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A New Approach of Control System Design for LLC Resonant Converter

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1. Introduction

Main task of power semiconductor converter is transfer of electrical energy from its input to the output and to the load. This energy flow is provided by control of the switching process of one or more semiconductor devices. Based on converter application it is necessary to choose correct control algorithm for selected switching frequency of converter. Algorithm itself has to be utilized with suitable hardware platform, whereby through the set of instructions the turn - on and turn - of control pulses are generated. Control system also has to secure other important functions for secondary processes. Nowadays a huge number of converter topologies exists, whereby each type should be suited for different conditions of use. For example uninterruptible power supply must generate constant output voltage with constant frequency and constant amplitude for wide range of output power. Converters for electric drive applications have to control their speed through generation of three phase voltage system with configurable amplitude and speed. From mentioned above it is clear to say that for each topology of power converter, the different type of control modulation (PWM - Pulse Width Modulation, PSM - Phase Shift Modulation, FM - Frequency Modulation) and different structure of regulator has to be used. Therefore selection of suitable control system depends on number of various factors, which are output power of converter, type of switching devices, type of load, possibility of hardware implementation and ways of switching.

In the field of DC/DC converters for switching power supplies, the main focus is on implementation of digital control, which means use of microcontrollers or DSP with implemented control algorithms and functions for communication with user as well. Analog control systems are well known and its design procedure is mastered, so it is easy to convert analog (continuous) controller into discrete and consequently implementing in microcontroller and DSP. But this approach ignore sample and hold effect of A/D converter and computing time of microprocessor. For proper discrete controller design, the method named direct digital design can be used. This method uses transfer function of converter in discrete form, including effect of sampling and computation delay.

For controller design purposes, transfer function of converter is necessary. This transfer function is based on model of power stage of controller. For PWM converters such as buck, boost, etc. the averaging method is widely used, but for new resonant topologies such as LLC converter, with this averaging method, the control to output transfer function cannot be used. In this chapter, new simulation based method for obtaining the transfer function of converter is discussed. This method uses MATLAB and OrCad PSPICE environments for

revealing the transfer function. Advantage of this method is, that it can be used for every type of power converter. Next in the chapter, the direct digital design of controller based on transfer function is discussed. This method uses MATLAB environment for designing the discrete controller.

2. The ways of regulation of electric quantities in power converters

From the various types of regulation of electric quantities (voltage, current) the most well-known are PWM, PSM, and FM. In pulse width modulation (PWM) technique, the mean value of output voltage or current is controlled through the change of on-time (t_{on}) or off-time (t_{off}) of power transistor. Generation of PWM signals is based on comparison between repeating sequence (sawtooth signal or triangular signal with constant frequency) and between reference value of voltage (u_{reg}) which is generated from regulator. This principle is for analog and digital system almost the same. The only difference in the case of analog system is that repeating sequence is generated from op-amplifier and consequently compared with reference value in analog comparator. For generation of repeating sequence the digital system instead of op-amplifier utilizes digital timer. Comparator is replaced by compare register. The proportional on-time in the case of direct quantities is called duty cycle - D , and is defined as follows:

$$D = t_{on}/T \quad (1)$$

where t_{on} is on-time of semiconductor devices, and T_s is switching period of converter.

In the case of phase shift modulation (PSM) the mean value of output voltage is controlled by phase shift of on-times of two or more semiconductor devices, such two transistors in upper or lower leg of fullbridge converter are switched simultaneously, whereby switching frequency and duty cycle are constant. The application of PSM is well suited in ZVS (Zero Voltage Switching) and ZCS (Zero Current Switching) resonant converters.

Frequency modulation is basically similar to PWM. Difference is that duty cycle in this case is always constant ($D = \text{const.}$), but frequency of switching signal is varying ($f_{sw} = \text{var.}$). Based on the change of control voltage u_{reg} , the switching frequency of PWM signal is being changed. In the case of analog circuits the frequency modulation is realized through utilization of voltage control oscillator (VCO). On the other hand, in the case of digital implementation the VCO is not required, because frequency of timer is able to be changed directly.

These previously mentioned ways of regulation of electric quantities in power converters are basic types, whereby also their combination is being utilized in practical applications.

3. LLC converter - properties and principle of operation

LLC resonant converter is multi-resonant converter and is characterized by its unique DC - gain characteristic, which has two resonant frequencies (f_{r1} and f_{r2}). This converter has several advantages compared to standard serial LC resonant topology. One of them is possibility of stable regulation of output voltage in a wide range of input voltages together with the change of output power from 1% to 100%. The next advantage is achievement of ZVS switching mode during various operational modes. LLC resonant converter is composed of three functional parts (Fig. 1a). It deals about pulse generator, resonant circuit with high-frequency transformer and rectifier with capacitive filter. Operation of LLC converter in different operational modes is described by DC gain characteristic (Fig. 1b),

which should be divided into ZVS and/or ZCS region. ZVS region in dependency on the switching frequency can be further divided into:

- region with switching frequency equal to resonant ($f_{sw} = f_{r1}$)
- region1 with switching frequency higher than resonant ($f_{sw} > f_{r1}$)
- region2 with switching frequency lower than resonant ($f_{sw} < f_{r1}$)
- region3 with switching frequency lower than resonant and with voltage gain < 1

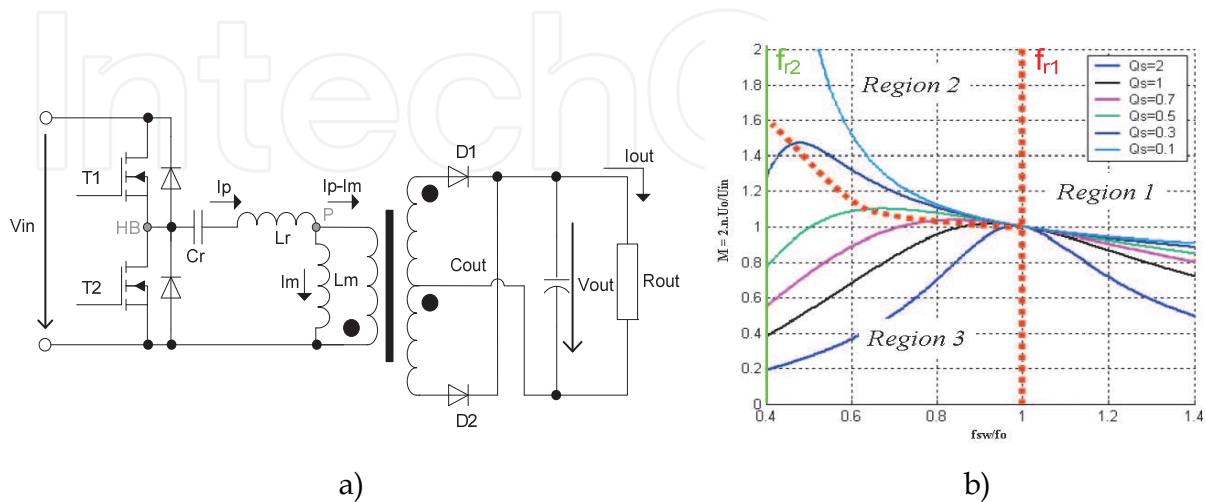


Fig. 1. a) Principle schematics of LLC converter, b) DC-gain characteristic of LLC converter

According to the operational modes of resonant converters the operation of LLC resonant converter is rather difficult. The principal waveforms of transformer and output diode during each operating mode are shown in Fig. 2. The impedance of series resonant circuit at the resonant frequency is equal to zero. Therefore the reflected output voltage is equal to the input voltage, what is described by the unity of voltage gain thus the circuit then operates optimally. LLC resonant converter can achieve greater gain, lower or equal to 1. If the switching frequency is less than the resonant frequency, magnetization inductance is involved into the resonance of the circuit so the converter can deliver higher gain.

For analysis of operation of LLC converter it is necessary to exactly examine voltage gain characteristic. Voltage gain characteristic is possible to be made from equivalent circuit of converter. Output part together with rectifier and load is replaced by equivalent output resistance which is marked as R_{AC} .

