INVESTIGATION OF A DC-DC RESONANT CONVERTER FOR POWER DISTRIBUTION APPLICATIONS

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Abstract- A high frequency power converter system suitable to replace a typical power distribution transformer is discussed. The new power converter systems contain a number of high power DC-DC converters as main components.

This paper presents the DC-DC converter with resonant commutation. The described converter employs a low profile high frequency transformer, a LCL resonant tank and two full bridge converters. The principle of operation of the converter is described and verified by SABER simulator. An analytical model and analysis are given to provide a basic for the calculation of the resonant circuit and the control of the converter. The results are verified by an experimental prototype of 10kW.

1. INTRODUCTION

Nowadays some authors [1,2] consider the use of power electronics for the power distribution network. Many of these future power electronic techniques are associated with multi-level converter structure for energy conversion at Medium Voltage (MV) and Low Voltage (LV). They represent a new basic technology for distribution and transmission [1,2,3]. New circuit topologies for these applications are presently being considered [2,3,5]. These new circuits allow the economical replacement of conventional power distribution transformer with high frequency (HF) 'DC-DC electronic transformer'.

The new topologies are based on a power DC-DC converter employing a high frequency transformer and having bi-directional power flow capabilities. This converter, also called 'DC-DC electronic transformer', is used as the central component of the system. As well known, increasing the switching frequency leads to reduce size and weight of the transformers witch helps the whole system to be easily transported with low expenses, important for fast replacement. Also a number of problems associated with conventional distribution transformers can be eliminated (for example - periodic oil or other dielectrics changing etc). Fig. 1 gives an overview of the system structure. The 'distributed resources' shown in Fig. 1 are small units such as gas turbines, fuel cells, or flywheels.

The typical power level of these new systems will be in the range of today's conventional low frequency MV/LV distribution transformers.

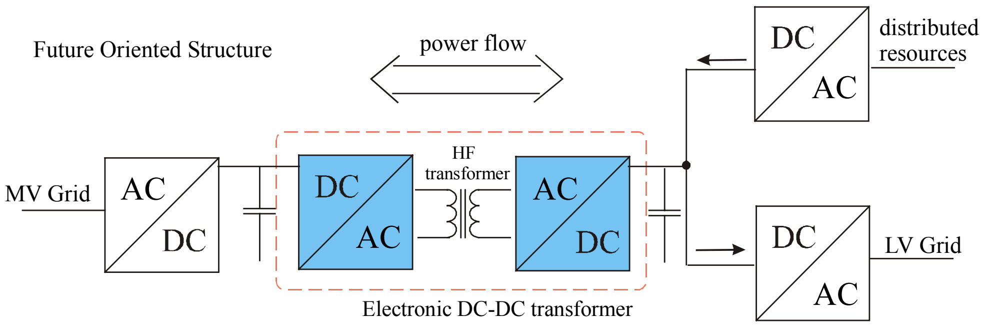

Fig.1. Application structure of an 'electronic DC-DC transformer'.

The voltage levels on the MV and the LV side are set by the AC grid voltages respectively of 20kV, 10kV or 6kV and 0.4kV.

An overview of the most relevant ratings in Bulgaria, of the power levels is given in Table.1 (for more ratings see [2]).

TABLE 1

SELECTED RATINGS OF TIPICAL POWER DISTRIBUTION TRANSFORMERS

Typical Transformer Ratings (kVA)									
10	20	40	63	100	250	160	400	630	1000

Higher power ratings (Table 1) can be obtained by paralleling more electronic transformers together like multi-level converters [2].

A bi-directional LCL resonant converter (LCL-RC) is derived by adding an inductor L_2 in series of the conventional parallel resonant converter, as shown in Fig.2.

