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STUDY OF THE APPLICATION OF A MULTIPHASE MATRIX CONVERTER FOR THE INTERCONNECTION OF THE HIGH SPEED GENERATION TO THE GRID

STUDIUM UKŁADU PRZYŁĄCZENIA SZYBKOOBROTOWEGO UKŁADU GENERACYJNEGO OPARTEGO NA PRZEKSZTAŁTNIKU MATRYCOWYM DO SYSTEMU ELEKTROENERGETYCZNEGO

Abstract

The article shows a new field of application for the matrix converter (MC) as the interconnecting device between the high speed, permanent magnet generator and the grid. The converter works under the developed control algorithm based on a so called 'area based' approach. The device consists of a converter, a transformer (or transformers) and filters and is supposed to substitute or revolution decreasing gear box or DC link based power electronic converter. Several structures, including multiphase structures (3, 12 phase) were investigated and their properties were assessed using the results of Matlab Simulink based simulations. The simulations were performed using the standard Simulink models and the developed, simplified permanent magnet motor model. The results were very satisfactory, i.e. input waveforms distortions, output current and machine torque ripples were at acceptable levels for the multiphase structures and high frequency input. The waveform distortions were found to be a function of input frequency and the number of phases in the conversion device, but the structure of the converter was limited to a 12x12 structure for economic reasons.

Keywords: *matrix converter, permanent magnet machine, high speed co-generation unit*

Streszczenie

W artykule pokazano aplikację Przekształtnika Macierzowego (MC – *Matrix Converter*) jako układu synchronizującego pomiędzy wysokoobrotowym generatorem synchronicznym z magnesami trwałymi a Systemem Elektroenergetycznym. Przekształtnik jest sterowany za pomocą skonstruowanego jednookresowego algorytmu kontroli – jednego z algorytmów należących do klasy algorytmów obszarowych. W proponowanym urządzeniu, które składa się z transformatora (transformatorów), filtrów oraz przekształtnika, MC ma zastąpić przekładnię mechaniczną lub przekształtnik AC-DC-AC. Podstawowe symulacje obejmujące część elektryczną mikroturbiny (generator, przekształtnik, transformator, filtry) wykonano w programie MATLAB/Simulink. W ramach pracy na podstawie symulacji oceniano wpływ rozmiaru struktury MC (3-, 12-fazowa) na pracę generatora z magnesami trwałymi (składowa zmienna momentu elektrycznego) oraz poziom zniekształceń napięć i prądów. Zniekształcenia, które były funkcją rozmiaru struktury MC oraz prędkości obrotowej generatora, uznano za akceptowalne i łatwe do odfiltrowania dla struktury 12x12. Większych struktur nie rozpatrywano, gdyż koszt takich urządzeń byłby nieuzasadniony.

Słowa kluczowe: *przekształtnik macierzowy*, *generator z magnesami trwałymi*, *mały moduł ko-generacyjny*

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1. Introduction

High parameter steam and gas miniturbines (mT) and microturbines (μT) are becoming an interesting option for small co-generation plants. The plants typically consist of high speed gas fueled turbines and generating units including transmissions for speed reduction and heat recovery systems or medium or high parameter boilers with high-speed steam turbines, transmissions (gear boxes), generators and heat exchangers to extract energy form the steam. The power range of such systems starts from 20–30 kW and goes up to 10 MW. Usually, the speed of the gas turbines ranges from 16 to 120 krpm. The speed of steam turbines (usually single stage turbines are used for small co-generation) depends on the parameters of the steam and on the turbine power and it ranges from 6 to 12 krpm. For all these arrangements, the combined cycle of work allows achieving high levels of efficiency at over 80%. The cogeneration unit structure usually involves the transmission decreasing the revolutions to match the generator's synchronous speed. For gas turbines, generators with a synchronous speed of 3000 rpm are used whereas for steam turbines, four pole generators with speeds of 1500 rpm are utilized. The typical performance of such units can be shown, for example, for the Capstone C-65 microturbine with an electrical efficiency of 29% for the nominal load of 65 kW and 70–112 kW of heat energy recovery depending on the type of heat recovery unit [1, 2].

In this research, it is proposed to replace the revolution decreasing gear box and 1500 or 3000 rpm generator with a high speed generator and electronic unit able to convert a high frequency alternating current into a 50 Hz current. The removal of the gear box and straight forward coupling of the turbine into the generator will decrease energy losses and will provide higher reliability of the mechanical part of the system. The changes will contain not only the generator (a permanent magnet high speed machine is proposed) but they also have to include the interconnection system to the grid. There are two basic structures of converters able to adapt high frequency generator output into a 50 Hz grid frequency: a structure based on AC-DC-AC conversion or a structure based on straightforward energy conversion. The first option is already in use and in this paper, the matrix converter (MC) is proposed as an alternative device.