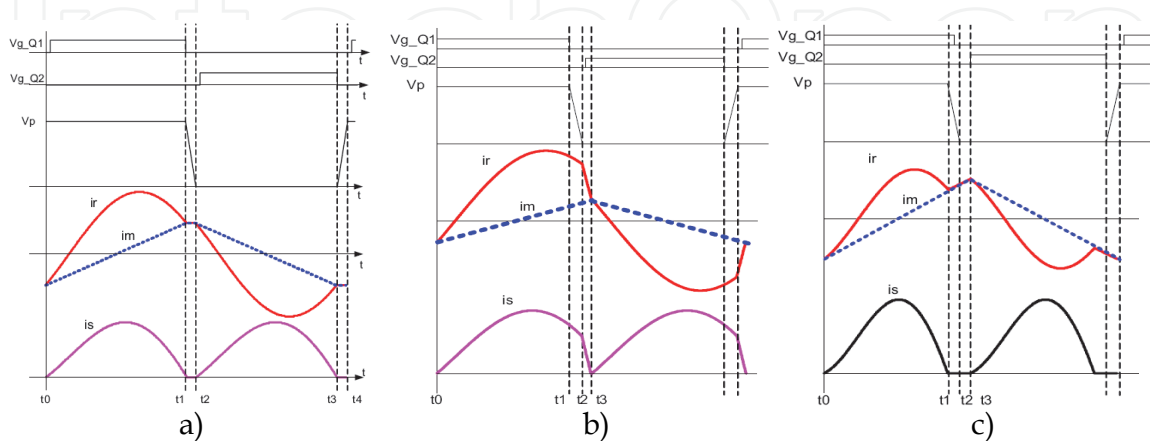


Fig. 2. Waveforms of currents and voltages of LLC converter at different operating conditions a) $f_{sw} = f_{r1}$, b) $f_{sw} > f_{r1}$, c) $f_{sw} < f_{r1}$

Considering, that converter is working with almost resonant frequency, only first harmonic is transferred through resonant circuit, and therefore it is possible to utilize simple approximation, where rectangular pulses are substituted by sinusoidal waveforms.

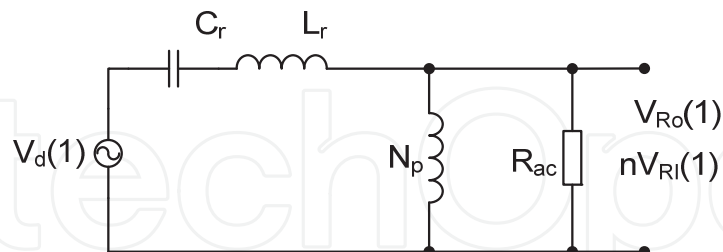


Fig. 3. Equivalent circuit of LLC converter

For voltage expressions of this equivalent circuit next formulas are valid:

$$V_{RI(1)} = \frac{4 \cdot V_o}{\pi} \cdot \sin(\omega t) \quad (2)$$

$$V_{d(1)} = \frac{4}{\pi} \cdot \frac{V_{in}}{2} \cdot \sin(\omega t) \quad (3)$$

where V_{RI} is voltage at the output of resonant circuit, and V_d is first harmonic part of supply voltage.

The equivalent circuit of converter is then similar to that which is shown on Fig.3. Equation of voltage gain characteristic is then equal to:

$$M = \frac{2nV_o}{V_{in}} = \left| \frac{\left(\frac{\omega^2}{\omega_{r1}^2} \right) \cdot \sqrt{m \cdot (m-1)}}{\left(\frac{\omega^2}{\omega_{r2}^2} - 1 \right) + j \cdot \left(\frac{\omega}{\omega_{r1}} \right) \cdot \left(\frac{\omega^2}{\omega_{r1}^2} - 1 \right) \cdot (m-1) \cdot Q} \right| \quad (4)$$

where:

$$f_{r1} = \frac{1}{2\pi \cdot \sqrt{L_R \cdot C_R}} \quad (5)$$

$$f_{r2} = \frac{1}{2\pi \sqrt{(L_M + L_R) \cdot C_R}} \quad (6)$$

$$Q = \frac{\sqrt{\frac{L_R}{C_R}}}{R_{AC}} \quad (7)$$

$$R_{AC} = \frac{8 \cdot n^2}{\pi^2} \cdot R_O \quad (8)$$

Voltage gain characteristic of proposed converter is shown on Fig. 4. X-axis is defined as switching frequency, or better said frequency of input sinusoidal voltage. Ratio between output voltage and input voltage is marked on y-axis. Each wave is related to different loads of converter (quality factors Q). Main parameters of converter are: $V_{in} = 400\text{ V}$, $V_{out} = 60\text{ V}$, $L_r = 6.6\text{ }\mu\text{H}$, $C_r = 900\text{ nF}$, $L_m = 36\text{ }\mu\text{H}$, $L_{r2} = 3\text{ }\mu\text{H}$, $R_{omin} = 2.4\text{ }\Omega$, $I_{max} = 25\text{ A}$

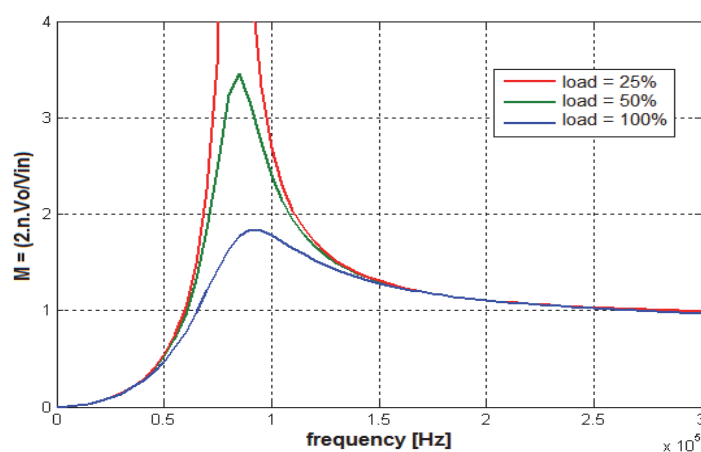


Fig. 4. Voltage gain characteristic of proposed converter.

3.1 Regulation of LLC converter

The regulation algorithm for the LLC converter maintains the requested value of output voltage, during the change of input voltage or output load. The LLC converter is controlled by variations of switching frequency, so the active part of the regulator is a voltage controlled oscillator (VCO) in analog or digital (software) form. The change of the output frequency is based on the input voltage of the VCO. As mentioned above, the switching frequencies of the LLC converter are between f_{r1} and f_{r2} during normal operation. The regulation algorithm works as follows: The normal operating point (Fig. 5a point 1) is characterized by $V_{IN}=400\text{ V}$, $U_{OUT}=60\text{ V}$. If the input voltage drops below 400 V , the regulation algorithm reacts in form of switching frequency reduction, so the operating point of the converter moves from the point 1 to the point 2. In this point, the converter works with the increased gain to maintain the output voltage at the constant value (60 V). The minimal input voltage is defined as 325 V , so it is not possible to maintain the output voltage on 60 V below this value.

If the input voltage rises back to 400 V , the control system increases the switching frequency - voltage gain decreases and the operating point of the converter moves back to the point 1. The next operating condition for the LLC converter is variation of the output load. Fig. 5b shows the point 1, where the converter works with full load, the operating point is on the curve with $Q=100\%$. When the output load drops, the operating point moves from the curve with $Q=100\%$ to the curve with $Q=10\%$, which means that for the constant switching frequency, the output voltage rises to 60% above the nominal value, so the regulation algorithm rises the switching frequency which leads to lower voltage gain and output voltage decrease to nominal value.

Specific case of operation is the start of the converter, when the switching frequency is higher than the resonant frequency f_{r1} to avoid current inrush during the initial charge of the output capacitor C_{OUT} . Generally, for the soft start, the switching frequency is two or three times higher than the resonant frequency. Voltage gain on this frequency is lower (Fig. 4), so the charging current of the output capacitor stays on an acceptable level.