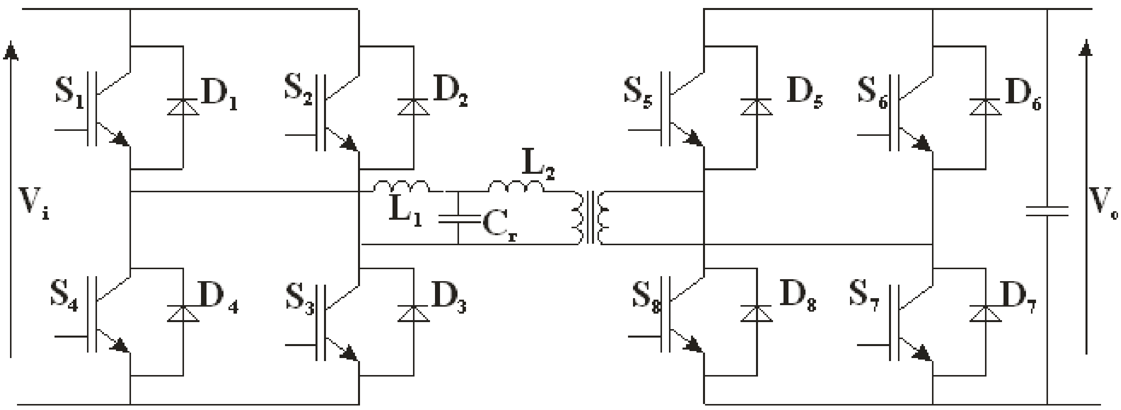

Fig.2. Bi-directional LCL-RC .

It consists of a feeding bridge (S_1–S_4 and D_1–D_4), a resonant LCL tank, an insulation HF transformer and a rectifying bridge (S_5–S_8 and D_5–D_8). This order defines the right direction of the power flow. If the power is converted from the rectifying to the feeding bridge a back direction case is presented.

The benefits of this converter are:

- Reduced switching losses.
- Symmetrical case for LCL resonant topology applicable for bi-directional converter structure.
- Transformer ratio 1:1 leading to low design cost.

Resonant conversion techniques lead to reduced switching losses and therefore increased converter efficiency [1,3]. The series resonant converter has a conversion gain less then unit (with 1:1 ratio of the insulation transformer). The parallel resonant converter has a high conversion gain but it is not a symmetrical case for bi-directional power flow capability. To overcome these disadvantages, a LCL resonant tank has been introduced in the DC-DC converter.

2. ANALYSIS OF THE CONVERTER AND SIMULATION RESULTS

The power converter circuit shown in Fig.3a, is investigated. The switches of the rectifying bridge are not controlled and the energy flows through their respective freewheel diodes D_5-D_8. The equivalent circuit of the LCL resonant converter is given in Fig.3b.

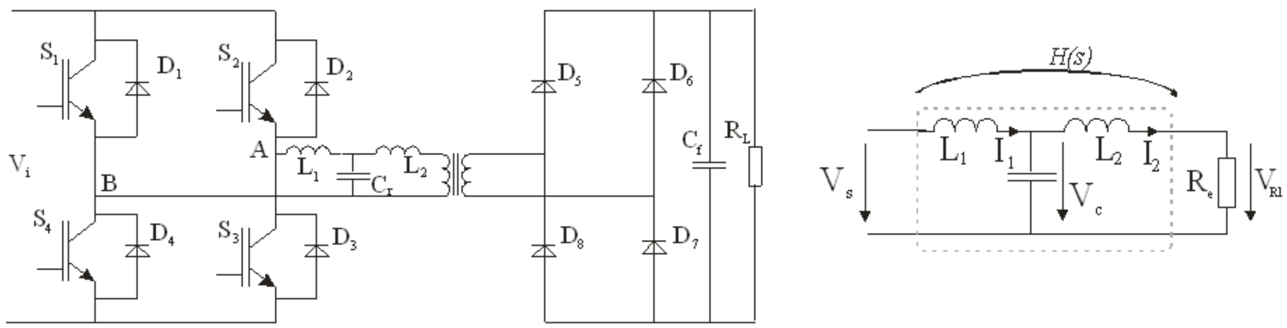

Fig. 3. Unidirectional LCL-RC, (a) main circuit. (b) equivalent circuits.

To simplify the equivalent circuit the following considerations are made:

- The switches are ideal and the converter loses are negligible.
- In power feeding bridge only the IGBTs (S_1-S_4) and in the rectifying bridge only diodes (D_5-D_8) are conducting.
- An ideal transformer is considered.
- The capacitance of the output filter C_f is large enough to ensure constant output voltage .

A switch network (S_1-S_4) produce a square wave voltage output therefore the input voltage is replaced by the voltage source $v_s(t)$ with amplitude V_s in fig 1. The output is replaced by depend voltage sink $v_{Rl}(t)$ with amplitude V_{Rl}.

