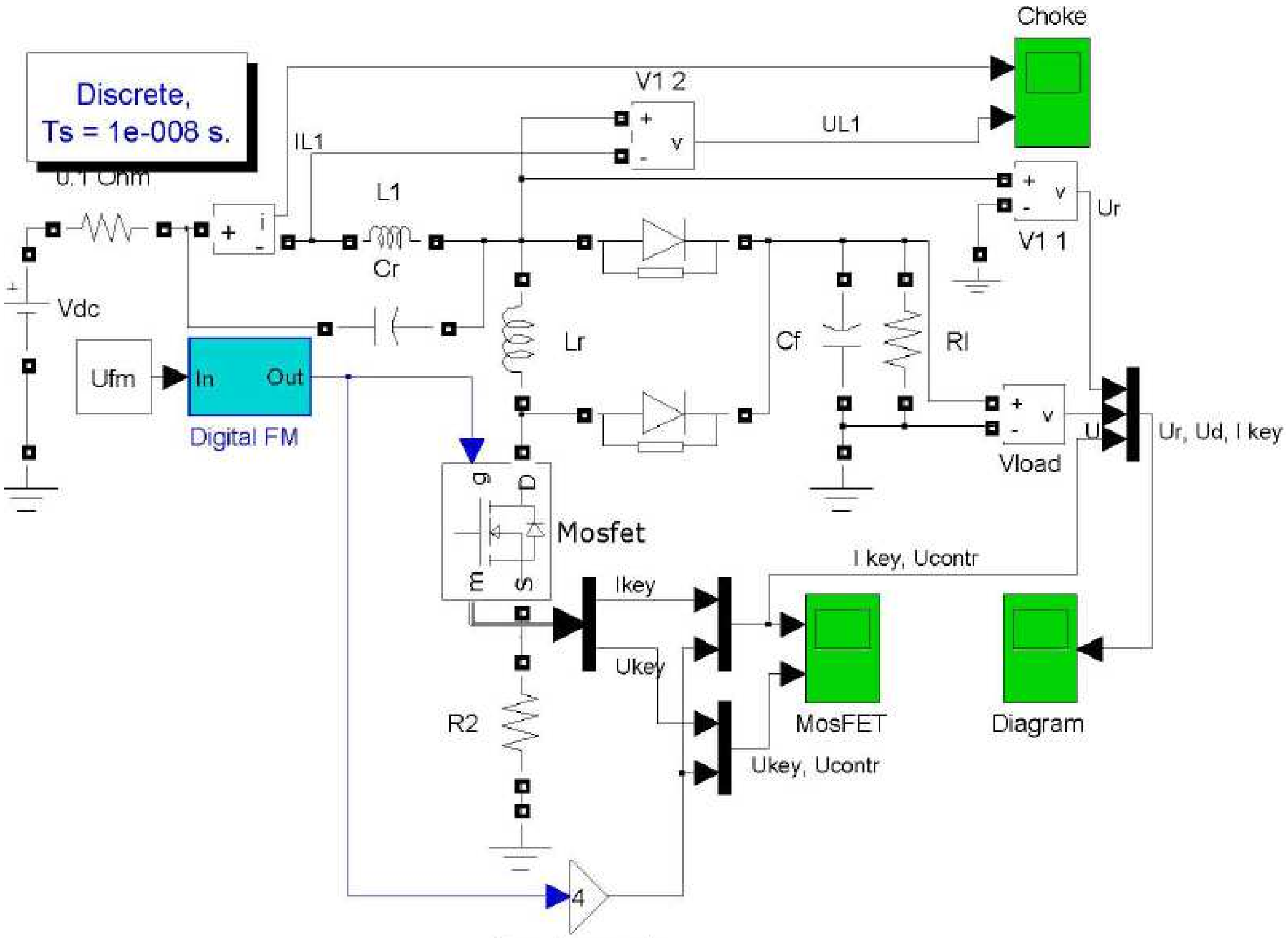

Fig. 1. A zero-current switching quasi-resonant boost converter model based on Power Electronics library components

The formation of control signals for the switch is performed using a frequency modulator Digital FM. The period of oscillations in the resonant circuit is $T_0 = 2\pi\sqrt{L_r C_r}$, where L_r is a value of the resonant inductance; and C_r is a value of the resonant capacitance. Since the frequency modulation is used in the ZCS-QRBC, the duty cycle of the control signal must satisfy the condition of the switching at zero current. The corresponding parameters according to [1] for this condition to be satisfied are *Lr*=0.61 uH, *Cr*=60 nF. Other parameters include *L1*=100 uH, *Cf*=100 uF.