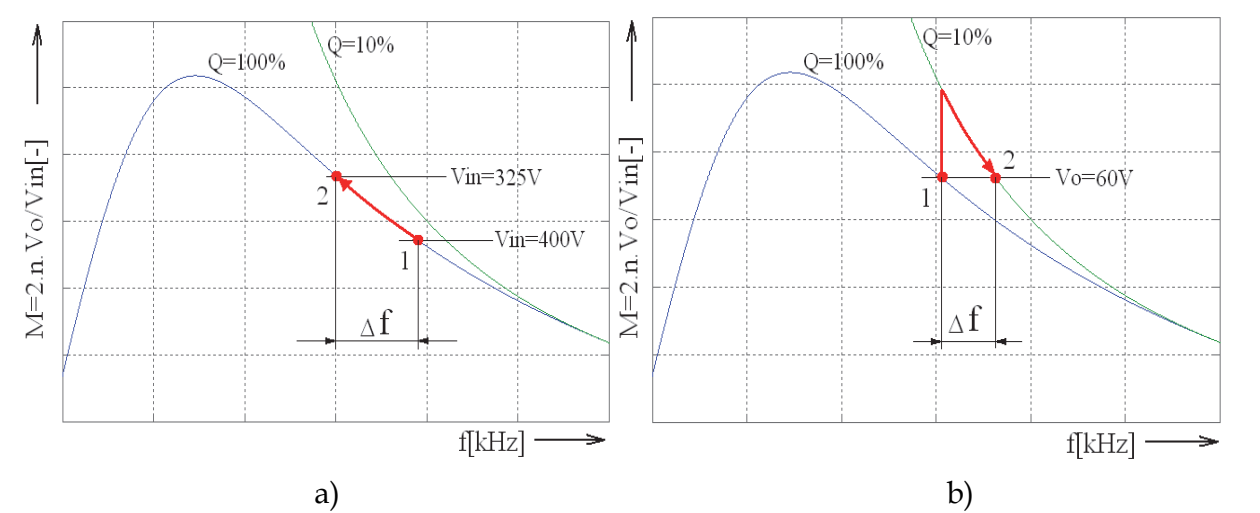
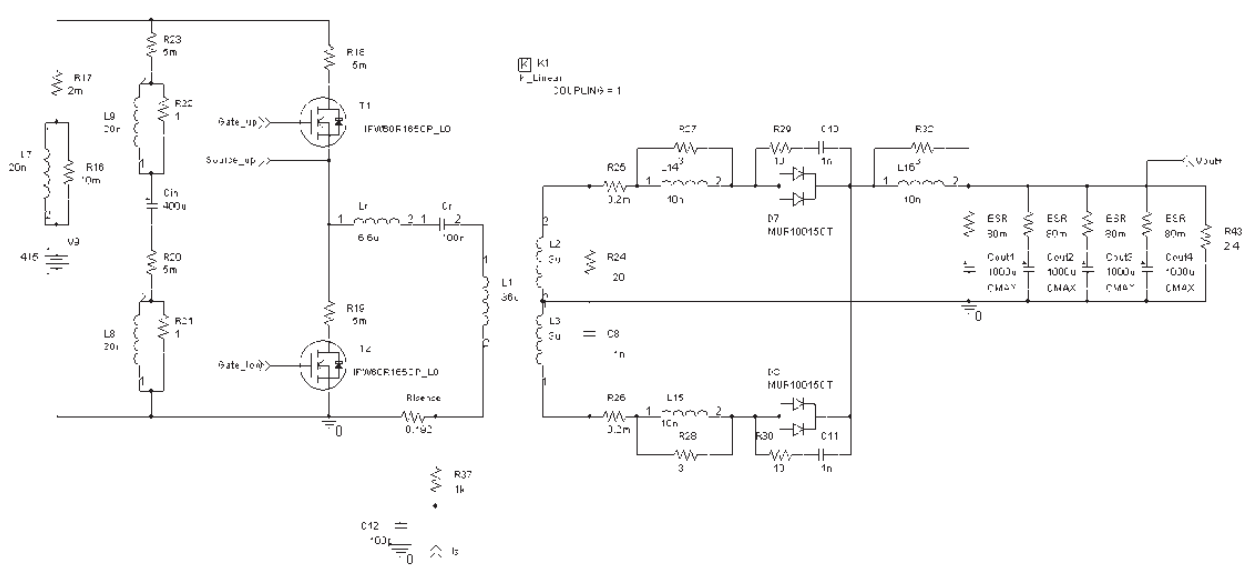


Fig. 5. Regulation of output voltage a) during input supply voltage decrease, b) during load variations

3.2 Simulation of LLC converter in OrCad PSPICE

For verification and mathematical model design, first, the simulation in Orcad PSPICE has been made. Data acquired from simulations in PSPICE are used in MATLAB for design of mathematical model. For best performance and accuracy of switching waveforms, all parasitic components were included into simulation. For power transistors the IPW60R165CP model was used, and MUR10015CT was used for output diodes. For transformer, the leakage inductance with all parasitic components was also simulated.



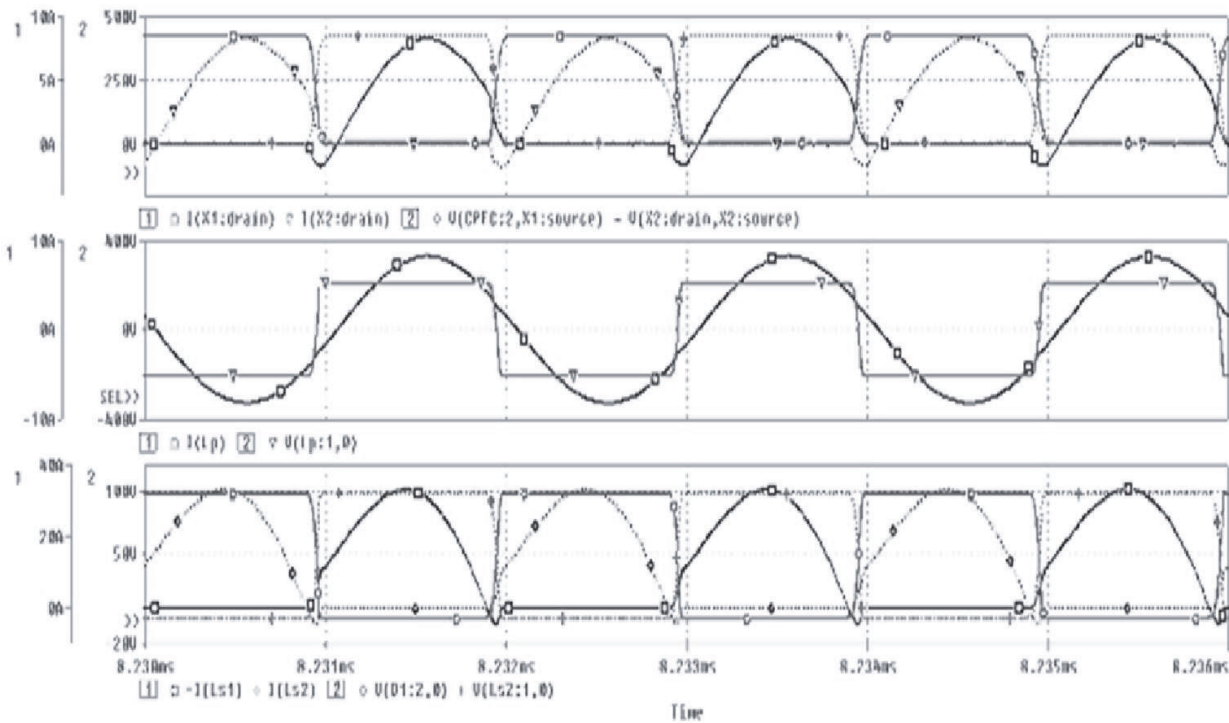


Fig. 7. Time waveforms of voltages and currents during the simulation experiment: $U_{in} = 425V$, $P_{out} = 1008W$ (from top: transistor T1and T2, transformer primary side, output diode D1 and D2)