The fundamental components are :

$$v_s(t) = \frac{4V_i}{\pi}\sin(\varpi \cdot t)\,; \quad V_{s=}\frac{4V_i}{\pi} \qquad v_{R1}(t) = \frac{4V_o}{\pi}\sin(\varpi \cdot t)\,; \quad V_{Rl=}\frac{4V_o}{\pi} \qquad (1)$$

The complex amplitudes of the currents and voltages are used for the analysis. Therefore the equations that describe the circuit from Fig.3b are given by:

$$\dot{V}_s = \dot{V}_c + 2\cdot s\cdot L_o \cdot \dot{I}_1 \qquad (2)$$

$$\dot{V}_{R1} = 2\cdot s\cdot L_o \cdot \dot{I}_2 - \dot{V}_c \qquad (3)$$

$$\dot{V}_c = \frac{(\dot{I}_2 - \dot{I}_1)}{s\cdot C} \qquad (4)$$

$$\dot{V}_{R1} = -\dot{I}_2 \cdot R_{e2} \qquad (5)$$

where $L_1=L_2$ and $L_o=L_1/2=L_2/2$

From (2),(3),(4) and (5), the voltage transfer function is:

$$H(s) = \frac{V_{Rl}}{V_s} = \frac{1}{1 + 4\cdot s\cdot L_o/R_e + 2\cdot s^2 \cdot L_o \cdot C + 4\cdot s^3 \cdot L_o{}^2 \cdot C/R_e} \qquad (6)$$

The magnitude of $H(j\varpi)$ is:

$$\|H(j\varpi)\| = \frac{1}{\sqrt{(1-2\cdot F^2)^2 + 16\cdot F\cdot Q^2(1-F^2)^2}} \qquad (7)$$

Where: $F=\omega_s/\omega_o$ is the normalized switching frequency, $\omega_o = 1/\sqrt{C\cdot L_o}$ is the resonant frequency, $Q=Z_o/R_e$, is the ac quality factor of the resonant circuit, and $Z_o = \sqrt{L_o/C}$

The resonant frequency as a function of the load resistor is given in [4]. However in described ideal circuit the load can be neglected.

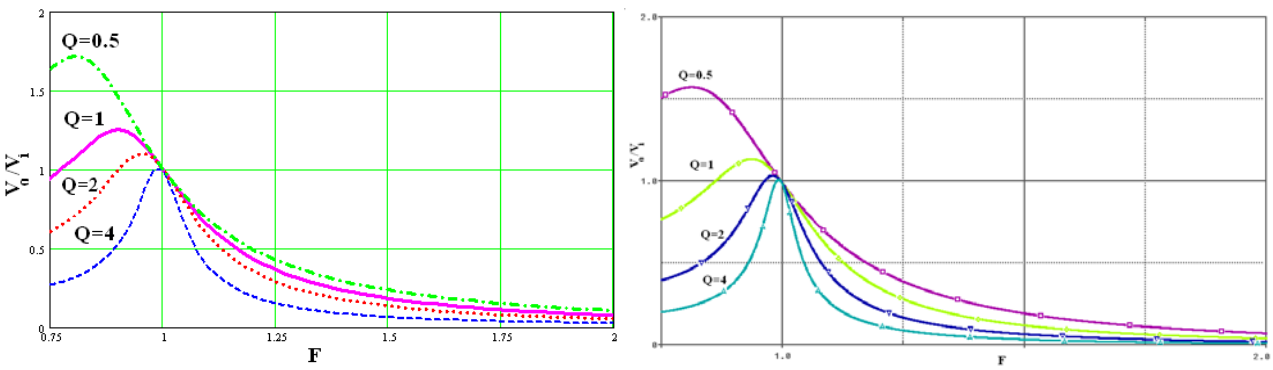

Fig.4. Frequency response of the LCL resonant tank (a). analytical results (b). simulation results.

As shown in Fig 4. the voltage transfer ratio i.e the ratio of the amplitudes of the first harmonic of the voltages, is plotted versus the normalized frequency F for four values of Q. We can see, the predicted performance using computer simulation Fig4.b agrees closely with the analytical results from Fig. 4.a, particularly for high quality factor.

To describe the operation of the proposed LCL-RC, simulation results were obtained using SABER simulator for the 10kW converter and 20kHz switching frequency.

The typical steady state voltage and current waveforms for the ideal LCL resonant tank operating at resonant frequency and nominal load conditions are shown in Fig. 5a. (Simulation conditions: V_i=300V, f=20kHz, R_{load}=9Ω, L_1=L_2=90μH, C_r=1μF). Fig.5b. shows the voltage across the power transistor S_2 and the current through S_2 and S_1.

The "behavioural IGBT model" is used for modeling the IGBTs devices.

