THE APPLICATION OF OUTPUT FILTER WITH VARIABLE INDUCTANCE IN ZERO-CURRENT-SWITCH QUASI-RESONANT CONVERTER

Nikolay Goryashin
Siberian State Airspace University after academician Reshetnev M. F
Nikolay Goryashin, 660032, Russia, Krasnoyarsk, post office box 27464.
Phone: +7(3912) 22-84-74
gorkolya@mail.ru

Abstract: *Various problems of quasi-resonant half-wave zero-current-switch (ZCS) buck converter operation are observed in this paper. The application of an output filter with variable inductance depending on load current is proposed. This allows improvement of voltage regulation in a wide range (more than 50%) of load currents. In this paper, a variant of output filter choke construction is suggested, and also the main elements of the original method for defining its inductance function applying a linearized small-signal model of ZCS converter. This method allows improving density and dynamic characteristics of such a converter. This is confirmed by experimental results quoted in the paper.*
Key words*: quasi-resonant converter, voltage regulator, inductors design.*

1. Introduction

High frequency soft-switching converters are widely used for direct current regulation. Applying soft-switching modes, conversion frequency and power density can be increased with low losses on power-switching transistors, and electromagnetic interference (EMI) level can be reduced.

This paper analyzes the zero-current-switch (ZCS) half-wave (HW) quasi-resonant (QR) buck converter with frequency modulation control [1, 2, 4, 7, 10]. A simplified functional diagram of such a converter is shown in Fig.1a, where VCO is the voltage control oscillator, CT is the current transformer, EA is the error amplifier, K_{fb} is the feedback gain. The basic waveforms of ZCS HW mode are shown in Fig.1b. To achieve zero-current switching in wide load range switch control signal should be synchronized on the signal of zero crossing tank inductor current, as switch on-time is defined by time intervals t_0-t_1 and t_1-t_2 (Fig.1b), both of which depend on load current [7]. It can be realized as shown in Fig.1a, where output VCO signal is synchronized on the signal of zero crossing current at moment t_2 (Fig. 1b) at each period.