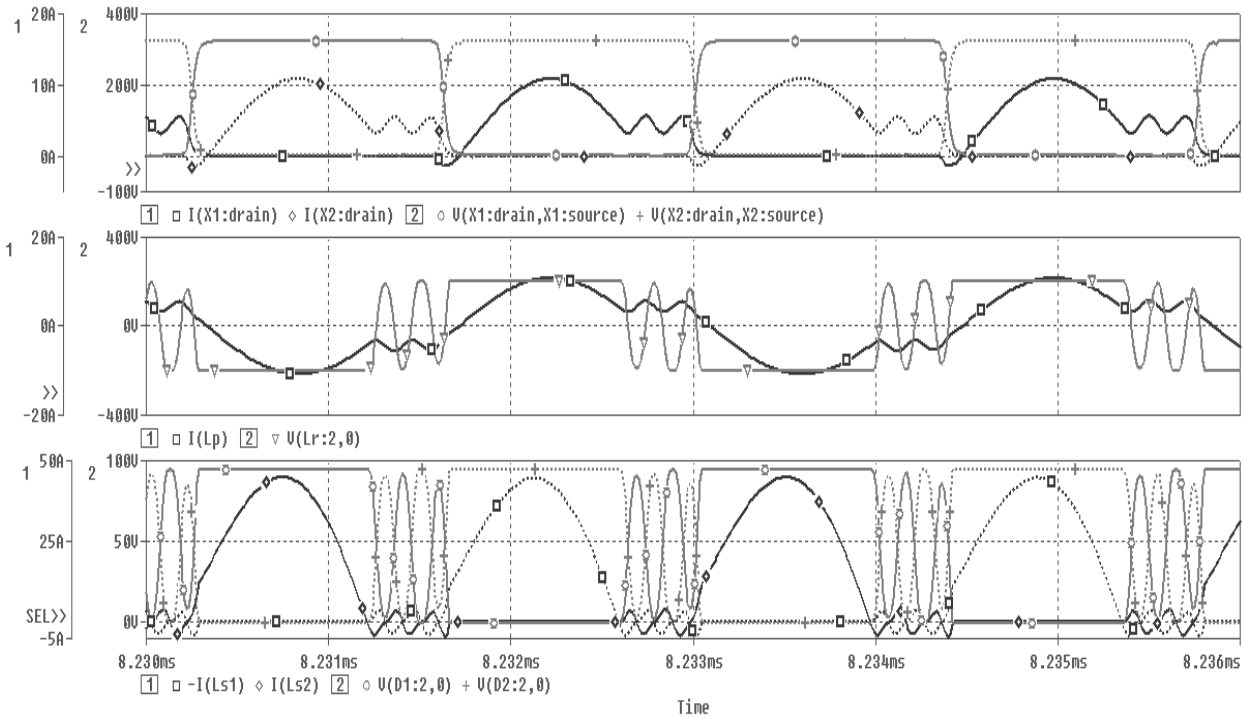


Fig. 8. Time waveforms of voltages and currents during the simulation experiment: $U_{in} = 325V$, $P_{out} = 1008W$ (from top - transistor X1a X2, transformer primary side, output diode D1 and D2)

From simulations above, it's clear to say, that design procedure was very accurate and results are showing acceptable performance.

4. Transfer function for controller

In previous sections, a operating principle of LLC converter was briefly mentioned, together with simulation of main circuit. Accurate simulation is critical for design and optimization of the control system for the LLC converter. For the design of control structure and the actual control system, a transfer function is necessary, which will describe response of output voltage and current to the change of the control variable.

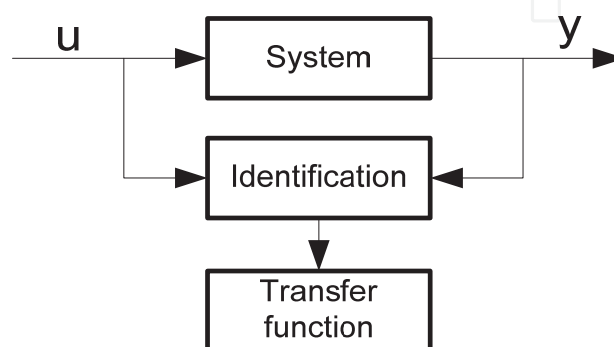


Fig. 9. Process of transfer function acquiring

Mathematical model of LLC converter requires control-to-output transfer function. Based on this transfer function, digital controller can be obtained. For PWM converters, standard "averaged" methods can be used for revealing the transfer function of converter. One of method with good results is "direct circuit averaging". This method can be easily implemented for standard PWM converters such as boost, buck, flyback etc. Transfer function obtained with this method has duty cycle as an input value and output voltage as an output value.

Unlike the PWM converters, the control transfer function of frequency controlled resonant converters cannot be obtained by state space averaging method, due to different ways of energy processing. While state space averaging methods eliminates the information about switching frequency, they cannot predict dynamic properties of resonant converters, so the proper control-to-output transfer function cannot be evaluated.

There is a several methods for solving this problems, but some of them are too simplified and idealized, others are too complex and difficult to use. In this paper, new simulation based method for revealing the control transfer function is proposed. This method is based on PSPICE simulation, which was discussed in previous chapter, and use of System Identification Toolbox in MATLAB environment. First, the simulation of main circuit in PSPICE must be created. Using of PSPICE simulation, the dependency of output (voltage, current) on input (switching frequency, duty cycle) can be simulated.

Another option for creation of the mathematical model is use of block called SLPS in MATLAB. This block creates interface between circuit model in PSPICE and mathematical models in MATLAB environment. Data acquired from simulation in PSPICE are used in MATLAB for creation of transfer function of LLC multiresonant converter. For obtaining of the transfer function in s-domain, the MATLAB System Identification Toolbox was used.

Whole process is shown on Fig. 10. First, the simulation of dynamic step response of LLC converter on control value (switching frequency) was created in OrCad PSPICE environment. Result from this simulation was dynamic output voltage response (output value) on step of switching frequency (input value). This simulated results from OrCad PSPICE, were used in MATLAB as input values for identification of this dynamic system.

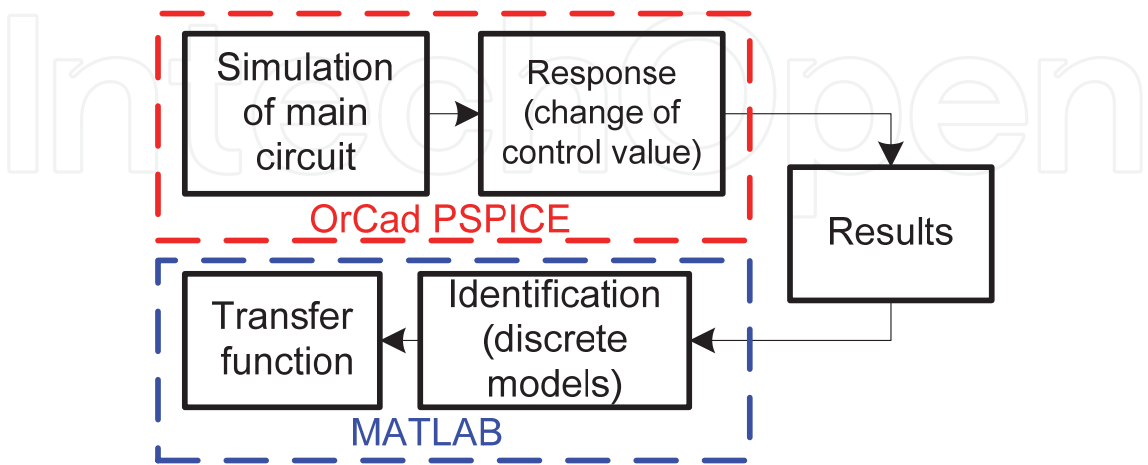


Fig. 10. Simulation based method for identification of transfer function

Use of System Identification Toolbox offers several models for identification of dynamic system. With use of different models from System Identification Toolbox (SIT), identification of all converters is possible.