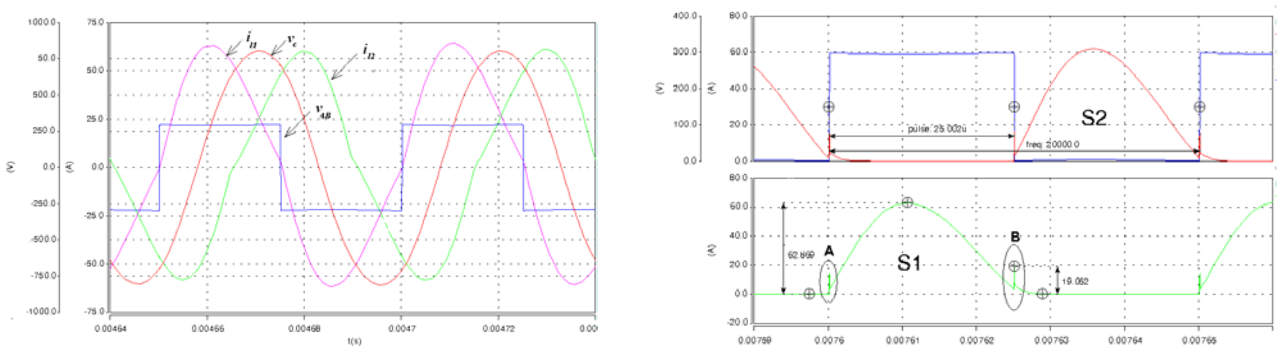

Fig. 5. Simulation results,(a) waveforms of i_1,i_2, v_c and v_{AB} for the LCL resonant tank. (b). Voltage across the power transistor S_2 and the current through S_2 (upper) and current through S_1(below).

The current is not exactly sinusoidal because of the dumping of the resonant energy. There are peak currents during the switch-on (A) and switch-off (B) times, shown in Fig.5b. These currents are three times smaller about 19A than the maximum current 62A in the on-stage phase. Additionally the conducting period is very small compared to the on-stages of 25us providing low switching losses of the IGBTs (S_1-S_4).

3. EXPERIMENTAL VEIFICATION AND RESULTS

A prototype of the proposed unidirectional LCL-RC converter has been built and tested. The obtained experimental results verify the principle of operation and converter behavior. The prototype has the following specifications: input voltage U_{in}=300V; output voltage U_{out}=300V; output power P_{out}=10kW; operating frequency f_o=20kHz.

A flexible control has been applied by using a phase shift control chipset. The advantage of this control method is a constant frequency operation at different voltage pulse duration applied to the load. This allows optimum design of the magnetic components and reducing EMI problems. The converter was constructed with 100A, 1200V IGBTs power switches – CM100TU-24H. Measured waveforms are illustrated in the figures 6 and 7.

There is a small difference to the calculated value of the resonant frequency 20kHz due to the difference between the calculated and actual value of L_s.

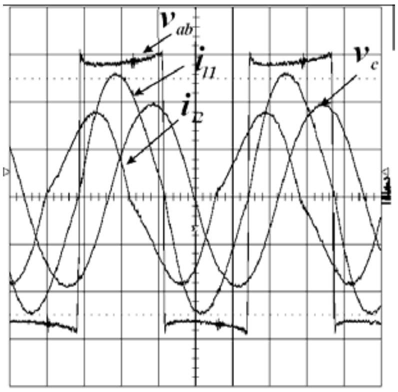

Fig.6. Experimental waveforms of v_{ab}(100 V/div),v_c(400V/div), i_{l1} 20A/div)and i_{l2} (30A/div) ;time scale 10us/div.

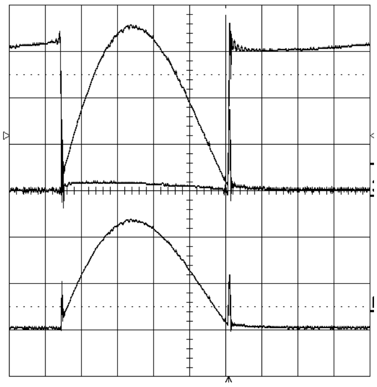

Fig.7. IGBT's waveforms, (upper) v_{CE} (50V/div) and i_c(10A/div), (below) i_c zoom-out; time scale 5us/div.

4. CONCLUSIONS

A DC-DC converter with LCL resonant commutation is presented. The reduced switching losses, the symmetrical case for LCL resonant frequency and the transformer ratio are the major futures of the converter.

The theoretical considerations are presented and verified by simulations and experiments of a 10kW prototype. Using the derived theoretical transfer function, the component stresses and the control characteristics can be found.

The presented converter system is applicable with benefits in replacing typical power distribution transformers.

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5. REFERENCES

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