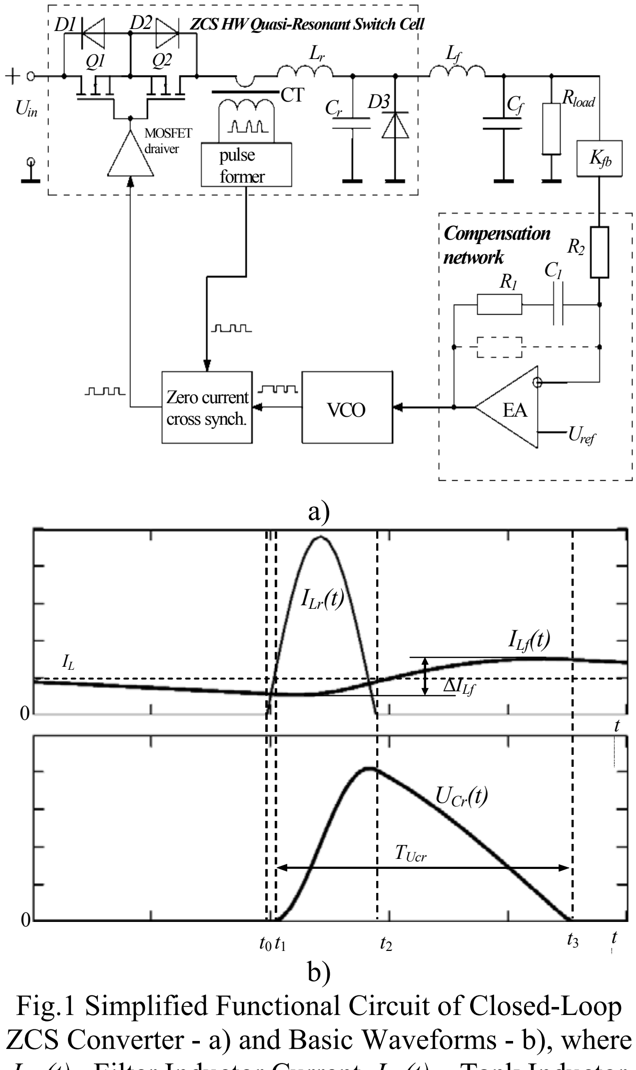

Fig.1 Simplified Functional Circuit of Closed-Loop ZCS Converter - a) and Basic Waveforms - b), where I_{Lf} *(t)*– Filter Inductor Current, I_{Lr}*(t)* – Tank Inductor Current, U_{Cr}*(t)*– Tank Capacitor Voltage.

Such a converter is the simplest one for practical application in comparison with other soft-switching

DC-DC converters [1, 2]. For example, a zero-voltage-switch quasi-resonant converter has a considerable drawback: ringing of the catch diode junction capacitance with tank inductance [3]. PWM resonant transition DC-DC converters have a hard-switching auxiliary switch, which increases EMI level [1, 2]. In the view of practical application, the zero-current-switching mode seems to be the most favorable.

2. ZCS Operation Drawbacks

There are several peculiarities that limit wider application of such converter. One of them is the fact that at time t_o (Fig. 1b), all the output current is flowing through catch diode D3 and with the activation of the switch, the tank inductor current, I_{Lr}, starts to ramp up linearly across L_r. It is possible only in the presence of a positive current in the output inductor due to the energy stored during the previous switching period [4, 10]. Thus, we can say that ZCS HW mode is possible only under the following condition: $\Delta I_{Lf}<2I_L$, where ΔI_{Lf} is the ripple-to-ripple output inductor current, I_L is the load current (Fig. 1b). This condition excludes the converter loadless operation, and decreases the light load efficiency. So, the application of this converter in a voltage regulator is possible in a limited load currents range. The wider the range, the higher the output filter inductance value must be. Under this condition (large output inductance) the system response and power density will become worse.

Another peculiarity of the ZCS HW converter is the nonlinear conversion ratio depending on load current in steady-state [7], which can be described by expression (1), where U_{Cr} is the average tank capacitor voltage equal to output voltage in a steady state (under condition of ideal output filter), f_s is the switching frequency, f_0 is the resonant tank frequency, Z_0 is the resonant tank impedance, and K_U is the conversion ratio of a ZCS HW quasi-resonant switch cell (Fig.1a). Fig.2 shows the curve of expression (1). As shown in Fig.2, if the load current range is widened, then the $K(I_L)$ change increases.

For example to provide the output voltage change of a closed-loop ZCS converter for not more than 1%, the open-loop gain should be not less than 99 [5]. Taking into consideration the nonlinear ratio (1), the given open-loop gain should correspond to the point on the curve $K(I_L)$ (Fig.2), equal to the maximum load current. So, reducing the load current, the open-loop gain will increase. This will negatively influence the stability and transient performance of the closed-loop ZCS converter. One of the possible solutions for this problem could be the introduction of a nonlinear dissipative controller into the forward loop as offered in [11]. Nevertheless, this does not solve the problem of light load operation.

$$\begin{cases} K_U = \dfrac{U_{Cr}}{U_{in}} = F_s K(I_L), F_s = f_s / f_0, J(I_L) = \dfrac{I_l Z_0}{U_{in}} \\ K(I_L) = \dfrac{1}{2\pi}\left[\pi + \dfrac{J(I_L)}{2} + \arcsin\left(J(I_L)\right) + \dfrac{1+\sqrt{1-\left(J(I_L)\right)^2}}{J(I_L)}\right] \end{cases}, \quad (1)$$

And for further analysis of the ZCS converter, we should consider the low frequency small-signal model, which elements are described in [7] and [12]. ZCS mode resonant tank frequency is more than switching frequency, so for low-frequency analysis we can consider only a low-pass LC filter, which transfer function (TF) is given (2) [8].