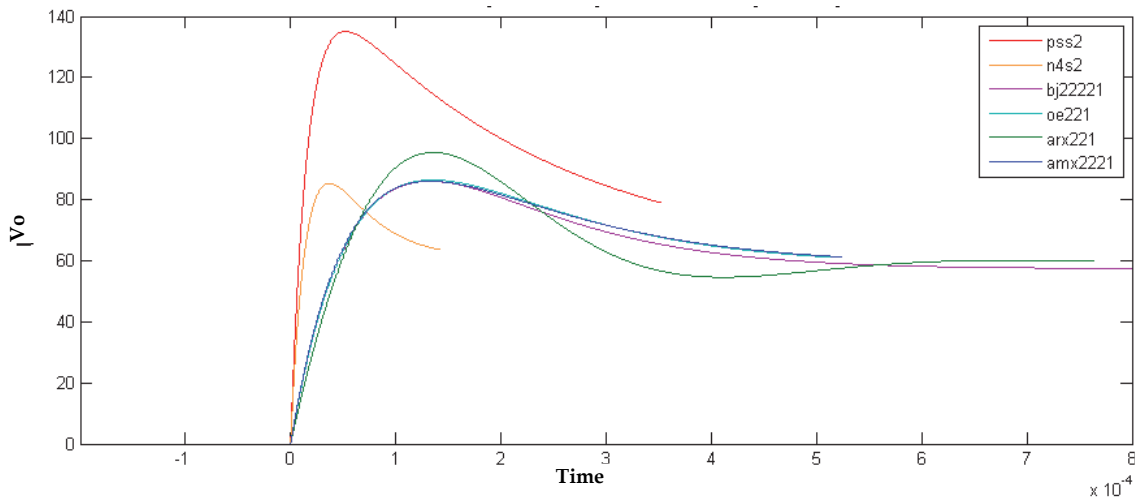


Fig. 11. Accuracy of some model types from SIT with different degree (step response)

System Identification Toolbox includes number of models in continuous or discrete form, which can be used for identification of systems: ARX (Auto Regresive Exogeneous Input Model), ARMAX (Auto Regresive Moving Average Exogeneous Input Model) OE (Output Error Model), BJ (Box-Jenkins Model), SS (State-Space Model). Accuracy of the models depends on degree of polynomials used in transfer function. Fig. 11 shows accuracy of identified transfer functions for different model types from simulated results of LLC converter. All models are in discrete form (z-domain), so the exact specification of sampling

interval is necessary, which means, that the integration step which was used in OrCad PSPICE, must be also used for MATLAB. From Fig. 11 can be seen, that the best accuracy has ARX and ARMAX model.

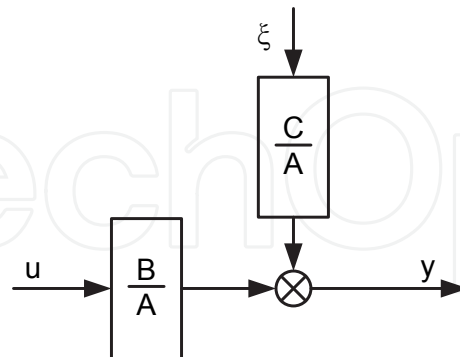


Fig. 12. Structure of ARMAX model

The ARMAX model, whose structure is on Fig. 12, is similar to ARX model, but with better accuracy. It extends the ARX model with polynomial $C(z)$ - equation of average value of perturbation function. The ARMAX model is suitable for those systems, where perturbation function affects input variable $u(n)$. Searched transfer function has the same form as in ARX model, but the computing algorithm is different. The equation for ARMAX model is as follows:

$$A(z)y(n) = (B(z)u(n-k) + C(z)\xi(n)) \quad (9)$$

Structure of the model is shown on Fig. 12. After adjusting, the form of Eq. (10) is:

$$y(n) = \frac{1}{A(z)} (B(z)u(n-nk) + C(z)\xi(n)) \quad (10)$$

Due to best accuracy of ARMAX model, only this model was used for revealing the transfer function. Another parameter necessary for the transfer function revealing, is degree of its polynomials. Fig. 13 shows accuracy of ARMAX model with different degree. Best accuracy offers model of 2nd degree, which means, that polynomials $A(z)$, and $C(z)$ are just 2nd degree. We can say, that the control to output transfer function of LLC converter has same degree as ARMAX model.

4.1 Transfer function

As mentioned above, the sampling interval used for models in SIT must be equivalent with integration step used for simulation in OrCad PSPICE. If sampling interval used in SIT differs from integration step in PSPICE, the dynamic results (from step response) will have different time representation in MATLAB, so the searched transfer function will have incorrect form.

Requested discrete transfer function is in form:

$$G(z) = \frac{B(z)}{A(z)} = \frac{b_0 + b_1z^{-1} + b_2z^{-2} + \dots + b_{nb}z^{-nb}}{a_0 + a_1z^{-1} + a_2z^{-2} + \dots + a_{na}z^{-na}} \quad (11)$$

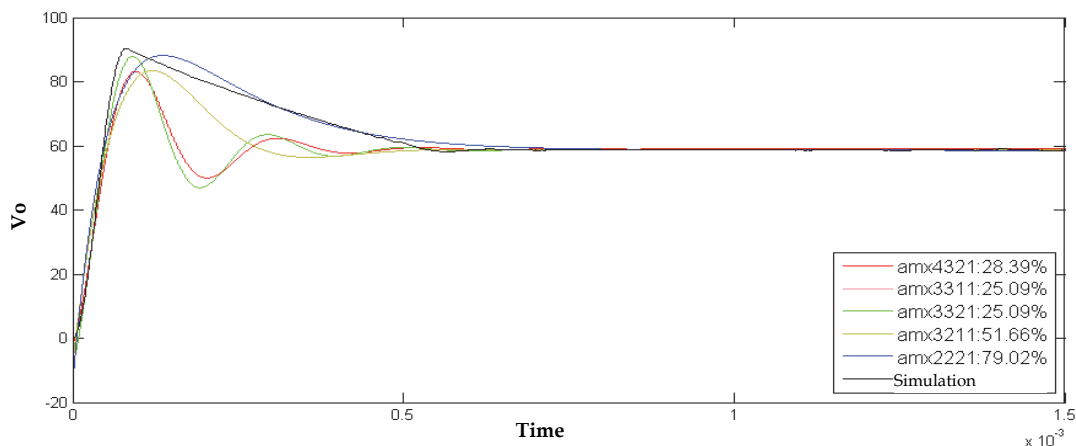


Fig. 13. Accuracy of ARMAX models with different degree (up to down 4,3,2)

For better view, Fig.14 shows comparison of ARMAX 2221 model, used for transfer function, with simulated dynamic step response from OrCad PSPICE.

