A New Concept of Two-Stage Multi-Element Resonant-/Cyclo-Converter for Two-Phase IM/SM Motor

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Abstract. *The paper deals with a new concept of power electronic two-phase system with two-stage DC/AC/AC converter and two-phase IM/PMSM motor. The proposed system consisting of two-stage converter comprises: input resonant boost converter with AC output, two-phase half-bridge cyclo-converter commutated by HF AC input voltage, and induction or synchronous motor. Such a system with AC interlink, as a whole unit, has better properties as a 3-phase reference VSI inverter: higher efficiency due to soft switching of both converter stages, higher switching frequency, smaller dimensions and weight with lesser number of power semiconductor switches and better price. In comparison with currently used conventional system configurations the proposed system features a good efficiency of electronic converters and also has a good torque overloading of two-phase AC induction or synchronous motors. Design of two-stage multi-element resonant converter and results of simulation experiments are presented in the paper.*

Keywords

Computer simulation, cyclo-converter, direct converter, frequency converter, resonant converter, two-phase AC motor, two-stage electronic converter.

1. Introduction

To increase power density and energy efficiency a resonant converter topology with up to 5 resonant (accumulating) elements - *LLCLC* are currently being developed. Although this topology contains several resonant elements as in the case of *LLC* converter, the magnetic components can be integrated with small size and lower losses. The proposed system also deals with several resonant elements converter as in the case of the *LLCLC* converter, and deals with the investigation of one of new topologies – *LC(T)LC* converter. This type of resonant *LC(T)LC* converter with two resonant *LC* circuits, serial and parallel, tuned to the harmonic, comprises integrated HF transformer, whose elements are an integral part of the resonant *LC* circuit. Current tendencies in the field of power electronics require new power converter topologies and/or architectures with high power density, high efficiency and with low EMI/EMC influence.

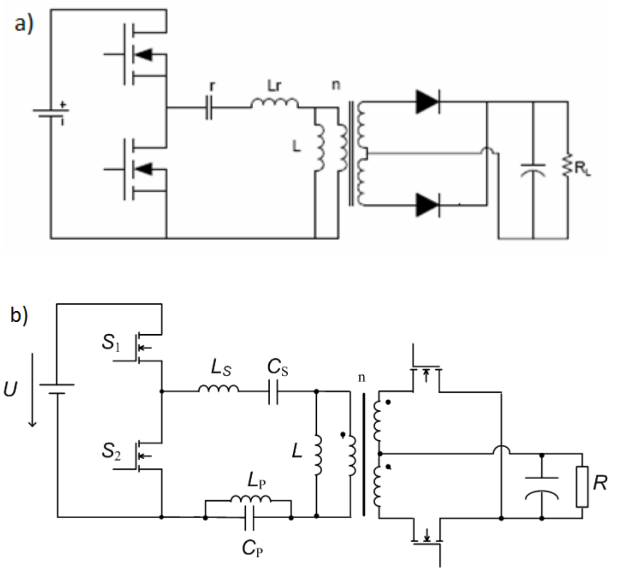

Fig. 1: Principle circuit scheme of: a) *LLC* and b) *LLCLC* converter with DC output [1], [2].

Typical architecture of power system utilized for distributed power system is shown in [1], [2] prototype of the module of a power resonant *LCLCL* converter, whose parameters are as follows: output power: 1 kW, switching frequency 1 MHz, power density 95 W/in^3 (= 95 W × 2,543/cm^3 = 1556 W/cm^3) and efficiency

95,5 %. To achieve the mentioned parameters of the power converter, next techniques and technologies are being used: increase of power density and efficiency of high-frequency *LLC* converters with the use of resonant mode and synchronous rectification techniques. The designed AC/DC/DC system converters with AC interlink, as a whole unit, has better properties as 3-phase reference VSI inverter [3].

