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THE DEVELOPMENT OF A FREQUENCY CONVERTER FOR HIGH SPEED PERMANENT MAGNET GENERATORS IN COGENERATION PLANTS

RAZVOJ PRETVARAČA FREKVENCIJE ZA VISOKOBRZINSKE GENERATORE S PERMANENTNIM MAGNETIMA U KOGENERACIJSKIM POSTROJENJIMA

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Professional paper

Abstract: *This paper describes the development of a frequency converter for high speed generators with permanent magnets that are used in cogeneration plants. A specific requirement of the converter is a transformable high frequency of the fundamental voltage harmonic. Therefore, two variants of the frequency converter in which the grid converter is the same for both structures are considered; while on the generator side of one variant, the converter based on a diode rectifier and step-up DC converter is used. On the generator side of the second variant, there is a three-phase inverter with IGBT transistors which have the same structure as the grid converter. The paper first describes the structure of power and control circuits of the frequency inverter, then the basic characteristics of the mechanical design of the power circuit of the three-phase IGBT inverter, as well as the control electronic boards that have been developed and tested. Furthermore, the paper also describes the basic features of the high speed motor generator group that serves to test the developed frequency converters. Finally, the results of the measurements on the laboratory model of the frequency converter with a diode bridge and a step-up DC / DC converter are presented.*

Key words: *frequency converter, permanent magnet generator, high speed electric machines*

Stručni članak

Sažetak: *U ovom radu opisan je razvoj pretvarača frekvencije za visokobrzinske generatore s permanentnim magnetima koji se koriste u kogeneracijskim postrojenjima. Specifičan zahtjev pretvarača je promjenljiva visoka frekvencija osnovnog harmonika napona. Stoga su razmatrane dvije varijante pretvarača u kojima je mrežni pretvarač potpuno isti za obje strukture, dok se na generatorskoj strani jedne varijante primjenjuje pretvarač temeljen na diodnom ispravljaču i uzlaznom istosmjernom pretvaraču, a u drugoj varijanti je na generatorskoj strani trofazni izmjenjivač s IGBT tranzistorima jednake strukture kao i mrežni izmjenjivač. U radu su prvo opisane strukture energetskih i upravljačkih krugova pretvarača frekvencije, a nakon toga i osnovne značajke konstrukcije energetskog dijela trofaznog IGBT izmjenjivača, kao i upravljačke elektroničke pločice koje su razvijene i testirane. Također, dane su osnovne značajke visokobrzinske motor generator grupe koja služi za testiranje razvijenih pretvarača frekvencije. Na kraju su prikazani rezultati mjerenja na laboratorijskoj maketi pretvarača frekvencije s diodnim mostom i uzlaznim DC/DC pretvaračem.*

Ključne riječi: *pretvarač frekvencije, generator s permanentnim magnetima, visokobrzinski električni strojevi*

1. INTRODUCTION

The project "Safer and more efficient cogeneration/trigeneration plants" is carried out within the framework of the European Fund for Regional Growth (2007-2013). The Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture is the project applicant, while the company Banko d.o.o. from Split is the project partner.

Cogeneration plants transform heat from different sources into electrical energy and exploitative thermal energy through a unique thermodynamic and power engineering process, while trigeneration plants also include production of cooling energy. Today, high-speed turbines with generators mounted on common shafts and frequency converters connected between the generator and the electrical grid are preferred for the conversion of thermal energy into electrical energy. As a consequence of generator high speeds (above 10000 min^{-1}), its voltage fundamental frequency is several times greater than the grid frequency, which requires the use of a frequency converter capable of generating voltages with high fundamental frequencies (up to 1000 Hz) in order to interface generators to the 50 Hz electrical grid.

One of the project objectives is to develop a frequency converter that will enable the connection of high speed permanent-magnet generators (PM generator) to the grid. Due to the high output frequency of the PM generator, two frequency converter structures are considered. These structures share an identical grid module while the generator module includes two variants: (1) converter consisting of a diode rectifier and a step-up DC/DC converter, (2) a three-phase converter with IGBT transistors identical to the grid converter.

In this paper, both converter structures are presented and their characteristics are explained, as well as the basic features considering the construction of power and control circuits of the three-phase converter with IGBT transistors which are an integral part of both converter structures. Furthermore, the high speed motor-generator group used for converter testing is described and the measurements results obtained on the laboratory setup of a step-up DC/DC converter based on the frequency converter are presented at the end of this paper.