$$W(s) = \frac{K}{T^2 s^2 + 2\zeta T s + 1} \quad (2)$$

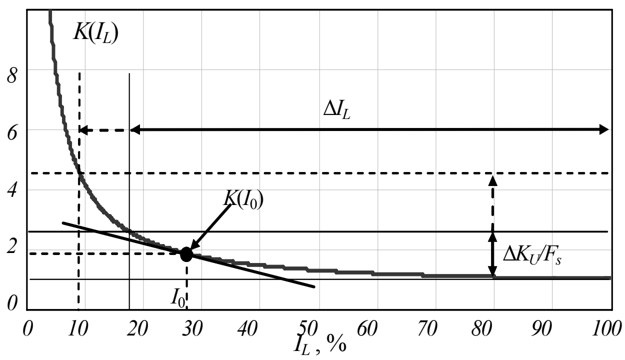

Fig.2 Nonlinear Conversion Characteristic of ZCS HW QR Switch Cell

3. AC Analysis

To linearize the given system we can approximate nonlinear mathematical object (1) by linear one in the following way (3):

$$\begin{cases} U_{Cr}(I_{lf}, F_s) = U_{in} F_s K(I_{lf}), \\ \Delta U_{Cr} = \dfrac{\partial U_{Cr}(I_{lf}, F_s)}{\partial F_s} \cdot \Delta F_s + \dfrac{\partial U_{Cr}(I_{lf}, F_s)}{\partial I_{lf}} \cdot \Delta I_{lf} \end{cases}, (3)$$

where I_{Lf} is the average output inductor current equal to I_L in steady-state. A small-signal flow-graph of the ZCS converter is given in Fig.3; R_{dis} is the resistance, equivalent to conduction loss in the converter power part; and L_f, C_f and R_{load} are output filter components and load resistance, respectively; $G(s)$ is the transfer function of voltage loop compensator; K_{fb} is a simple constant gain, and $K(I_0)$ is a constant gain equal to $K(I_L)$ under fixed current I_0 (Fig.2); K_{vco} is a VCO factor [Hz/Volt];

$$K_i = -\frac{\partial K(I_{Lf})}{\partial I_{Lf}} = \frac{-Z_0}{2\pi U_{in}}\left(\frac{1}{2} - \frac{1+\sqrt{1-\left(\frac{I_{Lf}Z_0}{U_{in}}\right)^2}}{\left(\frac{I_{Lf}Z_0}{U_{in}}\right)^2}\right). \quad (4)$$

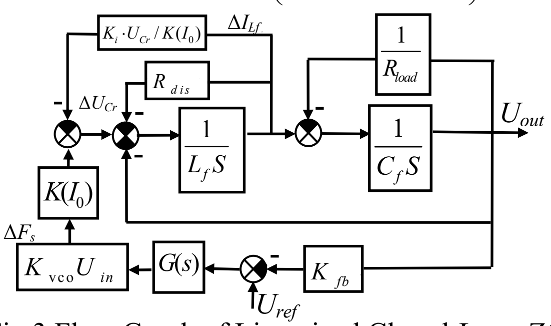

Fig.3 Flow Graph of Linearized Closed-Loop ZCS HW QR Buck Converter

Then, the open-loop TF of the ZCS HW converter power part can be presented as:

$$W(s) = \frac{K(I_0)K_R}{K_R C_f L_f s^2 + K_R\left[\frac{L_f}{R_{load}} + C_f\left(R_{dis} + K_i \cdot U_{Cr}/K(I_0)\right)\right]s + 1}, \quad (5)$$

where

$$K_R = \frac{R_{load}}{R_{load} + \left(R_{dis} + K_i \cdot U_{Cr}/K(I_0)\right)}. \quad (6)$$

Since TF (5) corresponds to (2), the damping factor can be expressed as:

$$\zeta = \sqrt{K_R}\,\frac{\left(\frac{L_f}{R_{load}} + C_f\left(R_{dis} + K_i \cdot U_{Cr}/K(I_0)\right)\right)}{2\sqrt{L_f C_f}}. \quad (7)$$

If we consider this system (Fig.3) in a wide range of load currents, we can use damping factor value ζ as a function of I_{Lf}. This function will allow judging about the stability and dynamic qualities of this converter under each load current value in steady state.