Fig. 2 shows a timing diagram of the current transient process in the storage inductor L1 after the supply voltage for ZCS-QRBC had been switched on and under fixed reference level at the input of the frequency modulator.

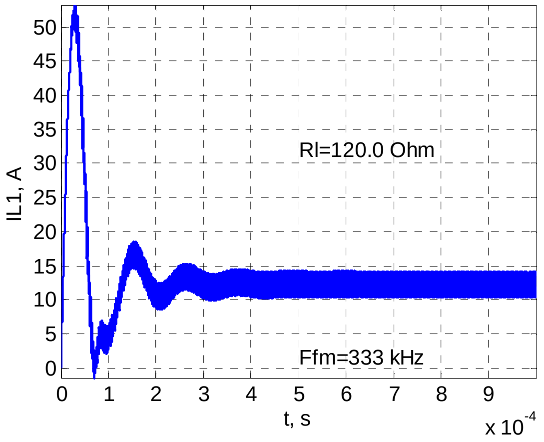

Fig. 2. A current transient process in the storage inductor

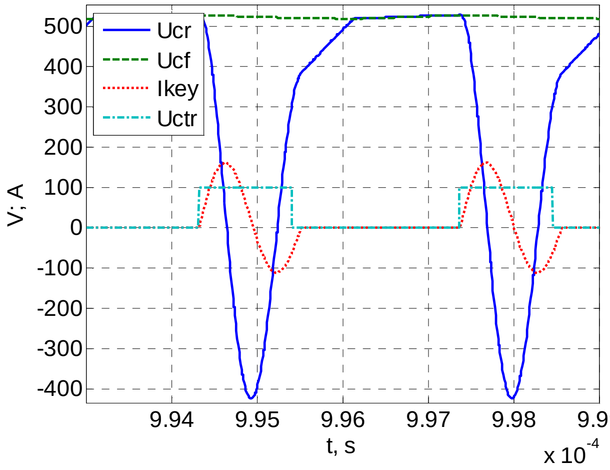

Fig. 3. Steady-state currents and voltages in a zero-current switching quasi-resonant boost converter

Fig. 3 shows the ZCS-QRBC operation within the switching period in the steady state. The switch current is *Ikey*, the voltage on the resonant circuit is *Ucr* and the load voltage is *Ucf*.

These diagrams allow estimating the operation ranges of the output voltage and switching the frequency of ZCS-QRBC depending on the load. A prerequisite for an adequate work is zero-current switching.

The unsatisfactory switching process requires a reduction of the switching frequency or load. With the load current increase (decrease load resistance) the voltage control range of ZCS-QRBC is narrowed at lower values.

In the used MOSFET model there are no elements that determine the quality of the switch gate control. It is assumed that the power switch is ideal with the logical level control, which does not require any special driver. However, the problem of an effective MOSFET opening and closing is presented even in a PWM boost converter, which works at high frequencies.

One of the most important parameters of MOSFET used in ZCS-QRBC is the resistance of the channel in the open state. However, the elements of the scheme which are not the most important at a glance can significantly distort the behaviour of the computer model with respect to the real object. It will not solve the major problem of the ZCS-QRBC design. These elements of the scheme include:

1) The series resistor in the gate circuit, which smoothes the switch ON voltage and protects the driver. Any operation of the scheme without this element is nearly becomes impossible.

2) The current sensor is needed to track zero crossing points of the source current, as well as for MOSFET protection under the critical conditions. In practice, this sensor in addition to the active component comprises also inductance that affects the operation of the device at high frequencies. This sensor is connected in series with the switch and therefore it affects the device efficiency.