2. BASIC STRUCTURES OF THE FREQUENCY CONVERTER POWER AND CONTROL CIRCUITS

A block diagram of a frequency converter with a generator module consisting of a diode rectifier and a step-up DC/DC converter is presented in Fig. 1, while Fig. 2 presents the structure of a frequency converter with identical generator and grid converters, both realized by a three-phase IGBT converter. In both structures, the grid module consists of a three-phase IGBT converter and an LCL filter. Along with its basic function of transferring energy from the DC link to the AC grid, the grid module provides an almost ideal sine waveform of the grid current (THD_i < 5%) and the possibility to adjust the power factor (cos φ) depending on the grid voltage and reactive power demand at the point of common coupling.

The advantages of the converter structure with a diode rectifier on the generator side are a less complex control structure and a DC/DC converter that is invariant to the frequency of the PM generator voltage. Therefore, the generator maximum speed is not limited by the converter structure. The basic drawback of this structure is a high amount of generator current harmonic distortion which produces additional generator losses, temperature increase and leads to lower generator efficiency. On the other hand, the structure with a three-phase IGBT converter and a sine filter on the generator side is characterized by an almost ideal sine waveform of the current and a significantly more complex vector control structure of the PM generator with different limitations due to the high frequencies of the generator voltage and the presence of a sine filter between the generator and the converter. The PM generator control structure is that of a well-known vector control implemented in the *dq*-rotating frame with the *d*-axis aligned to the rotor magnetic axis, which has been used in almost all servo drives dominated by motors with permanent magnets. Therefore, this control structure will not be presented in this paper. Instead, this paper will present the control structure of the frequency converter based on a diode rectifier and a step-up DC/DC converter, which represents a unique solution that can be implemented in systems which include generators with a permanent magnet as well as classic synchronous generators with field windings.

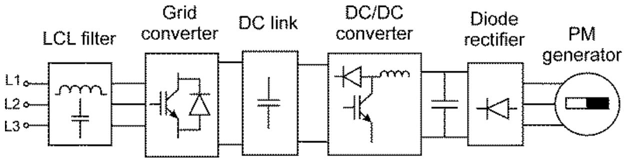

Figure 1. Block diagram of a frequency converter with a generator module consisting of a diode rectifier and a step-up DC/DC converter

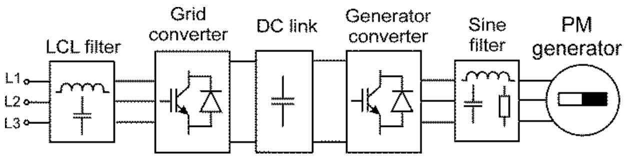

Figure 2. Block diagram of a frequency converter with an identical generator and grid converters

Fig. 3 presents a block diagram of the control structure for the frequency converter given in Fig. 1. The control of the grid converter and the step-up DC/DC converter is separated. The control structure of the grid converter provides a constant DC link voltage while the energy is transferred from the PM generator through the step-up DC/DC converter, the DC link and the grid converter to the grid. The control structure of the step-up DC/DC converter ensures the transfer of energy for a wide range of PM generator speeds, i.e. for the variable output voltage of the diode rectifier which is proportional to the generator speed.

The control structure of the grid converter is based on the vector control method implemented in the synchronous *dq*-rotating frame with the *d*-axis aligned to the grid voltage space vector [3]. This provides the control of the *d*- and *q*- current components which are proportional to the active and reactive power, respectively. The control structure is cascaded with two current feedbacks. The *d*- current control loop is an inner loop for which the referent value (i_d*) is generated by the PI regulator of the DC link voltage (u_{DC}), which indicates that the outer control loop is used to control the DC link voltage measured on the capacitors. The DC link voltage is 10-15% greater than the maximum value of the grid line-to-line voltage which can be achieved as a result of the LCL filter connected in the circuit. In other words, this three-phase converter can be considered a boost converter.

The *q*- current control loop is independent of the DC link voltage control and its referent value (i_q*) is set according to the desired power factor. The *d*- and *q*- voltages and currents needed for the control are obtained by measuring the instant values of phase voltages and currents, and afterwards a two-step transformation of the variables is used. First, three-phase values are transformed into a two-phase (αβ) stationary reference frame which is then transformed into the synchronously rotating *dq*-reference frame by using the rotational angle $\theta=\omega t$.