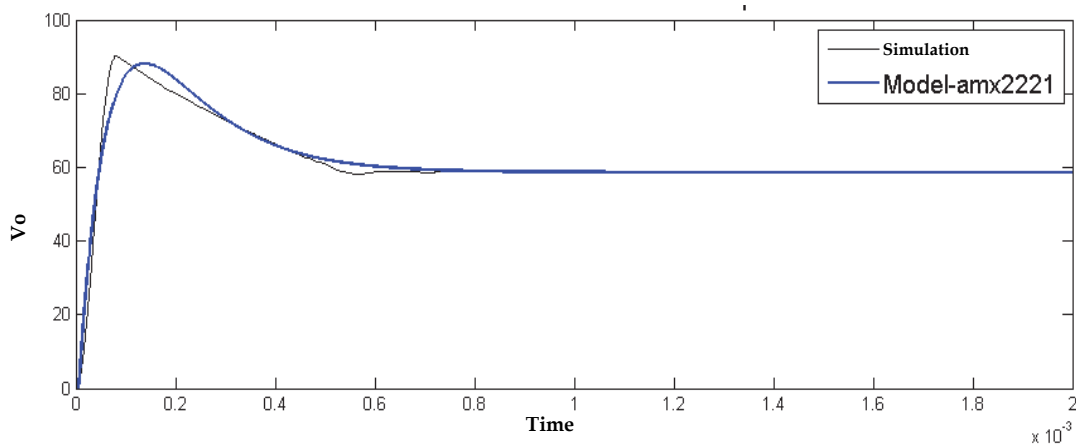


Fig. 14. Comparison of simulated results (PSPICE) with ARMAX model of 2nd degree (MATLAB)

For LLC converter, whose waveforms are in Fig. 7 and Fig. 8, resulting transfer function is in Eq. (12).

$$G(s) = \frac{2.054 \cdot 10^6 s + 6.895 \cdot 10^9}{s^2 + 2.29 \cdot 10^4 s + 1.176 \cdot 10^8} \tag{12}$$

After acquiring of transfer function, we can obtain basic mathematical model of LLC converter. This mathematical model can be used for design of discrete model, with all effects from discrete control system. The following figures show the bode characteristics of the systems marked G_{dlyz3} and G_{dlyz4} with discrete controllers. The design of controllers was made in Matlab using the SISOTOOL. This tool allows to design not only regulators, but also analyze the characteristics and quality of the proposed control circuit.

5. Design of discrete controller

Due to implementation in microprocessor, the controller must be in discrete form. There are two ways to design a discrete controller - design by emulation and direct digital design.

In the design by emulation approach, also known as digital redesign method, first an analog controller is designed in the continuous domain, by ignoring the effects of sampling and hold of A/D converter and computing delay of microprocessor. In next step, the controller can be converted into discrete-time domain by one of discretization method. This approach is good for systems of lower degree, but in discrete systems of higher degree, the transient responses does not reflect the required values because of ignoring sample and hold and computation delay effects.

On the other side, direct digital design approach offers design of controller directly in z -domain, without conversion, including effects of A/D converter and microprocessor. Block diagram of this approach is on Fig. 15.

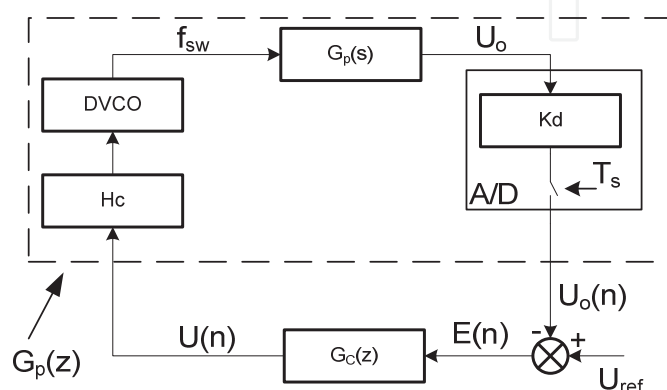


Fig. 15. Direct digital design control loop

Sampling of measured value with A/D converter can be represented by ideal Zero-Order-Hold block with sample time T_s . Gain of A/D converter is represented by block K_{adc} . Computing delay of microprocessor, also with delay from PWM module are represented by block T_{comp} . A/D converter with PWM module together form a sampling-and-hold device. Sample and hold block brings additional time delay of $T_s/2$ and phase lag of $\omega T_s/2$, which means, that reconstructed signal has time or phase lag. Block T_{comp} represents delay between conversion of A/D converter and PWM duty cycle or modulo update. Time between this two events is necessary for computing the values for PWM block. Discrete transfer function of whole converter including Zero-Order block, Sample-and-Hold effect and gain of A/D converter is:

$$G(z) = Z \left\{ \frac{1}{s} (1 - e^{-sT_s}) \cdot H_c(s) \cdot G_p(s) \cdot K_d \right\}$$

Fig. 16 shows effect of sampling interval with computing delay on stability of closed control loop. Tab. 1 shows transfer functions with different sampling intervals and different computational delays. Sampling times were used from A/D converter included in DSC 56F8013, the computing times were used from same processor. Application was for digital control system for 200kHz LLC multiresonant converter. In this system discrete regulator of third order was used.

For design of controller in z -domain, all above mentioned delays must be taken into account. With use of MATLAB Siso Design Tool, the proper discrete controller can be designed. Advantage of this tool is possibility of direct placing of zeroes and poles of controller on bode diagram of closed or open loop. After placing the poles or zeros

of controller, the different responses of closed control loop can be displayed for verification.

Sampling time T_s	Computing delay T_{comp}	Mark
5 μ s	0	Gz1
10 μ s	0	Gz2
5 μ s	3 μ s	Gdlyz1
10 μ s	3 μ s	Gdlyz2
5 μ s	6 μ s	Gdlyz3
10 μ s	6 μ s	Gdlyz4

Table 1. Sampling times and computational delays for transfer functions in Fig. 16

From Fig. 16 is clear, that computing delay has significant effect on stability of the control loop. With rising computing and sampling time stability of system drops.

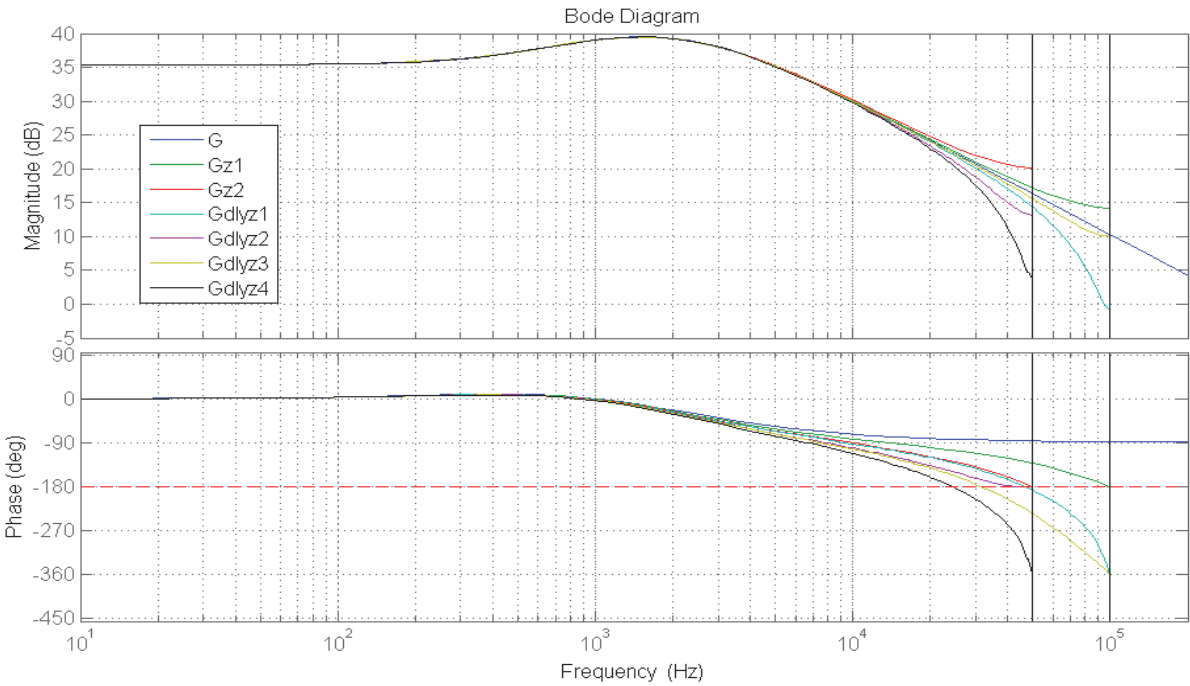


Fig. 16. Effect of sample and hold and computation delay on stability of control loop

Fig. 17 shows the system G_{dlyz3} with poles and zeros of the regulated system (blue) and regulator (red). Fig. 18 shows the closed-loop response of the system to a unitary jump. Time of control settling is about 70 microseconds, overshoot as high as 17%. Transfer function of designed controller is in form:

$$G_c(z) = 0.041204 \cdot \frac{z - 0.886}{z - 0.995}$$

(13)

Fig.19 shows the bode characteristics of system marked G_{dlyz4} , with the proposed controller. Poles and zeros of the transfer function of the regulated system are shown blue, poles and zeros of the controller are shown red. As in the previous case, in Fig. 20 a closed control loop

response to unitary jump is shown. Time of control settling is 100 microseconds, overshoot is 20%, which is caused by a longer interval sampling interval of system Gdlyz4.

