Resonant-mode power supplies, DC/AC converters, LCLC resonant filter, transfer function, Fourier analysis, Bode diagram

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DESIGN PROCEDURE FOR LCTLC CONVERTER

The paper deals with design analysis and synthesis of the storage elements of LCTLC power resonant inverter with sinusoidal output voltage. The filter used for creating it has to remove higher harmonic components from the supplying voltage to reach the harmonic distortion roughly 5% in the whole range of the load (0-100%). Non-symmetrical control is used for voltage to be constant. Right choosing and design of LC storage components is important from the point of view voltage and current stresses, overvoltages and requested THD values. Design procedure of them is demonstrated and confirmed by computer simulation.

PRÍSTUP K NÁVRHU LCLC PRVKOV REZONANČNÉHO MENIČA

Príspevok je zameraný na analýzu a sysntézu akumulačných prvkov LCTLC výkonového rezonančného meniča s harmonickým výstupným napätím. Takýto filter nesmie neprepúšťať vyššie harmonické zložky napájacieho napätia aby harmonické skreslenie bolo menšie než 5% v celom rozsahu zaťaženia (0-100%). Pre dosiahnutie konštantného výstupného napätia je využité nesúmerné riadenie. Správny výber a návrh akumulačných LC prvkov je dôležitý z hľadiska napäťového a prúdového namáhania, prepätí a dosiahnutia požadovaného harmonického skreslenia. V príspevku je ukázaný postup návrhu a potvrdený počítačovou simuláciou.

1. INTRODUCTION

There are many applications when load has to be supplied from HF transformer with stiff harmonic voltage due to synchronization, constant frequency, and precise phase control. It can be provided by different type of converters.

One of the novel types of converters are LCLCL converter based on LLC resonant scheme, and LCTLC inverter [1], [2], [3] consists of DC/DC buck converter, LCLC resonant filter and HF transformer. The HF transformer can also be connected after the LCLC filter, if necessary. The inverter (LCTLC) is usually used as power supply for either

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HV rectifiers [4], [5] or HF cycloconverters or matrix converters, for motor- or constant frequency applications, respectively.

The basic scheme of LCTLC inverter is shown in Fig. 1

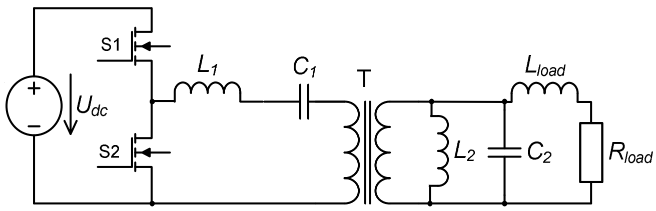

Fig. 1. Basic scheme of LCTLC inverter with direct HF AC output

Based on works [4]-[6] one can create following equivalent scheme of the LCTLC circuit, Fig. 2.

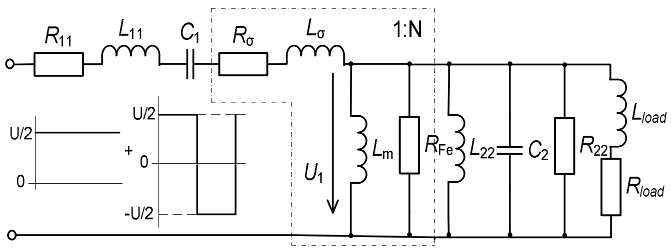

Fig. 2. Equivalent scheme of LCTLC circuit

For equivalent circuit considering

$$R_1 = R_{11} + R_\sigma; \quad \frac{1}{R_2} = \frac{1}{R_{Fe}} + \frac{1}{R_{22}}$$

$$L_1 = L_{11} + L_\sigma; \quad \frac{1}{L_2} = \frac{1}{L_m} + \frac{1}{L_{22}} \tag{1}$$

where R_σ, L_σ, R_{Fe}, L_m are equivalent parameters of the transformer; R_{11}, R_{22} are resistances of LCLC filter elements.

Then using the state-space equations one can write

$$\frac{d}{dt}\begin{pmatrix} i_{L1} \\ i_{L2} \\ u_{C1} \\ u_{C2} \\ i_L \end{pmatrix} = \boldsymbol{A}\begin{pmatrix} i_{L1} \\ i_{L2} \\ u_{C1} \\ u_{C2} \\ i_L \end{pmatrix} + \boldsymbol{B}\begin{pmatrix} u_1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

where i_{L1}, i_{L2} are currents through the inductors L_1 and L_2, respectively; i_L is current through the load R_{load}, L_{load}; u_{C1}, u_{C2} are capacitors voltages of C_1 and C_2, respectively; $u(t)$ is output voltage of the converter (filter input voltage).

Using suitable numerical method or directly Matlab functions the time waveforms of the quantities of LCTLC inverter can be obtained, Fig. 3.