The following topologies are being developed: *LLC* converter with Schottky rectifier (Fig. 1(a)); *LL-CLC* converter with synchronous MOSFET rectifier (Fig. 1(b)); *LC(T)LC* converter (Fig. 2) with serial- and parallel resonant circuits. The final parameters of such a multi-element converter reach the latest published values.

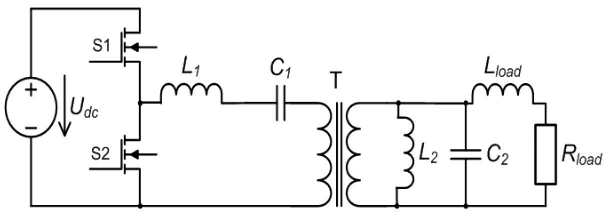

Fig. 2: Principle circuit scheme of *LCLC (LCTLC)* converter with HF AC output [5].

2. New Concept of Two-Stage Multi-Element Resonant-/Cyclo-Converter

Based on the schemes of the resonant converters mentioned in Chapt. 1 one can choose the principle conception of two-stage multi-element resonant-/cyclo-converter (TS-MERC) with HF interlink, Fig. 3.

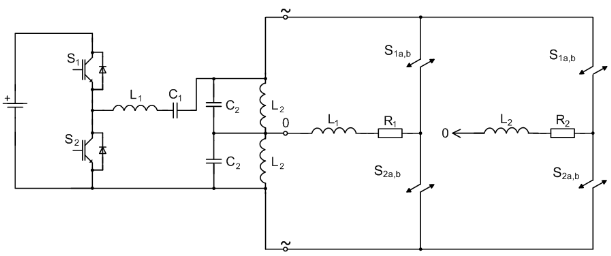

Fig. 3: Scheme of power circuits of 2-stage two-phase converter with HF interlink; Sa,b - bidirectional electronic switches.

The TS-MERC converter consists of input DC/DC converter, LCL_2C_2 resonant interlinks with HF output and two-phase half-bridge cyclo- or matrix converter, [4], [5]. Due to decreased phase voltage of half-bridge cyclo-converter we proposed a new converter connection with increasing autotransformer HF interlink, Fig. 4.

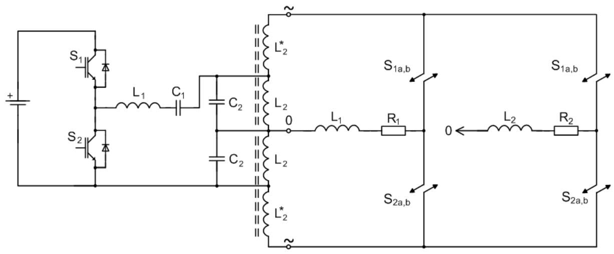

Fig. 4: Possible scheme of power circuits of 2-stage two-phase converter with increasing autotransformer HF interlink.

As bidirectional switches there can be used MOSFET transistors, IGBT transistors, reverse blocking RB IGBT transistors or SCR/GTO thyristors. The choice depends on power of application and used switching frequency, Fig. 5.

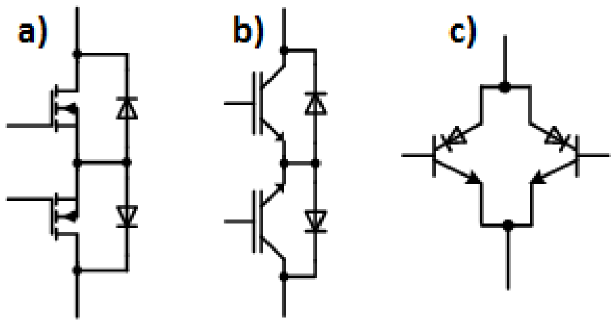

Fig. 5: Possible connection of bidirectional switches with: a) MOSFET transistors, b) IGBT transistors, c) reverse blocking RB IGBT transistors or SCR/GTO thyristors.