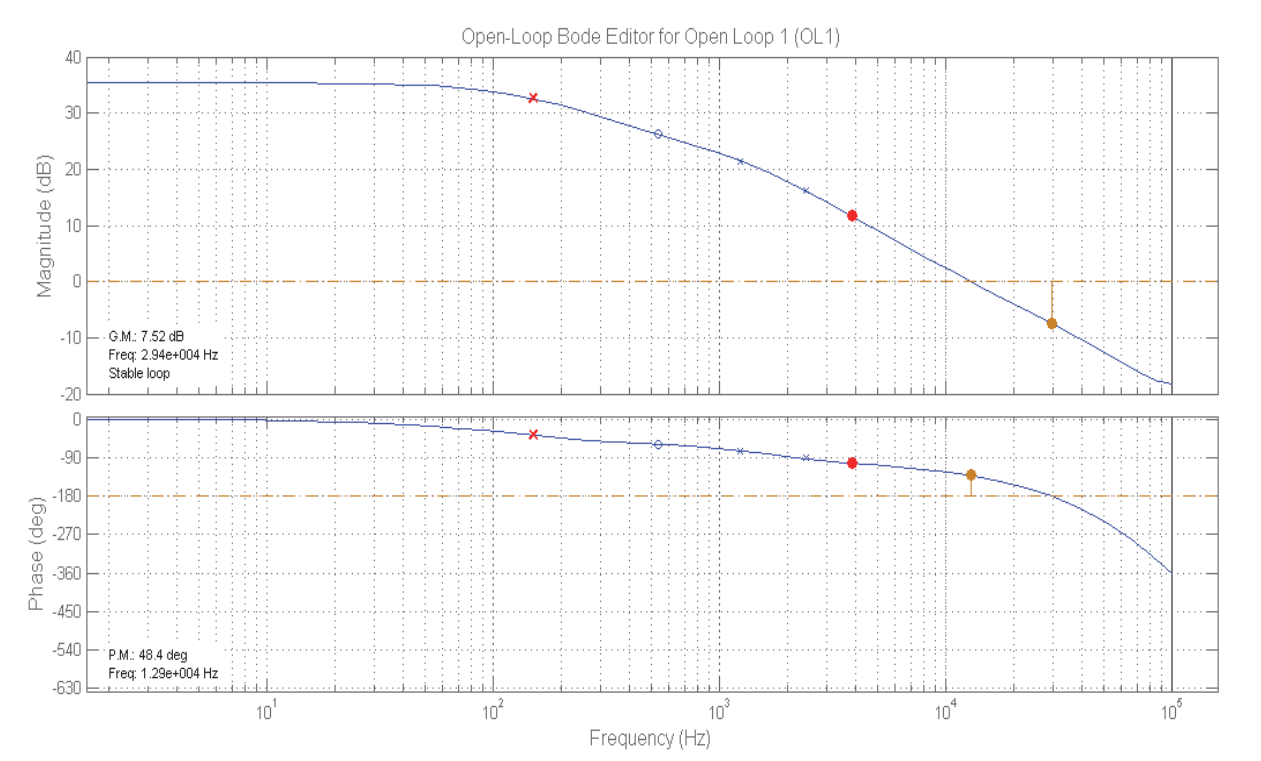


Fig. 17. Design of controller using transfer function of open loop for system G_{dlyz3}

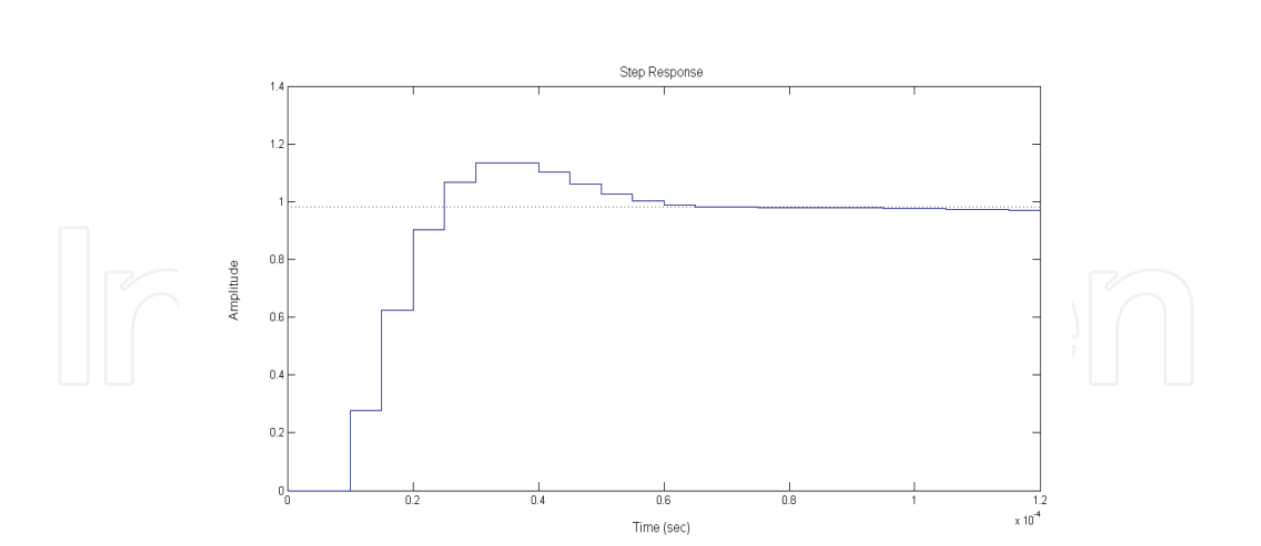


Fig. 18. Closed-loop response with designed controller for unitary jump

Both designed controllers controls at 97% of requested value, due to the reduction of regulators gain, because of limitation of overshoot below 20% of the requested value. The elimination of this problem was realized by increasing the requested value of the output voltage by 3%