On the other hand, with the reduction of load current in closed-loop converter the conversion frequency reduces considerably by nonlinear law. As a result, the ripple-to-ripple output inductor current value increases. It can negatively influence the stability and dynamic qualities of the given system. It is connected with the fact that during the transient under large load current stress, the condition $\Delta I_{Lf} > 2I_L$ can be fulfilled. Hence, resonant duty cycle becomes uncontrollable. As was already mentioned, such a problem is solved by the increase of the output filter inductance value, which satisfies the given ripple-to-ripple output inductor current value under the minimum load current. Such a method reduces the system response speed of the closed-loop converter, increases the dimensions of the output filter, and reduces efficiency.

4. Variable inductor application and design

Another method of solving this problem is to apply a variable inductance choke depending on the current. This choke can be constructed from two put-together cores, which are made of different magnetic materials, for example, as shown in Fig.4, one of the cores should be made of unsaturable material (carbonyl), and the other of a saturable one (ferrite). Such a choke will have a minimum inductance value under the maximum load current and maximum inductance value under the minimum load current. This method allows considerable reduction of the dimensions of the output filter and realization of the ZCS mode in the given voltage regulator in a wide load range.

The next task is to define the nonlinear characteristic of this choke, which will influence the dynamic properties of this converter in the optimum way. At first, let us represent formula (7) as the function from the average output inductor current:

$$\zeta(I_{Lf}) = \sqrt{K_R(I_{Lf})}\,\frac{\left(\frac{L_f I_{Lf}}{U_{Cr}} + C_f\left(R_{dis} + K_i(I_{Lf}) \cdot U_{Cr}/K(I_{Lf})\right)\right)}{2\sqrt{L_f C_f}} \quad (8)$$

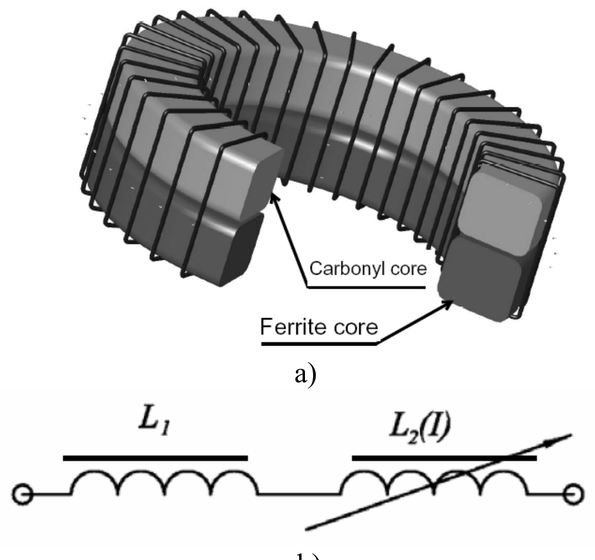

Fig.4. Example of a Choke with Variable Inductance - a) and its Equivalent Circuit - b)

Function (8) shows that the damping factor will only depend on the average inductor current equal to the load current in steady state. The damping factor reduces under load current increase. Thus, to achieve closed-loop ZCS converter high stability, the law of output filter inductance variation must provide the maximum value of damping factor at each point of the load currents range. In practice, it is very difficult to realize an inductor with a strictly assigned nonlinear characteristic, that is why to design such a choke we can define only two points corresponding to minimum and maximum inductance value.