2.1. The First Stage Design and Control of TS-MERC Converter

1) Design of LCL$_2$C$_2$ Element

As mentioned above, the first stage consists of the simple input DC/DC converter and the LCL_2C_2 resonant interlink with HF output. The resonant frequency of L_1C_1 and L_2C_2 should be the same as basic fundamental frequency of the converter and is governed by load requirements. Thus, based on the Thomson relation

$$\omega_{res} = \sqrt{\frac{1}{L_1C_1}} = \sqrt{\frac{1}{L_2C_2}}, \qquad (1)$$

or, respectively

$$L_1\omega_{res} = \frac{1}{\omega_{res}C_1} = L_2\omega_{res} = \frac{1}{\omega_{res}C_2}, \qquad (2)$$

where ω_{res} is equal to $2\pi \times$ 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, $\omega_{res}L_1$ and other values of (2) can be chosen from a wide range.

For our first design approximation we suppose a simple resonant circuit with a resonant frequency equal to the input switching frequency ($\omega_{res} = \omega_{sw}$).

The LC design process can be considered from three different points of view or criteria, [6], [7], [8]:

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

In order to not exceed nominal voltages of the storage elements, we use the value of internal impedance of the storage element equal to the nominal load $|Z_N|$:

$$L\omega_{res} = \frac{1}{\omega_{res}C} = |Z_N| = \frac{U_1^2}{P_1}, \tag{3}$$

where U_1, P_1 are nominal output voltage or power, respectively (fundamental harmonic).

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

$$q_N = \frac{L\omega_{res}}{|Z_N|} = \frac{1}{\omega_{res}C|Z_N|}. \tag{4}$$

The above equation is similar to the quality factor defined by $q = (L_{load}\omega_{res})/R_{load}$, however q_N does not depend on the actual value of load resistance R_{load}.

From the Eq. (3) and Eq. (4) one can obtain the design formulas for LC storage elements of series chain

$$L = \frac{U_1^2}{\omega_1 P_1} q_N, \quad C = \frac{P_1}{\omega_1 U_1^2} \frac{1}{q_N}. \tag{5}$$

The voltage on storage elements at nominal steady-state is calculated as

$$U_L = L\omega_{res} I_N q_N = L\omega_{res} \frac{P_1}{U_1} q_N, \tag{6}$$

$$U_C = \frac{1}{\omega_{res}C} I_N q_N = \frac{1}{\omega_{res}C} \frac{P_1}{U_1} q_N. \tag{7}$$

That means that for q_N equal to one, the voltages across the storage elements will be nominal values, and they depend proportionally on q_N factor.

From the above derived relations we can design the resonant element of LCL_2C_2 as follows

$$L_1 = \frac{U_1^2}{\omega_1 P_1} q_N, \quad C_1 = \frac{P_1}{\omega_1 U_1^2} \frac{1}{q_N}. \tag{8}$$

where U_1, P_1, ω_1 are nominal output voltage, power and frequency, respectively (fundamental harmonic).

$$L_2 = \frac{\left(\frac{U_1}{2}\right)^2}{\omega_1 \frac{P_1}{2}} \frac{1}{q_N}, \quad C_2 = \frac{\frac{P_1}{2}}{\omega_1 \left(\frac{U_1}{2}\right)^2} q_N. \tag{9}$$

2) Control of LCL$_2$C$_2$ Resonant Converter

The control can be done by:

- classical asymmetrical duty cycle control for regulation of output voltage magnitude (fundamental harmonic) [10], Fig. 6,
- frequency control (by changing the switching frequency),
- LF modulation using bipolar PWM control.

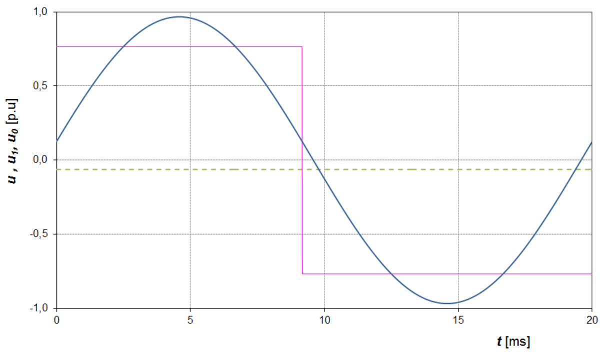

Fig. 6: Asymmetrical duty cycle control [10] for 165/195° el. asymmetry.