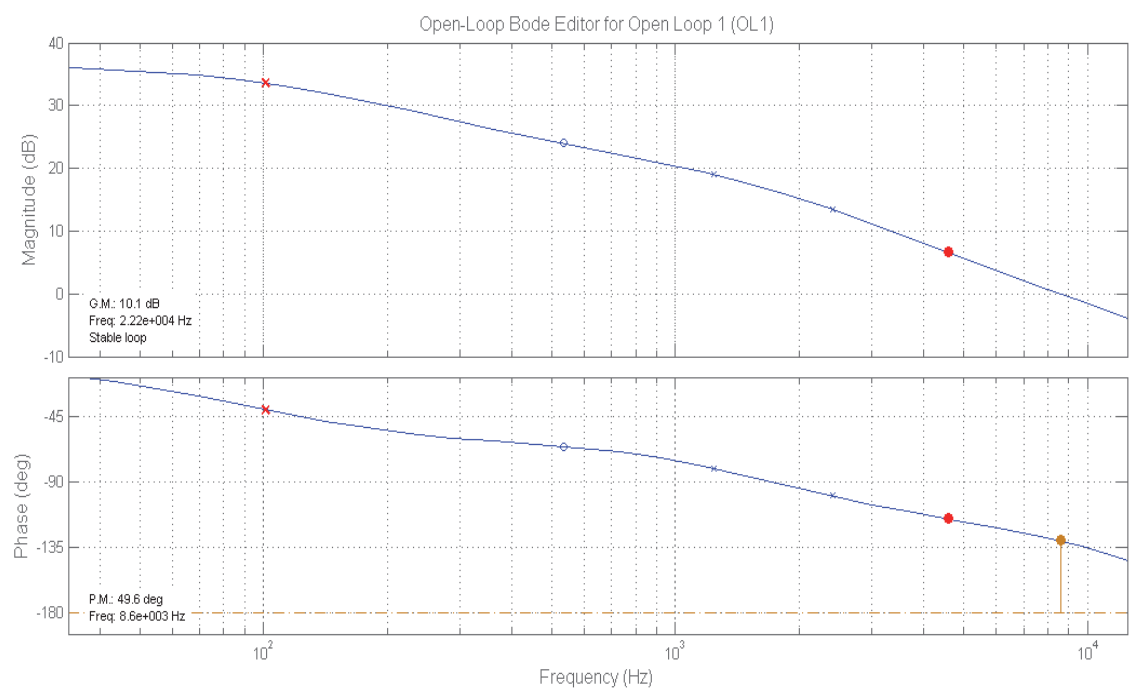


Fig. 19. Design of controller using transfer function of open loop

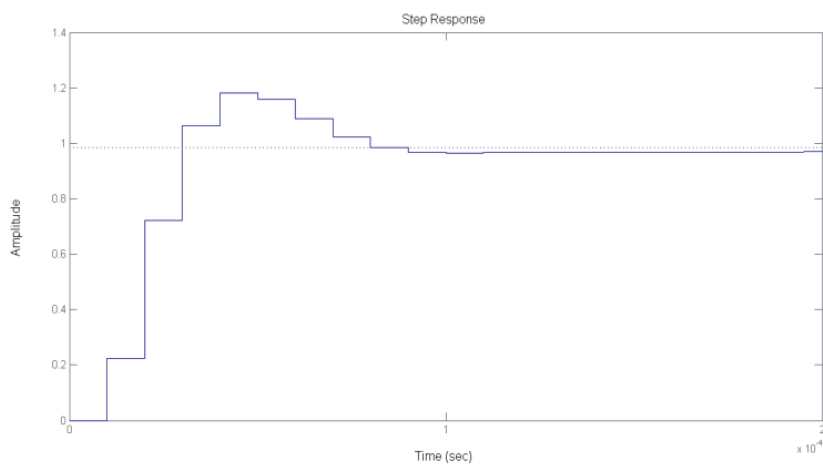


Fig. 20. Closed-loop response with designed controller for unitary jump

Transfer function of designed controller is in form:

$$G_C = 0.028539 \cdot \frac{z - 0.748}{z - 0.994} \tag{14}$$

SISOTOOL enables also the analysis of the quality and stability of the regulatory circuit. The advantage is, that information on the quality and stability control is available directly during the design procedure of the controller. As seen from figures 4.7 and 4.9 the systems with closed loop are stable , with safety margin about 50°.

5.1 Implementation in DSC

Discrete controller proposed in previous chapter was implemented into 16b digital signal controller (DSC) Freescale 56F8013, which is primary designed for motor and converter control. Advantage of this microprocessor are high performance peripherals which can operate with 96Mhz clock frequency. On the other side, disadvantage of this processor is low core frequency - 32 MHz, and fixed point arithmetic. For better performance, fraction arithmetic with intrinsic functions were used in this DSC.

Block scheme of digital control system with DSC 56F8013 on 200 kHz LLC converter is on Fig. 21. For better performance and lower amount of additional hardware, the concept with microprocessor on secondary side of converter was used. Also, new available fast digital isolators were used instead of standard optocouplers.

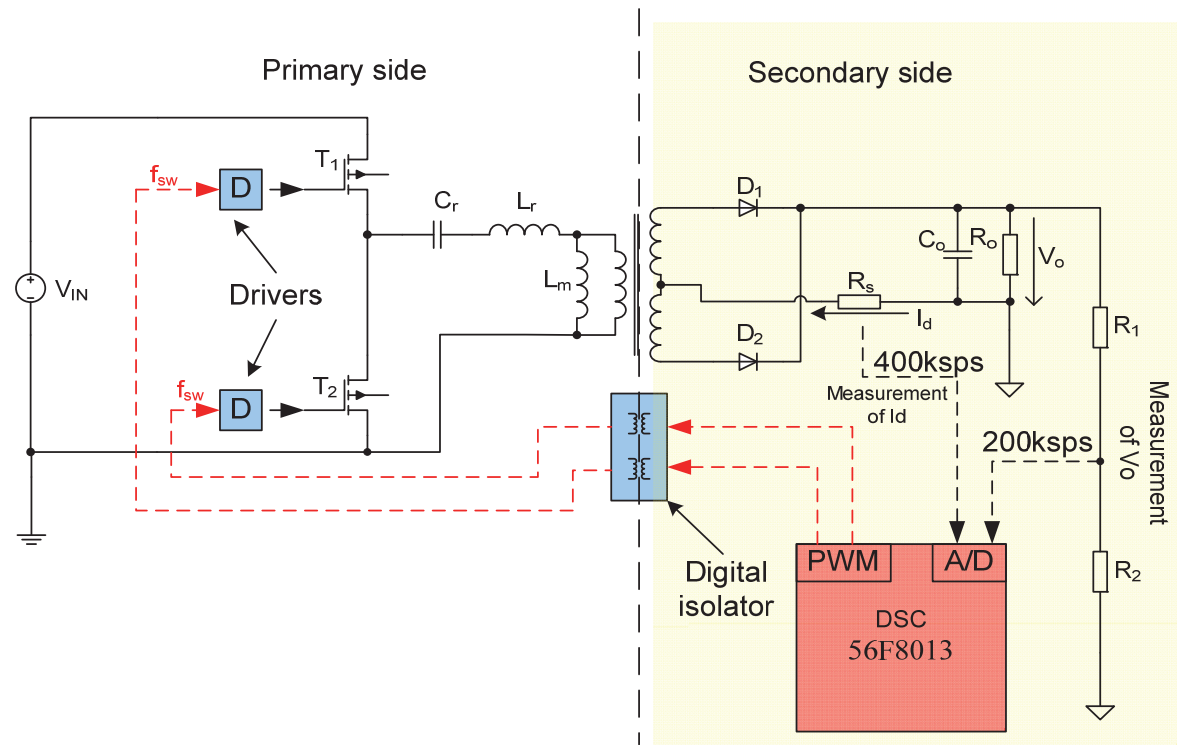


Fig. 21. Block scheme of full digital control system with DSC 56F8013

Processor	Bits	Core frequency	A/D sampling time	Computing of control loop	Computing of current value
56F8013	16b	32Mhz	1.126µs	2.98µs	3.01µs
ColdFireV1	32b	50,3Mhz	2.252µs	1.8µs	1.12µs

Table 2. Sampling times and computational delays for two processors

Another option for implementation is use of 32b microprocessor ColdFire V1 which offers better computing performance, but sampling time of A/D converter is twice as in DSC

56F8013. For measurement of output voltage, this time is sufficient, but for current sensing, the A/D converter on ColdFire is too slow. This problem was eliminated by use of special algorithm for computing of diode current from value of output voltage, value of load and ripple of output voltage. This algorithm is based on computing of output current from output voltage drop, during load connection. Detailed method is described in. Times required for computing on both processors are in Tab. 2.

6. Conclusion

The method for creation of mathematical model discussed in this chapter is based on circuit model of LLC converter in OrCAD PSPICE and use of MATLAB System Identification Toolbox. This approach eliminates the problems of transfer function obtaining, whose results from use of standard “averaging” methods. Instead of that, this approach uses simulation in OrCad PSPICE, based on circuit model of converter, for acquiring the results and subsequent use of MATLAB for creation of accurate control to output transfer function (in s- or z- domain). Advantage of this method is in use of all parasitic components (resistors, capacitances, inductors) in OrCad PSPICE simulation, so the transfer function is very accurate. Also, the approach for identification of the system, proposed in this paper, uses new, discrete model based method. This method allows rapid acquiring of mathematical model of converter with use of computing power of modern PC. Another advantage of this method is possibility of use for any type of converter without limitation in structure of converter.

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