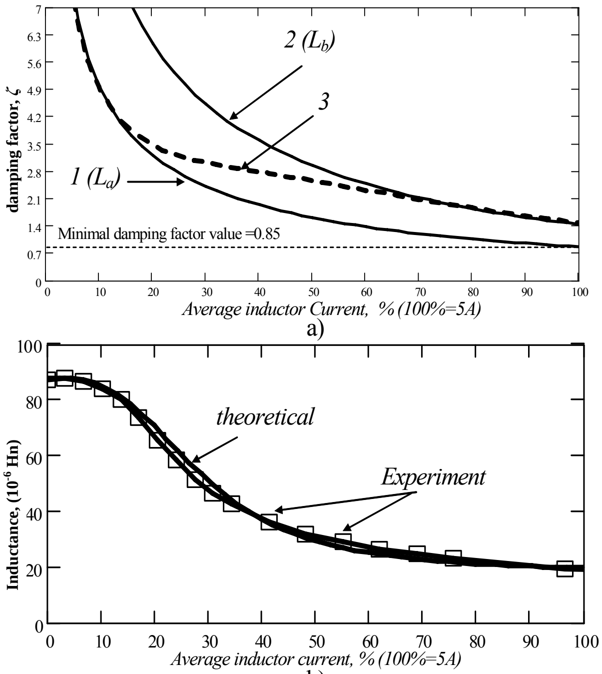

Fig.5. Curves of Damping Factor Under Different Filter Inductance Values - a), and The Dependences Between Filter Inductance and I_{Lf} - b).

Curves 1 and 2 in Fig.5a show the dependence of the damping factor (7) of the small signal model on the average inductor filter current value under different inductance values, where the inductance L_a corresponding to curve 1 is much higher than the inductance L_b corresponding to curve 2. L_a was defined under the condition of minimum load current, and L_b under the condition of maximum load current, and also taking into consideration the frequency control and nonlinear ratio (1) under operation in the wide load currents range (more than 50%). In this case, the above-described choke with characteristic that corresponds to curve 3 in Fig.5a is the most effective. Curve 3 corresponds to the theoretical curve in Fig.5b, where theoretical and experimental nonlinear characteristics of the output filter inductor are shown. The damping factor value in this case stays high enough for this system to have a necessary phase margin to apply a low-inertia simple linear controller [9].

The solution given above (Fig.4) allows achieving characteristic in Fig.5b. According to the equivalent circuit (Fig.4b) we can propose a formula for calculating choke inductance as:

$$L = \frac{\mu_0}{\ell}\left[\mu_1 \cdot N_1^2 \cdot S_1 + \mu_2(H) \cdot N_2^2 \cdot S_2\right] \quad , \qquad (9)$$

where ℓ is the magnetic path length of the core, μ_0 the magnetic permeability in vacuum, N_1, N_2 are the numbers of turns covering the first and second cores, S_1, S_2 are the sectional areas of first and second cores, μ_1 is the effective magnetic permeability of first core (unsaturable), and $\mu_2(H)$ is the magnetic permeability function of field intensity H inside the coil [6].

In its turn, a formula (9) can be connected with the average filter inductor current value by following law (10) [6].

$$NI = \sum_1^n H_i \ell_i \approx H\ell \quad . \qquad (10)$$

As a result, curve 3 in Fig.5a can be described by function (8) under the condition that fixed value L_f should be replaced by function $L_f(I)$ in accordance with formulas (9) and (10).

The presented method for combined core curve defining is approximate, as magnetizing curve has no analytic definition, that's why at first the combined core with the acceptable curve was chosen, and then adequate approximate analytical function was received (Fig 5b). So function $\mu_2(H)$ can be defined approximately.