In order to control the three-phase IGBT converter, inverse transformation is used, i.e. the referent values of the converter voltage components in the *dq*-reference frame (u_d*, u_q*) are transformed to the αβ-reference frame (u_α*, u_β*) by using the same rotational angle θ as for the transformation of the measured quantities. The space vector modulation method is used to generate grid converter AC voltages.

The control structure of the step-up DC/DC converter is also cascaded with the inner loop controlling the generator current ($i_{g=}$) and the outer control loop controlling the generator voltage ($u_{g=}$). However, the generator voltage and current are AC quantities, and the measuring sensors are located on the DC side of the diode rectifier since the mean values of the voltage and current on the DC side are proportional to the corresponding RMS values on the AC side. The pulse width modulation method is used to control the IGBT transistor of the DC/DC converter. During operation, the output voltage of the DC capacitors is constant (controlled by the grid converter), while the output voltage of the diode rectifier varies. This voltage is proportional to the generator voltage, which is proportional to the rotor speed for PM generators, and the presented control structure can be used to control the generator speed, which is the final objective considering the cogeneration plant operation.

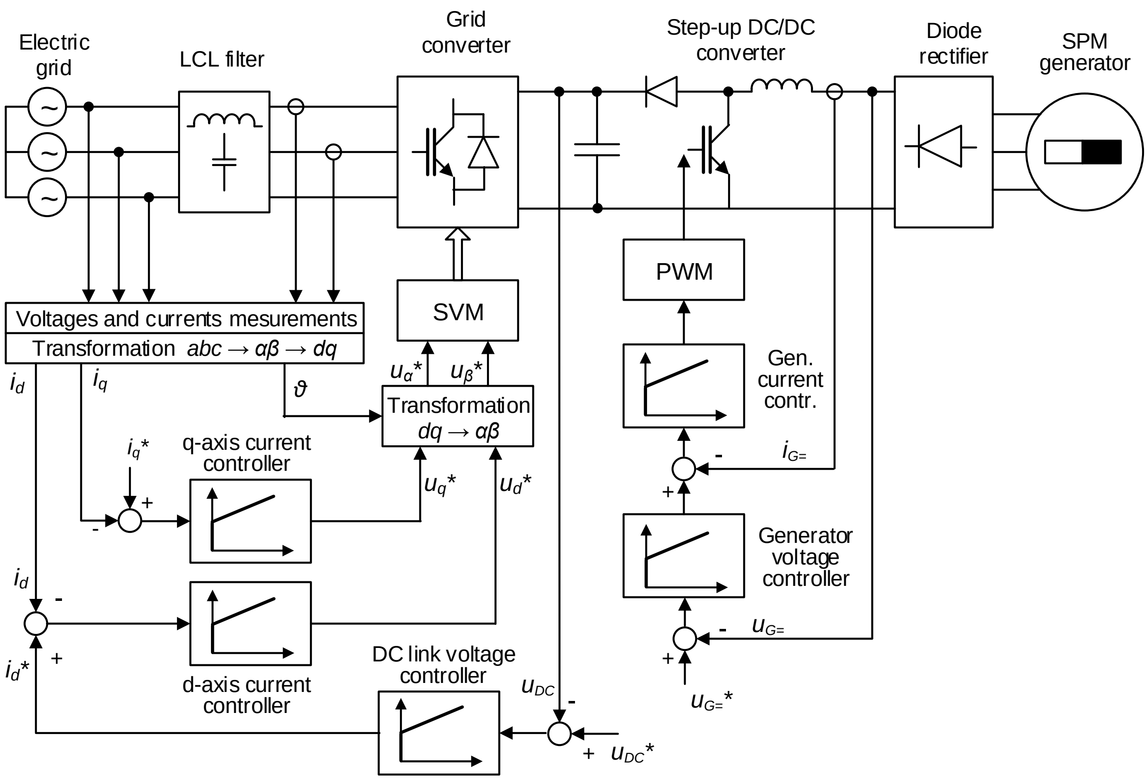

Figure 3. Block diagram of a grid converter and step-up DC/DC converter control structure

3. DEVELOPMENT OF THE FREQUENCY CONVERTER PROTOTYPE

Prototypes of both frequency converter structures are being developed within the project framework and the following section presents the basic characteristics and construction of a three-phase IGBT converter power circuit, as well as its control circuits.