3) Even though it might seem inessential, parasitic parameters of the circuit elements working at high frequencies can also significantly affect the results. The main problem that may arise encompasses non-zero-current switching when the power dissipated in the switch increases rapidly and the most important advantage of ZCS-QRBC is lost.

III. SPICE MODEL OF A ZERO-CURRENT SWITCHING QUASI-RESONANT BOOST CONVERTER

Due to the nature of pulse switches and taking into account their direct interaction with real objects, it is advisable to use such Simulink extension as Simscape, which allows simulation of the physical systems containing mechanical, hydraulic, pneumatic, thermal, electrical and electromagnetic components, representing the physical devices and their mathematical descriptions directly.

A SimElectronics extension works with Simscape and opens up the possibility of physical modelling of electromechanic and electronic systems.

A SimPowerSystems toolbox is specially designed for modelling of semiconductor devices by the means of Simulink.

Unfortunately, these models do not allow analyzing the behaviour of a pulse converter with sufficient reliability. Thus, in a model of MOSFET with induced channel (from POwerGUI library), Fig. 4, the input capacitance is not shown. This is critically important in ZCS-QRBC when switching to a high frequency and the shape of the gate voltage affects the transient processes significantly.

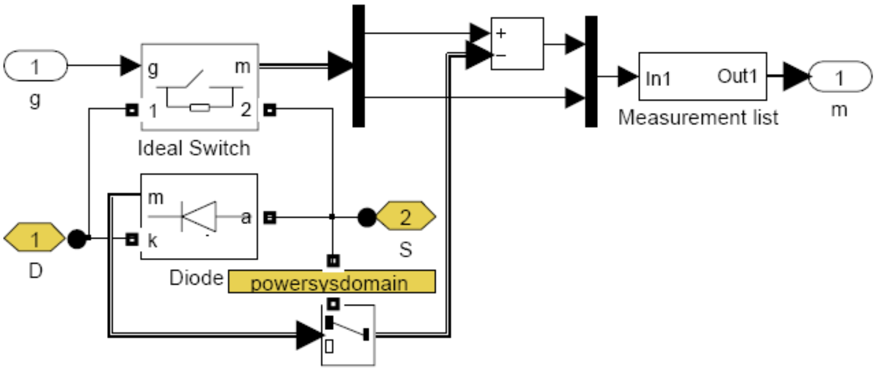