5. Laboratory Test

In Fig.6 there are experimental results (downloaded from a digitizing oscilloscope: Instek GDS840S) for the output voltage of ZCS HW QR buck regulator with simple compensation circuit (Fig.1a) under current load stress. In cases (a, b) the output filter with fixed inductance value L=80μHn was applied, in cases (c, d) the output filter choke has the nonlinear characteristic given in Fig.5b. Other parameters of the inductors are shown in the table I. In Fig.7 there are estimated Bode plots of the open loop system under fixed output inductor and minimal for this case damping factor value 0.85 (Fig5a). A MOSFET IRF540N and Schottky diodes MBR20200CT were used in the experimental setup. The output filter capacitance is composed of ten 2.2μF ceramic capacitors in parallel with a 25μF tantalum capacitor. The resonant tank parameters are L_r=1.177μHn, C_r=47nF. The maximum and minimum output power is P_{max}=102W, P_{min}=15W. Efficiency under maximum power and nonlinear inductor is η=92% (for measuring two ammeters with instrumental error ±37.5mA for applied range were used and digital voltmeter with absolute error 0.4% was used).

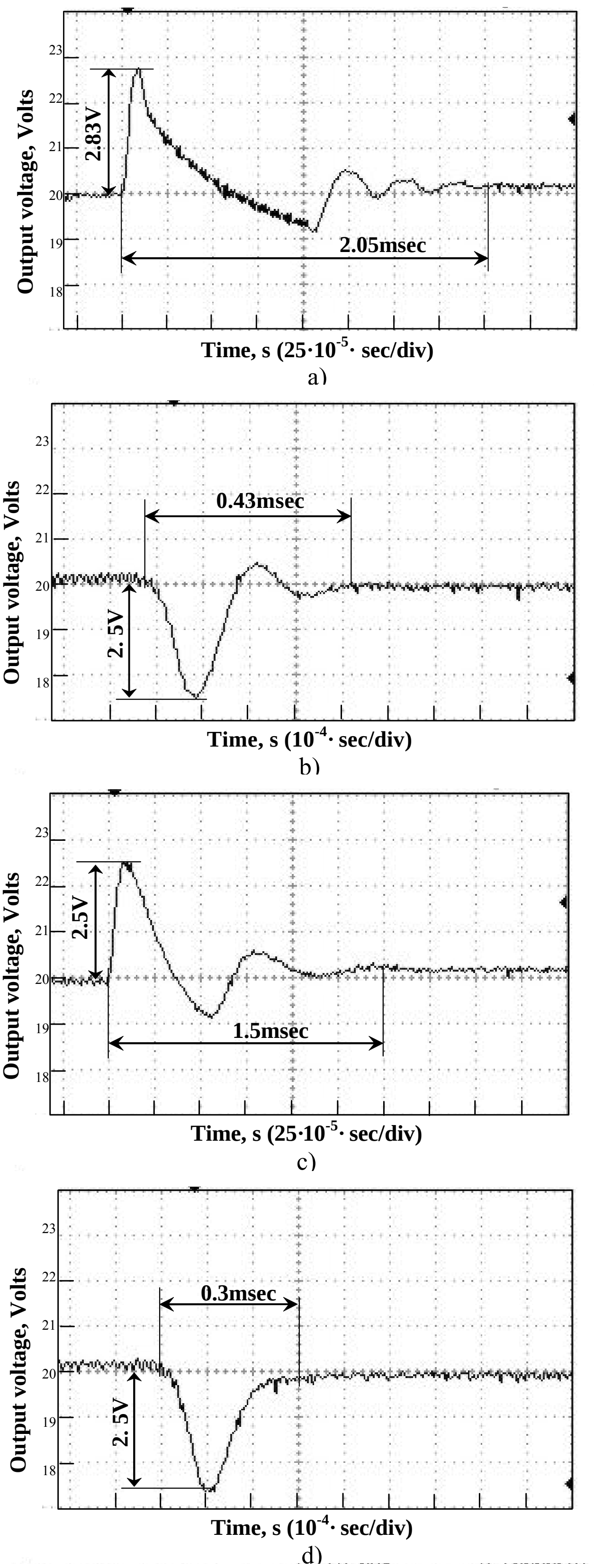

Fig. 6 Transient Response Under Load Current: Step Down (a, c) – 5.1A …0.9A, Step Up (b, d) – 0.9A…5,1A.