Fig. 4 presents the basic structure of the power circuit and the block representation of units needed to control the frequency converter with a diode rectifier and step-up DC/DC converter. In comparison with the structure presented in Fig. 3, the DC link includes a braking circuit consisting of a resistor connected in a series with an IGBT transistor. This IGBT is turned on only when the DC link voltage exceeds the allowed limit which can occur if the converter is cut off from the grid, and in this case power needs to be dissipated on the resistor during a short period of time to avoid an uncontrolled increase of the DC link voltage.

The three-phase IGBT converter, consisting of six IGBT transistors with freewheeling diodes, is based on FF900R12IE4 IGBT modules, manufactured by Infineon, with maximum ratings of 1200 V and 900 A. The aforementioned module presents the one phase leg of a three-phase converter with two IGBT transistors and two diodes (see Fig. 4), which suggests that the three-phase converter includes three IGBT modules mounted on a bonded fin heat sink air-cooled by a ventilator. An electronic board with six-channel driver circuits (driver unit in Fig. 4) is mounted directly on three IGBT modules and is used to transmit control signals generated by the microcontroller-based control unit. The driver unit is also used to shape control signals and to decouple the control unit from IGBT modules. It includes a short-circuit protection of IGBT modules which is implemented by measuring the collector-emitter voltage during the conduction stage. Positive and negative DC buses consisting of 3mm wide copper sheets are mounted above the driver unit and 3mm wide isolation material is inserted between them. DC buses are connected to the capacitor block which consists of a series-parallel combination of electrolytic capacitors and resistors used to distribute the DC link voltage evenly among the series combinations of capacitors. DC buses construction requirements include a large surface area, minimal thickness and minimal space between the positive and negative buses which is needed in order to minimize stray inductances between the capacitors and IGBT modules. In fact, sudden changes in IGBT currents can lead to overvoltage on stray inductances that are transferred onto IGBT modules and can cause the destruction of modules. In addition to the minimization of stray inductances, protective block capacitors are mounted with the identical purpose. Fig. 5 shows the three-phase IGBT converter with three HAT600 current transducers used to measure the current through the AC connections of IGBT modules.