Fig. 4. MOSFET model from POwerGUI library

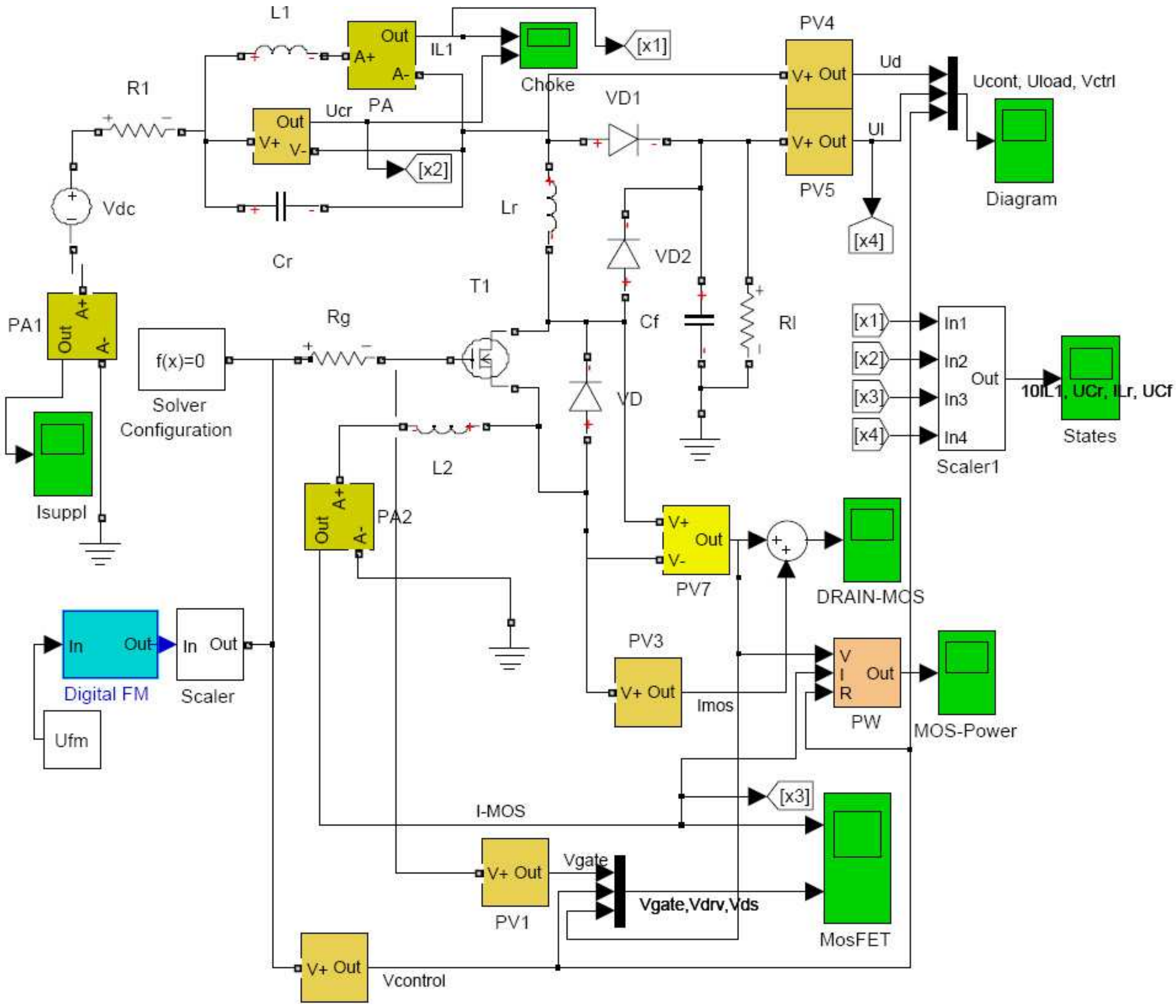

Fig. 5. SPICE model of a zero-current switching quasi-resonant boost converters based on Simscape elements

In order not to involve the external programs of low-level modelling of electronic components (e.g. Cadence), the library Simscape → Additional Components → SPICE-Compatible Components is available to use. Fig. 5 shows a SPICE model of the investigated ZCS-QRBC based on the elements from Simscape.

The most important differences of this model compared to the one shown in Fig. 1 include the active components' models, e.g. a model N-Channel MOSFET (T1). Since for the basis of the model the physical processes in the transistor are used, the abovementioned "fine points" may be studied. The SPICE models for simulation of ZCS quasi-resonant buck converters were successfully used [23], [24].

Fig. 6 shows the simulation results for ZCS-QRBC (timing diagrams of the state variables), which uses the characteristics of the MOSFET model RFP27N60K. Other parameters of the components are similar to the model in Fig. 1.

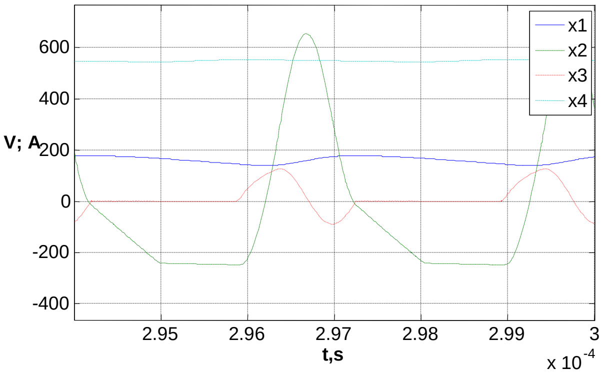

Fig. 6. State variables in a zero-current switching quasi-resonant boost converter

The variables depicted in Fig. 6 are the following:

x1 is the current of the storage inductor *L1*;

x2 is the voltage of the resonant capacitor *Cr*;

x3 is the current of the resonant inductance *Lr*;

x4 is the voltage of the filter capacitor *Cf*.