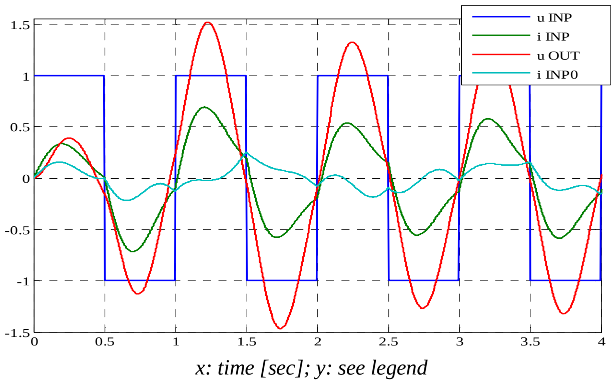

Fig. 3. Basic simulated waveforms of the LCTLC inverter

2. DESIGN PROCEDURE FOR LCLC COMPONENTS

The resonant frequency of L_1C_1 and L_2C_2 should be the same as basic fundamental frequency of the converter and is requested by load demands. So, based on Thomson relation

$$\omega_{res} = \sqrt{\frac{1}{L_1C_1}} = \sqrt{\frac{1}{L_2C_2}}$$

or, respectively

$$L_1\omega_{res} = \frac{1}{\omega_{res}C_1} = L_2\omega_{res} = \frac{1}{\omega_{res}C_2} \rightarrow L\omega_{res} = \frac{1}{\omega_{res}C} \tag{3}$$

where ω_{res} is equal $2\pi\times$ fundamental frequency of the converter.

Values of storage LC components and their parameters are important for properties of LCLC filter and/or LCTLC inverter, respectively. Theoretically, values or size, respectively of the storage elements can be chosen from wide set. As first approximation for the design let's suppose simple resonant circuit (Fig. 4) and that resonant frequency is equal switching input frequency ($\omega_{res} = \omega_{sw}$).

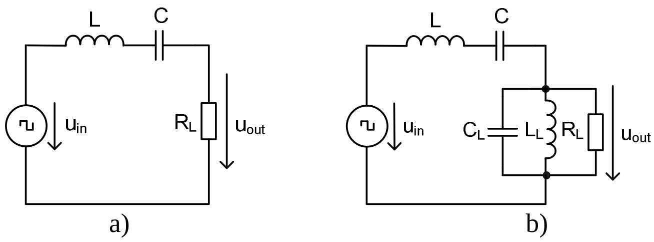

Fig. 4. Simple resonant LC circuit with resistive a) and complex loads b)

LC design can be considered from 3 different points of view:

1st: nominal voltage and current stresses at steady-states
2nd: minimum voltage and current stresses during transients
3rd: required value of total harmonic distortion of the output voltage

If quality factor defined as $q = {}^{L\omega_{res}}/_{R}$ is sufficiently large (>1-10) we can consider just fundamental harmonics of the quantities for next calculations.

Not to exceed nominal voltages of the storage elements we take value of internal impedance of the storage element equal the nominal load $|Z_N|$.

$$L\omega_{res} = \frac{1}{\omega_{res}C} = |Z_N| = \frac{U_{N(1)}^2}{P_{N(1)}} \tag{4}$$

where U_1, P_1 are nominal output voltage or power (RMS or AV values), respectively.

Let's define the nominal design factor q_N for LC components as

$$q_N = \frac{L\omega_{res}}{|Z_N|} = \frac{1}{\omega_{res}C|Z_N|} \tag{5}$$

It is similar to quality factor but since q depends on the load R the q_N does not.

From (4) and (5) one can obtain the design formulas for LC storage elements

$$L = \frac{U_{N(1)}^2}{\omega_{res}P_{N(1)}}q_N \qquad C = \frac{P_{N(1)}}{\omega_{res}U_{N(1)}^2}\frac{1}{q_N} \tag{6}$$

Then voltage on storage elements at nominal steady-state

$$U_L = L\omega_1 I_{N(1)} = \frac{U_{N(1)}^2}{\omega_{res}P_{N(1)}}q_N\omega_1\frac{P_{N(1)}}{U_{N(1)}} = U_{N(1)}\frac{\omega_1}{\omega_{res}}q_N$$
$$U_C = \frac{1}{\omega_1 C}I_{N(1)} = \frac{1}{\omega_1\dfrac{P_{N(1)}}{\omega_{res}U_{N(1)}^2}\dfrac{1}{q_N}}\frac{P_{N(1)}}{U_{N(1)}} = U_{N(1)}\frac{\omega_{res}}{\omega_1}q_N \tag{7}$$

where ω_1 is fundamental or switching, respectively, frequency of input power supply.

That means that for q_N equal one the voltages on storage elements will be nominal ones, and are proportional depend on that factor.

Going back to LCLC filter, Figs. 1 and 2, using (3) then it will be

$$L_1 = \frac{U_{N(1)}^2}{\omega_{res}P_{N(1)}}q_N \qquad C_1 = \frac{P_{N(1)}}{\omega_{res}U_{N(1)}^2}\frac{1}{q_N}$$
$$L_2 = \frac{U_{N(1)}^2}{\omega_{\mathrm{res}}P_{N(1)}}\frac{1}{q_N} \qquad C_2 = \frac{P_{N(1)}}{\omega_{\mathrm{res}}U_{N(1)}^2}q_N \tag{8}$$

where $U_{N(1)}$, $P_{N(1)}$, ω_{res} are nominal output voltage, power or frequency ($\omega_{\mathrm{res}} = \omega_{\mathrm{sw}}$), respectively (for fundamental harmonic).