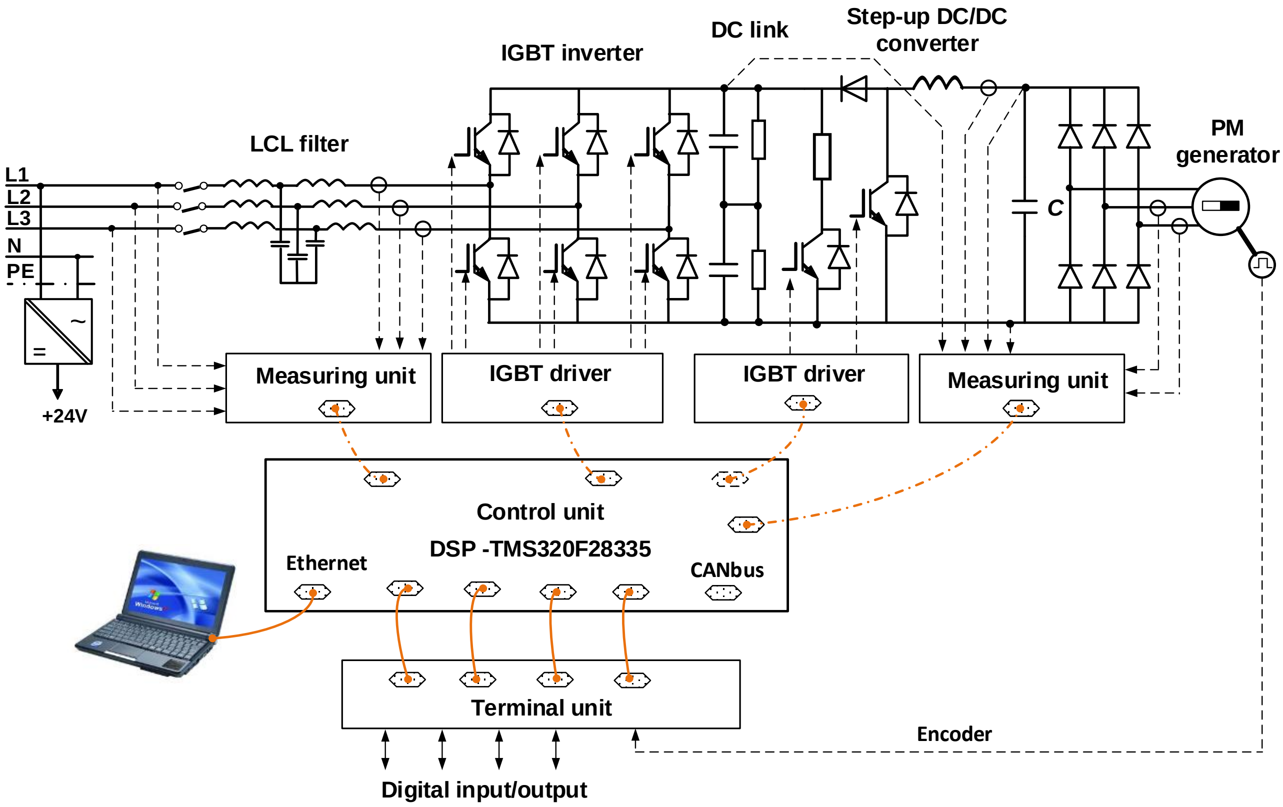

Figure 4. Structure of the power circuit and block representation of units needed to control the frequency converter with a diode rectifier and step-up DC/DC converter

Apart from the driver unit, three additional electronic boards were developed and constructed for the purpose of frequency converter control and are shown in Fig. 5:

- **Control unit** is a six-layered SMD electronic board based on the TMS320F28335 microcontroller, manufactured by Texas Instruments. Besides the microcontroller, used to implement control algorithms, the control unit is used to process analogue measurement signals (16 AI), as well as the input/output digital signals (8 DI, 8 DO, 12 PWM), and the unit itself houses several communication channels (CANbus, RS485, RS232, Ethernet …).
- **Measuring unit** processes analogue signals for four-channel voltage measurements, three-channel current measurements and the one-channel measurement of the IGBT module temperature. For voltage measurement, LV25 voltage transducers are used and mounted on the unit while the three aforementioned current transducers (see Fig. 4) are connected to the measuring unit by four-wire cables. Within each of the IGBT modules there is a resistive temperature sensor (NTC thermistor). The electronic circuit within the measuring unit processes temperature signals of all three IGBT modules and forms a single analogue output signal proportional to the highest temperature signal.
- **Terminal unit** represents the classical wire interface between the converter and the process, as well as with the superior control system, and it is used to connect the encoder for the PM generator's rotor speed and position measurements.