Fig. 7 shows the simulation results of transient process of ZCS-QRBC load voltage after a sudden appearance of the switching frequency *Ffm* = 333 kHz.

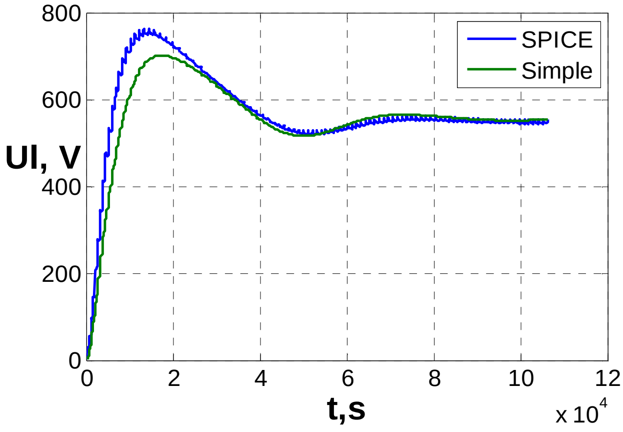

Fig. 7. Transient response in a zero-current switching quasi-resonant boost converter

As it can be seen from Fig. 7, the reaction of ZCS-QRBC on the step of frequency corresponds to the oscillating unit with the following transfer function:

$$K_{QRBC}(s) = \frac{K_o}{D_2 s^2 + D_1 s + 1}, \qquad (1)$$

where K_0 is a static transfer coefficient of ZCS-QRBC switching frequency; D_1, D_2 are the coefficients of the denominator of the transfer function of ZCS-QRBC.

After the identification of ZCS-QRBC as an object of control [16] the following coefficients were obtained:

$K_0 = 1.74$ V/kHz; $D_1 = 15.7\cdot 10^{-6}$ s; $D_2 = 40.5\cdot 10^{-11}$ s^2.

In Fig.7 the ‘Simple’ curve represents the response of the oscillating unit with the transient function (1).

IV. SIMPLIFIED MODEL OF A ZERO-CURRENT SWITCHING QUASI-RESONANT BOOST CONVERTER

During the process of simulation of ZCS-QRBC control system the use of SPICE model can quickly lead to the memory overflow.

Assuming a linear dependence between the ZCS-QRBC output voltage and the control signals frequency, the model of ZCS-QRBC can be significantly simplified (Fig. 8).

The control signal from the frequency modulator comes to the input port, and a sum of gain blocks allows building the linearized control curve based on the two points:

$$K_{QRBC} = \frac{U_{L\max} - U_{\mathrm{L}\min}}{F_{\max} - F_{\min}}. \qquad (2)$$

Using (2) one can write:

$$U_{QRBC} = U_{L\max} - K_{QRBC} F_{\max} = U_{\mathrm{L}\min} - K_{QRBC} F_{\min}. \qquad (3)$$

The coordinates of two points of control curve (3) can be obtained experimentally.

For the frequencies $F_{min} = 200$ kHz, $F_{max} = 400$ kHz and voltages $U_{Lmin} = 11.0$ V, $U_{Lmax} = 14.0$ V we can obtain:

$K_{QRBC} = 0.015$ V/kHz; $U_{QRBC} = 10.4375$ V.

In addition, while examining the dynamic processes in the system with ZCS-QRBC, it is recommended to include into a simplified model a delay element, the value of which should be confirmed experimentally.

A simplified model is useful for studying the behaviour of a system containing ZCS-QRBC as it allows significant savings of the computing resources. However, it should be noted, that this model is valid only for the fixed values of the input voltage.

V. CONCLUSIONS

In this article three simulation approaches for high-frequency zero-current switching quasi-resonant boost converter were proposed, and appropriate models were analyzed in Matlab Simulink, which are deemed the most suitable for the various stages of studying the systems with zero-current switching quasi-resonant boost converter in order to effectively achieve the experimental prototyping.