Using the Fourier theory for waveform in Fig. 6 one can derive relation ([10]) for basic harmonic amplitude of output voltage of inverter

$$\frac{U_{1M}(\beta)}{U} = \frac{2\sqrt{2}}{\pi}\sqrt{1 - cos(\beta/2)}, \tag{10}$$

where β is pulse-width of input rectangular voltage of LCL_2C_2.

Using an asymmetrical control, the output voltage of inverter comprises all harmonic components, both odd and even ones of Fourier series as it in Fig. 7, [9].

So, the first two methods are not suitable for deep control of output voltage because harmonic content and non-linear transfer function of the LCL_2C_2 circuit.

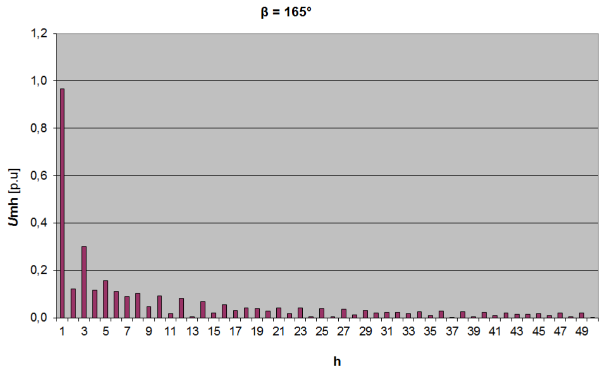

Fig. 7: Harmonic content of input voltage of the LCL_2C_2 inverter under asymmetrical control 165/195° el. [9].

3) LF Modulation Using Bipolar PWM Control

Principle of LF modulation is based on multiplication of carrier HF voltage with F control harmonic waveform, Fig. 6. The problem is that we have not HF carrier harmonic voltage to disposal.

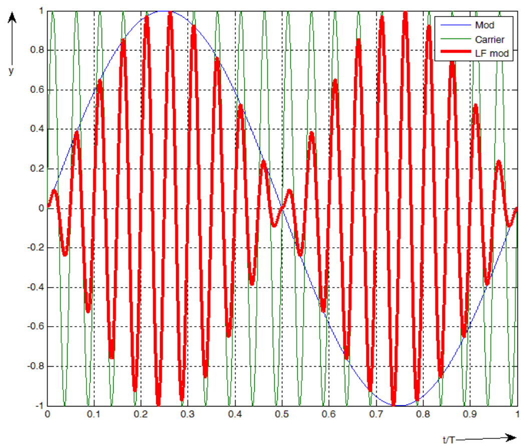

Fig. 8: Principle of LF modulation carrier HF voltage by LF control signal.

Although the principle of modulation is easy, practical realization make some problems, because we cannot compare both waveforms as we have not any HF carrier harmonic voltage. Thues we have to calculate each switching time (i.e. duty cycle during each switching period). The obtained result is shown in Fig. 9, and details of the method of calculation are prepared for publishing together with my colleagues.

Simulation of the LCL_2C_2 stage operation is given in the chapter 3.

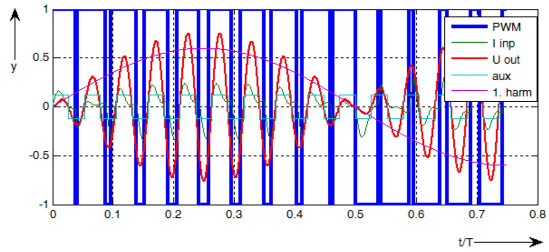

Fig. 9: Principle of LF modulation carrier HF voltage by LF control signal.

2.2. The Second Stage Design and Control of TS-MERC Converter

The second stage of TS-MERM converter consists of a half-bridge matrix converter for each phase of two-phase induction/synchronous motor, Fig. 8.