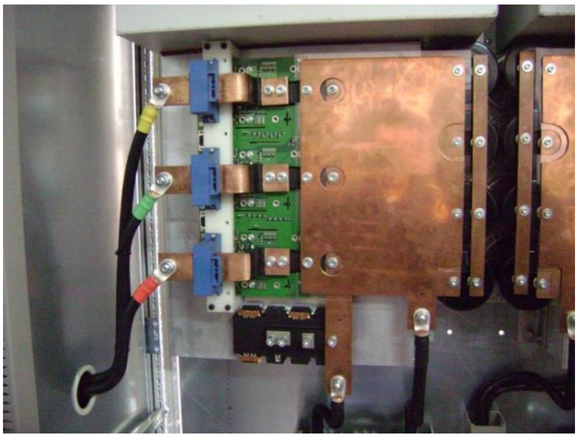

Figure 5. Power circuit of the three-phase IGBT converter

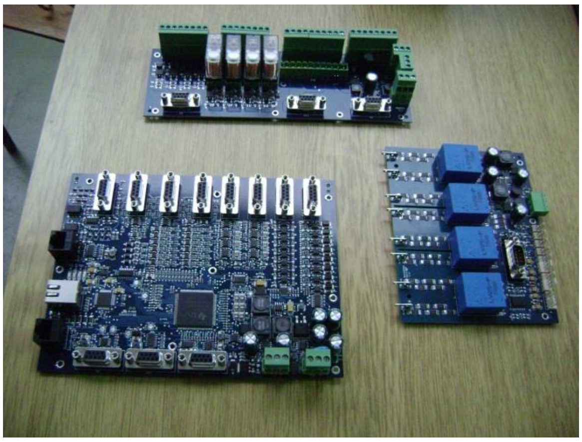

Figure 6. Control, measuring and terminal units

4. HIGH-SPEED MOTOR-GENERATOR GROUP

The motor-generator group consisting of a squirrel-cage induction motor and a surface permanent magnet machine (SPM machine) was acquired in order to test the constructed frequency converters. The nominal data of both machines are basically the same, and are defined for the sine waveform currents: P = 100 kW, U = 400V, I = 166 A, n=20000 min^{-1}, M = 48 Nm. A 3D model of the squirrel-cage induction machine with visible cooling channels is shown in Fig. 7, while Fig. 8 shows the motor-generator group. Machines are designed and constructed by the company HSTec from Zadar and their core business is the design and construction of high-speed motor spindles for tool machines. Machines of the motor-generator group are designed and constructed in such a manner that the stator frames with windings and rotors are obtained from the foreign manufacturer of high-speed machines, while the HSTec manufactured or acquired all other integral components such as the rotor shaft, cast iron stator casing with water cooling channels, incremental encoder for the rotor speed and position measurement, two temperature sensors for the stator windings and the terminal box. After a demanding and precise assembly of components, machines were tested in HSTec facilities, at no load conditions and nominal speed, during which the temperatures and vibrations were measured. Afterwards, machines were mounted on a common base and their shafts were mechanically coupled by using a flexible clutch. Both machines are fitted with incremental encoders that generate 256 pulses per revolution. One encoder has 5V TTL output signals while other has sine/cosine output signals with 1 V_{pp} amplitude.

For the purpose of the lubrication of ceramic bearings, an oil + air lubrication system, manufactured by SKF, was installed. This unit lubricates eight bearings in total by injecting approx. 20 mm^3 of oil into the plastic tubes of the system by using compressed air (6 bar). The lubrication of bearings is repeated every six minutes. The air flow generates an additional cooling effect for each bearing.

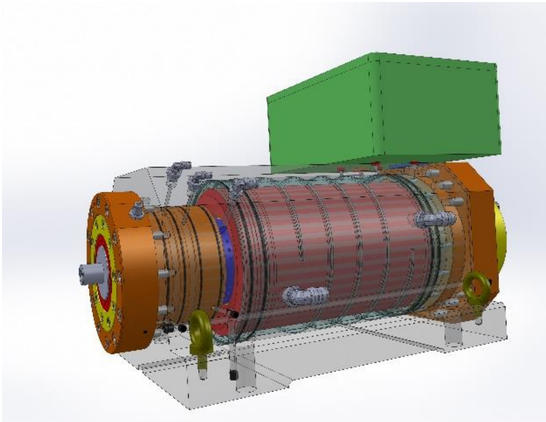

Figure 7. 3D model of a squirrel-cage induction machine

Figure 8. High-speed motor-generator group with a lubricating oil unit and cooling system

In order to cool the machines by using water, a hydraulic system was installed and it ensures a constant flow of coolant comprised of water and anticorrosive additives. This system requires a flow of 16 l/min, input coolant temperature between 10 and 40^{0}C with a maximum temperature increase of 10^0C at the machine's nominal load.

5. EXPERIMENTAL RESULTS

Measurements were carried out by using the laboratory setup of the frequency converter with a diode rectifier and step-up DC/DC converter on the generator side (structure shown in Fig. 4). This laboratory setup is shown in Fig. 9 and it was constructed before the final prototype of the frequency converter with three-phase IGBT converters on both the grid and generator side. Apart from testing the operation of the frequency converter with a step-up DC/DC converter, the motor-generator group was tested for the first time at 50% of the motor nominal current and speed of approx. 13000 min^{-1}. During testing, the induction machine was used as a motor and it was connected to the 1Q VACON NXP0300 frequency converter, while the SPM machine was used as a generator connected to the abovementioned frequency converter.