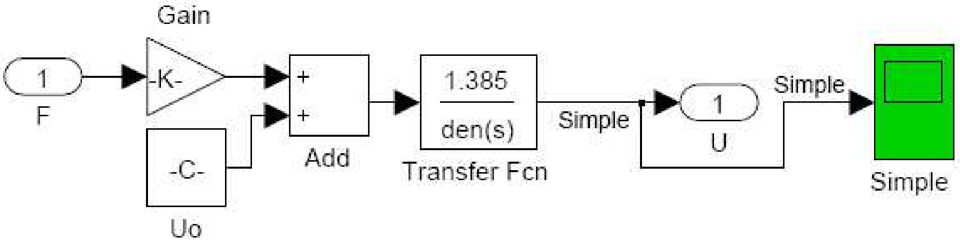

Fig. 8. Simplified model of a zero-current switching quasi-resonant boost converter

The widely used simulation approach, which is based on the use of Power Electronics library components from the SimPowerSystems Toolbox, is found to be the most effective for a quick introduction to the basics of quasi-resonant boost converter operation and for educational purposes.

The SPICE-model of ZCS-QRBC, which is based on the physical principles of elements' operation, is preferable to use for a quick obtaining of practical results, elaboration of ZCS-QRBC topology, selection of components and building the background for experimental investigations.

In the following stages of the system design, the limited use of the simplified model is possible in order to comply with the requirements of existing computational resources. It allows estimating the influence of a control method on the system dynamics, control accuracy or stabilization of specific parameters.

REFERENCES

[1] Kwang-Hwa Liu, R. Oruganti and F.C.Y. Lee, "Quasi-Resonant Converters-Topologies and Characteristics," IEEE Transactions on Power Electronics, vol. PE-2, no. 1, pp. 62-71, Jan. 1987.

[2] I. Pichkalov, "Optimal coordinated control of diesel generator and battery storage system of stand-alone Microgrid," 2014 IEEE 2nd Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), pp.1-4, 28-29 Nov. 2014, doi: 10.1109/AIEEE.2014.7020331

[3] A. Suzdalenko, "Development of single-switch model for current sensorless control of bidirectional half-bridge AC/DC converter," 2014 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), pp. 38-42, 14-14 Oct. 2014, doi:10.1109/RTUCON.2014.6998200

[4] D. Vinnikov, J. Zakis, O. Husev and R. Strzelecki, "New high-gain step-up DC/DC converter with high-frequency isolation," 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1204-1209, 5-9 Feb. 2012, doi:10.1109/APEC.2012.6165972

[5] O.M. Afanasyev and A.A. Shcherba, "Method for determining energy losses in switched-mode converter power switches depending on storage inductor current modes," 2013 IEEE XXXIII International Scientific Conference Electronics and Nanotechnology (ELNANO), pp. 339-343, 16-19 April 2013, doi:10.1109/ELNANO.2013.6552058

[6] M.Yu. Artemenko, L.M. Batrak, S.Y. Polishchuk, V.M. Mykhalskyi, and I.A. Shapoval, "Minimization of cable losses in three-phase four-wire systems by means of instantaneous compensation with shunt active filters," 2013 IEEE XXXIII International Scientific Conference Electronics and Nanotechnology (ELNANO), pp. 359-362, 16-19 April 2013, doi:10.1109/ELNANO.2013.6552031

[7] A. Chub, O. Husev and D. Vinnikov, "Passive modular structure of a SEPIC based DC/DC converter," 2014 IEEE International Conference on Intelligent Energy and Power Systems (IEPS), pp. 81-85, 2-6 June 2014, doi:10.1109/IEPS.2014.6874208

[8] Y. Demchenko, "Energy performance comparison of active high frequency power factor correctors," 2014 IEEE 34th International Conference on Electronics and Nanotechnology (ELNANO), pp. 447-450, 15-18 April 2014, doi:10.1109/ELNANO.2014.6873444

[9] S.A. Stepenko, "Energy efficiency analysis in power factor corrector under different pulse-width modulation modes," Tekhnichna elektrodynamika, no. 4, pp. 78-80, 2014.