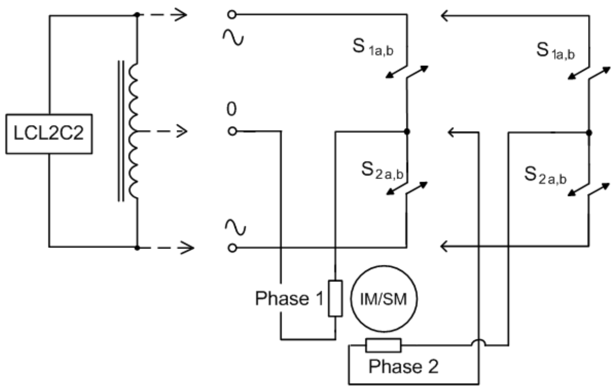

Fig. 10: Circuit scheme of two/phase half-bridge cycloconverter with IM-SM motors.

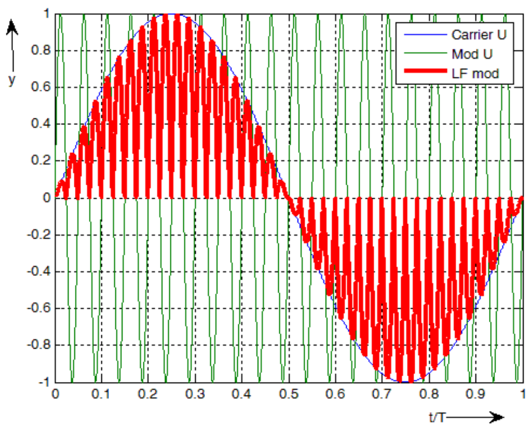

Fig. 11: Output voltage of cycloconverter PWM modulated control of the first stage.

The maximum voltage of each phase is one half of the entire input voltage of the second stage. So, the motor should be adapted for this voltage or the voltage should be increased by the first stage of TS-MERC converter.

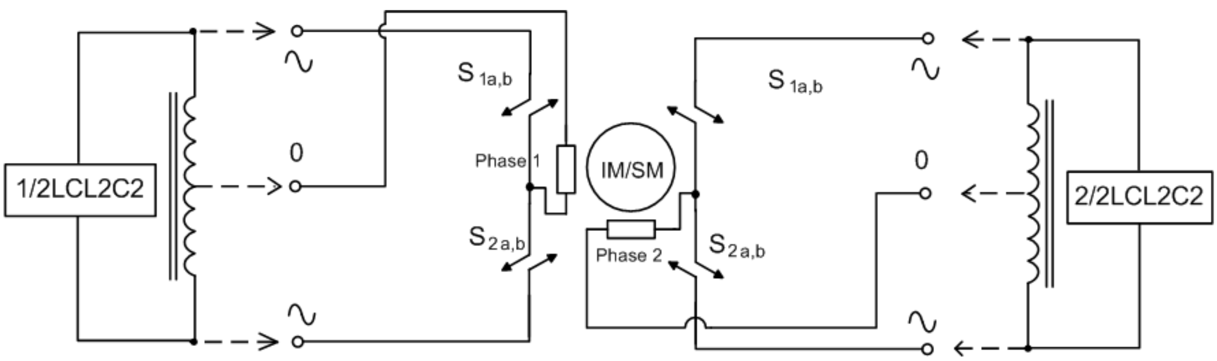

Fig. 12: Power circuit scheme of TS-MERC converter with PWM modulation of each phase of IM-SM motors.

There was chosen a two-phase application with IM/SM motor that is widely described in references [11], [12], [13], [14], [15].

Output voltage of cycloconverter can be controlled:

- by the first stage as mentioned above, Fig. 6, Fig. 8,
- or by a cycloconverter using phase control, Fig. 11.

Because of two phase's application each phase must be controlled separately - both phases cannot be controlled by the same PWM signal from the first stage, but they must be shifted by 90 degrees. The adequate power circuit connection is shown in Fig. 12.