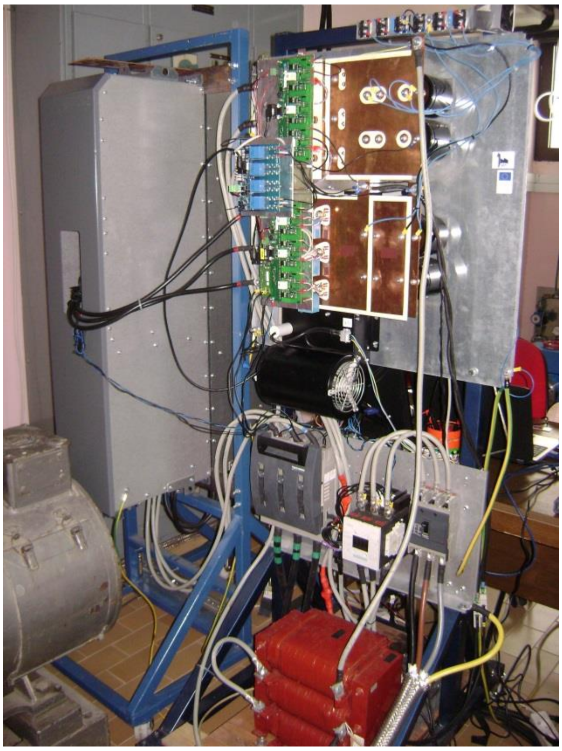

Figure 9. Laboratory setup of the frequency converter with a diode rectifier and step-up DC/DC converter

Fig. 10 presents the steady-state waveforms of the SPM generator current (red line) and current through the step-up DC/DC converter's inductor (blue line). Due to the operation of the diode rectifier, the generator current exhibits a non-sine waveform which presents a problem considering the additional heating and pulsating torque components of the SPM generator. The current through the inductor, besides the DC component (approx. 100A), contains a pulsating AC component generated due to the switching operations of the step-up DC/DC converter's IGBT transistor. The AC component frequency is determined by the transistor switching frequency which is equal to 10 kHz. For the same operating point, Fig. 11 presents the grid current (red line) and the DC link voltage (blue line). The grid current exhibits a sine waveform with low pulsations around the peak values, while the DC link voltage is constant and equal to 630 V, which is approx. 12% higher than the grid line-to-line voltage maximum value (√2·400V).

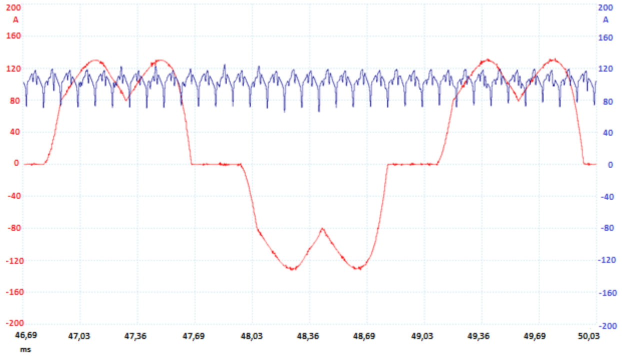

Figure 10. Measured SPM generator's current (red line) and current through the step-up DC/DC converter's inductor (blue line)

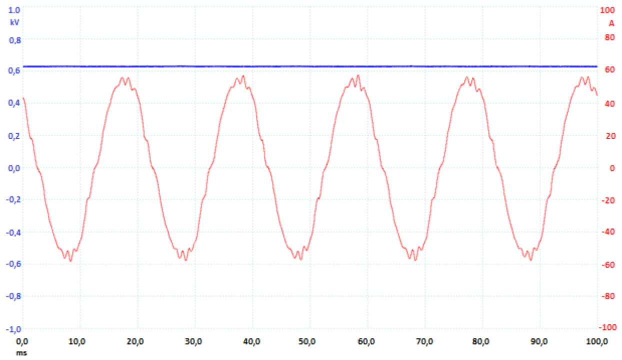

Figure 11. Measured grid current (red line) and the DC link voltage (blue line)

6. CONCLUSION

The development of frequency converters for high-speed permanent magnet generators used in cogeneration plants is specific in terms of the high frequencies of the generator's voltage fundamental harmonic. This enables the implementation of well-known frequency converters used in 4Q electrical drives consisting of two three-phase IGBT converters with the main issue being the high switching frequency of the generator converter due to the high frequency of the generator's voltage fundamental harmonic. On the other hand, a simpler solution involving a diode rectifier and step-up DC/DC converter is not affected by the high frequencies of the generator's voltage fundamental harmonic, but the additional heating and additional pulsating torque components are generated due to the non-sine waveform of the generator current.

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