[10] O.F. Bondarenko, P.S. Safronov, I.V. Bondarenko and V.M. Sydorets, "Direct energy and energy storage circuit topologies of DC power supplies for micro resistance welding," 2014 IEEE 34th International Conference on Electronics and Nanotechnology (ELNANO), pp. 468-471, 15-18 April 2014, doi:10.1109/ELNANO.2014.6873431

[11] Y. Denisov and S. Stepenko, "Power Factor Corrector Based on Parallel Quasi-Resonant Pulse Converter with Fast Current Loop," Electrical, Control and Communication Engineering, Vol. 3, Issue 1, pp. 5–11, September 2013, doi:10.2478/ecce-2013-0008

[12] Y.O. Denisov, S.A. Stepenko, A.N. Gorodny and A.O. Kravchenko, "Input current parameters analysis for PFC based on quasi-resonant and conventional boost converters," 2014 IEEE 34th International Conference on Electronics and Nanotechnology (ELNANO), pp.393-397, 15-18 April 2014, doi:10.1109/ELNANO.2014.6873446

[13] Yu.O. Denisov and S.A. Stepenko, "Structural realization of two-loops PFC based on zero current switching quasi-resonant pulse converters," Tekhnichna elektrodynamika, no. 1, pp. 29-36, 2015.

[14] V.P. Voitenko, "Algorithm stages of quasi-optimal regulation in system with a pulse converter," Tekhnichna elektrodynamika, no.3, pp.125-126, 2012.

[15] M. Khomenko, V. Voytenko and Y. Vagapov, "Neural network-based optimal control of a DC motor positioning system", Int. J. Automation and Control, Vol. 7, Nos. 1/2, pp. 83–104, 2013, doi:10.1504/IJAAC.2013.055097

[16] V.P. Voytenko. Quasi-optimal industrial regulators with neuro-identification of the object of control. Chernigov: Chernigov State Technological University, 2013, ISBN: 978-966-7496-42-5

[17] A. Suzdalenko, A. Lazdans and I. Galkin, "Development of multi-channel analogue signal data logger based on MSP430," 2012 5th European DSP Education and Research Conference (EDERC), pp. 40-43, 13-14 Sept. 2012, doi:10.1109/EDERC.2012.6532221

[18] S. Stepenko, O. Husev, D. Vinnikov and S. Ivanets, "FPGA control of the neutral point clamped quasi-Z-source inverter," 2012 13th Biennial Baltic Electronics Conference (BEC), pp. 263-266, 3-5 Oct. 2012, doi:10.1109/BEC.2012.6376867

[19] S.Y.R. Hui, E.S. Gogani and Jian Zhang, "Analysis of a quasi-resonant circuit for soft-switched inverters," IEEE Transactions on Power Electronics, vol.11, no.1, pp. 106-114, Jan 1996, doi:10.1109/63.484423

[20] J.J. Jafar and B.G. Fernandes, "A new quasi-resonant DC-link PWM inverter using single switch for soft switching," IEEE Transactions on Power Electronics, vol. 17, no. 6, pp. 1010-1016, Nov 2002.

[21] SimPowerSystems User's Guide, Ver. 3. Hydro-Québec, TransÉnergie Technologies. Natick, MA: The MathWorks, September 2003.

[22] R. Shaffer. Fundamentals of Power Electronics with MATLAB. Boston, MA: Charles River Media, 2007, ISBN: 1-58450-852-3

[23] S. Ben-Yaakov, D. Edry, Y. Amran and O. Shimony, "SPICE simulation of quasi-resonant zero-current-switching DC-DC convertors," Electronics Letters, vol. 26, no. 13, pp. 847-849, 21 June 1990, doi:10.1049/el:19900555

[24] J. Xu and M. Grotzbach, "Time-domain analysis of half-wave zero-current switch quasi-resonant converters by using SPICE," IEEE Transactions on Industrial Electronics, vol. 40, no. 6, pp. 577-579, Dec. 1993, doi:10.1109/41.245895