The maximum and minimum switching frequency is $f_{s\ max}$ =180KHz, $f_{s\ min}$=65KHz. The input voltage is 70V. Output voltage is 20V. The maximum output voltage change is 1%.

As pictures in Fig.6 show, nonlinear inductor core application allows reducing transient response time by 25-30% under current load stress and decreasing oscillation at transient effect.

TABLE I

Parameters	Fixed inductor	Nonlinear inductor
Weight [gram]	103.64	65.4
Toroidal Core dimensions [mm]	D=44, d=28, h=15	For saturable core: D=33.35, d=19.75, h=6
		For unsaturable core: D=33.35, d=19.75, h=11.5
Numbers of turns	23	28
Core material	Molybdenum permalloy $\mu \approx 120$	For saturable core: ferrite $\mu \approx 2000$ (ferrite core with air gap)
		For unsaturable core: carbonyl $\mu \approx 10$

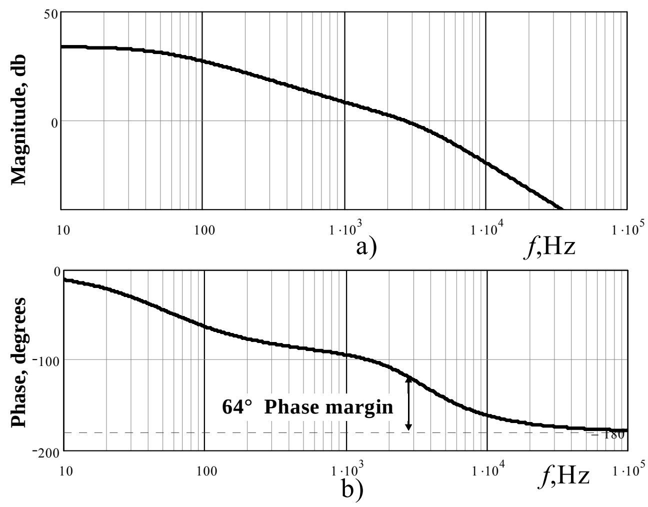

Fig. 7 Estimated open loop system gain - a) and phase - b)

6. Conclusion

The main result of this work is qualitative evaluation of variable filter inductor application capability for ZCS HW converter. Variable inductor optimization (i.e. magnetic materials choice, their combination in core, core geometry choice, etc.) is an engineering task and depends on required converter characteristics. The aim of this manuscript was not to give quantitative evaluation of weight, dimensions and cost advantages of variable inductor. In this manuscript it was shown that if we receive such inductor with nonlinear characteristic, which provides with maximum possible damping factor value in all load range, then the dynamic characteristics and stability will improve. This coincides with theoretical supposition. The wider the load currents range is, the more effective the application of such inductor is.

Applying an output filter choke in a ZCS converter with inductance, which changes due to the law described in this paper, we can achieve a reduction of the response time and transient oscillation under load current stress (Fig. 6). The weight of choke can be significantly reduced due to the fact that one of the cores has high magnetic permeability.

To estimate the influence of the ZCS converter nonlinearity on dynamic qualities, it is efficient to utilize the damping factor as a function of average inductor current.

To main advantages of soft-switching converters for ZCS HW QR buck converter with nonlinear output filter inductor we can add the following:

- Low magnetic loss due to low conversion frequency under light load operating.
- Much higher damping factor value of loop control in comparison with hard switch PWM buck converter.
- Low EMI due to sinusoidal switch current and catch diode voltage waveforms.

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