From the point of view of the transient states (2nd criterion) the request is that overvoltages during the transients to be minimal ones. It's known that maximal overvoltages occur during switching-off process at the full load as well as during switching-on process at the no load. During start-up the L_2C_2 circuit is energized to nominal energy

$$E_2 = E_{L2} + E_{C2}$$
$$E_{L2} = \frac{1}{2} L_2 I_{N(1)}^2 = E_{C2} = \frac{1}{2} C_2 U_{N(1)}^2 \quad (9)$$

However, charging current frequency cannot be ω_{res} because of parallel resonant circuit. Similarly, during nominal load switching-off the energy of L_1C_1 circuit which is nominal,

$$E_1 = E_{L1} + E_{C1}$$
$$E_{L1} = \frac{1}{2} L_1 I_{N(1)}^2 = E_{C1} = \frac{1}{2} C_1 U_{N(1)}^2 \quad (10)$$

and it should be discharged to the minimal value determined by no-load current.

$$E_0 = E_{L10} + E_{C10}$$
$$E_{L10} = \frac{1}{2} L_1 I_0^2 = E_{C10} = \frac{1}{2} C_1 U_0^2 \quad (11)$$

Where I_0 is no-load current and U_0 is capacitor voltage at no-load current.

The overvoltages are higher when energy of is higher. Energy depends on L, C and q_N values. That means that energy of LC circuit (and q_N, too) should be minimal one then the overvoltages will be also minimal. The examples of overvoltages during transients are shown in Figs. 5a,b.

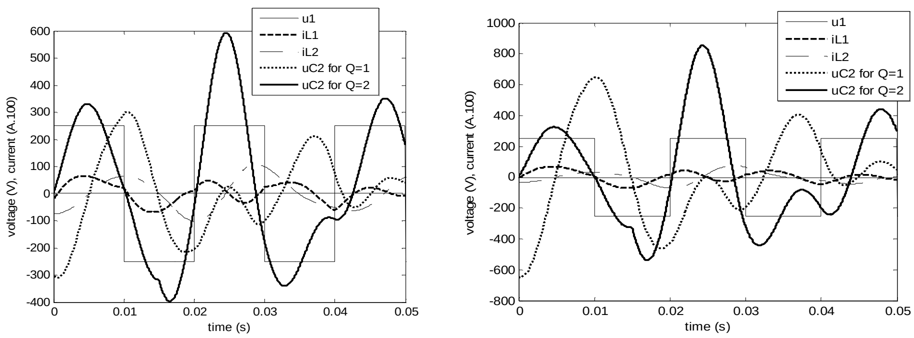

Fig. 5. Simulation of transients during switch-off of the load: q_N=1 a) and q_N=2 b)

L_1=L_2=7.3e-1 H; C_1=C_2=1.38e-5 F; L=1 mH; R=230 Ω;

Regarding to the 3rd criterion the total harmonic distortion can be calculated using voltage transfer function [5].

$$F = \frac{U_2}{U_1} = \frac{|Z_2|}{|Z|} = \frac{\sqrt{\left[\frac{1}{Z_L}\right]^2 + \left[\frac{1}{Z_N}\left(k - \frac{1}{k}\right)\right]^2}}{\sqrt{\left(\frac{R_1|Z_N|Z_L M + 1}{Z_L}\right)^2 + \left[\left(k - \frac{1}{k}\right)^2 \cdot \frac{|Z_N|^2 M - 1}{|Z_N|}\right]^2}} \quad (12)$$

Dependence of THD on nominal design factor q_N is given in Tab. 1.

Tab. 1. THD of output voltage of LCTLC inverter

Nominal design factor	1	1.5	2	2,5	3	3,5	4	4,5	5
THD [%]	16,6	11,0	8,2	6,6	5,5	4,7	4,1	3,6	3,3

3. CONCLUSIONS

The design procedure of LC storage component for LCTLC inverter has been introduced and demonstrated. Simulation results of 4th order LCLC resonant filter shows, that designed parameters of LC filter confirms good quality of output quantities (voltage and current).

Using nominal design factor (q_N) is possible to fulfill the requested criteria (1st , 2nd and 3rd) but not by only one parameter of (q_N). High value of design factor causes higher value ov voltages and current of storage elements as nominal ones, and also the higher overvoltages as can be seen from Figs. 5*a* and *b*. On the other hand high design factor provides low value of total harmonic distortion factor.

So, using right take-off into account the choosing and design of storage components of LCTLC inverter with integrated filter and transformer should not be problem.

4. ACKNOWLEDGEMENT

The authors thank for the financial support to R&D operational program Centre of excellence of power electronics systems and materials for their components No. OPVaV-2008/2.1/01-SORO, ITMS 26220120046 funded by European regional development fund (ERDF) and VEGA No. 1/0470/09.

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