2.3. Simulation Experiments

In Fig. 13 and Fig. 14 there are shown output quantities of LCL2C2 stage in steady state (without control, duty cycle $D = 0,5$) and with PWM control.

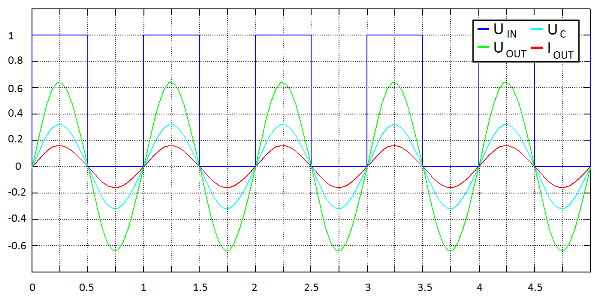

Fig. 13: Output quantities of LCL_2C_2 stage in steady state without control (duty cycle $D = 0,5$).

One can see clearly harmonic voltage of the first stage without (Fig. 12) and with PWM modulated control (Fig. 13). The time course of the output voltage of the second stage controlled by duty cycle control from the first stage is presented in Fig. 15.

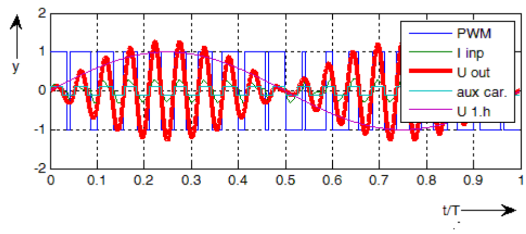

Fig. 14: LF modulation PWM control with modulation indexes m$_a$=1, m$_f$=20.

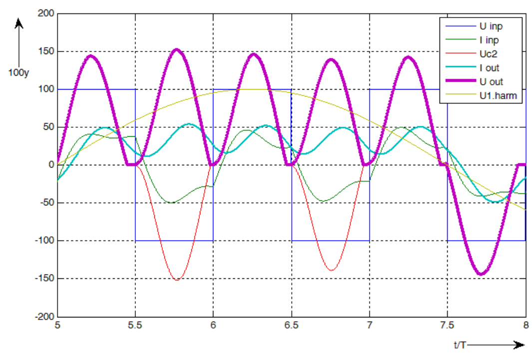

Fig. 15: The output voltage of six-pulse cycloconverter and its fundamental harmonic.

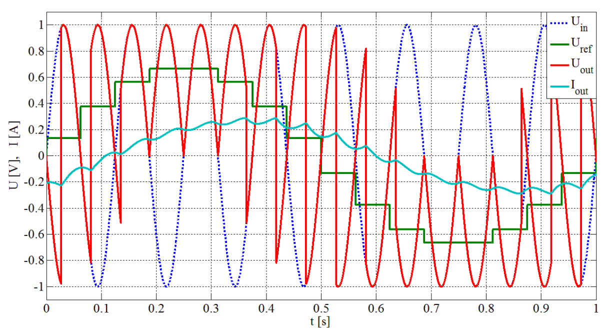

Fig. 16: Output quantities of cycloconverter under classical phase-shift control and RL load.

During these experiments it was necessary to synchronize control system quantities (reference values) with output voltage of cycloconverter.

3. Conclusion

New concept of power electronic two-phase system with two-stage TS-MERC converter and two-phase IM/PMSM motor is presented in the paper. The system with the TS-MERC converter can be used in:

- AC variable frequency motor application,
- hardening the metal with AC currents of the frequency 5–40 kHz, also for demagnetization by production of bearings – without second stage,
- power supply for the high frequency applications in the aerospace industry and cosmonautics and finally,
- as a source of AC harmonic voltage (e.g. UPS - the uninterruptible power supply 50 Hz), working parallel to the system, as a cold or hot reserve - using an output rectifier instead of cyclo-converter.

The real experimental verification is preparing to be done and will be published, too.

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