2. The Structure and control algorithm for Matrix Converter

A NxM multi-phase matrix converter (MC) is an array of NxM fully controlled bi-directional switches (Fig. 1) able to convert N phase input voltages into M phase output voltages of different amplitude, phase and frequency than the input. Recently, due to its simplicity, the matrix converter (MC) has received a lot of attention. The main problems in large scale industrial application are the complexity of the control schemes, a large amount of low order harmonics in converter currents and their non-continuity.

The energy conversion in the MC is accomplished without the use of a DC current circuit or any energy storage elements between the converter input and the output. The matrix converter is a straightforward device which creates the output voltage as a combination of the input voltages.

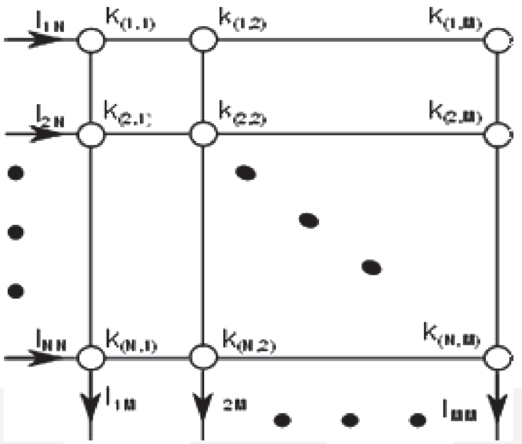

Fig. 1. The structure of the *N*x*M* matrix converter

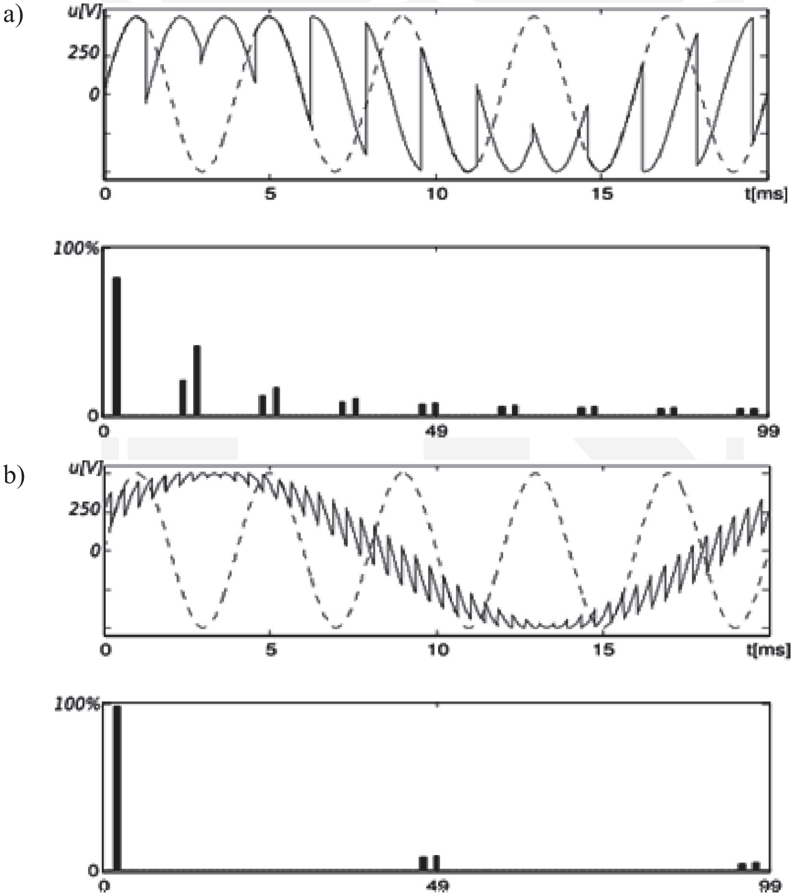

Fig. 2. Output voltage of 3x3 (a) and 12x12 (b) MC – (dotted line input voltage) and its FFT

In general, the output voltage $V_{mM}(t)$ for every m^{th} output phase can be written as:

$$V_{mM}(t) = \sum_{n=1}^{N} k_{(n,m)} V_{nN} \tag{1}$$

where:

$k_{(n,m)}$ – membership function for n^{th} input phase which determines when and how long the m^{th} output phase consists of n^{th} input phase,

V_{nN} – voltage for the n^{th} input phase.

The proposed in this research control single periodical algorithm [3, 4] is based on the so called ‘area based algorithm’ [5–7] and was chosen from among other possible algorithms developed by the authors. The algorithm, as opposed to other algorithms found in the literature, uses all fragments of the input sinusoids to create the shape of the output sinusoids, whereas the gross algorithms described in literature utilize only the parts of the input sinusoids which are close to the peaks of the waveforms [8–10]. The method of output waveform creation used by the proposed control technique can be clearly seen in Fig. 2a) for 3x3 MC structure and in Fig. 2b) for 12x12 MC structure. Any output phase can be connected at a certain instant to any input phase which creates ties not only for voltages but also for converter currents [11].

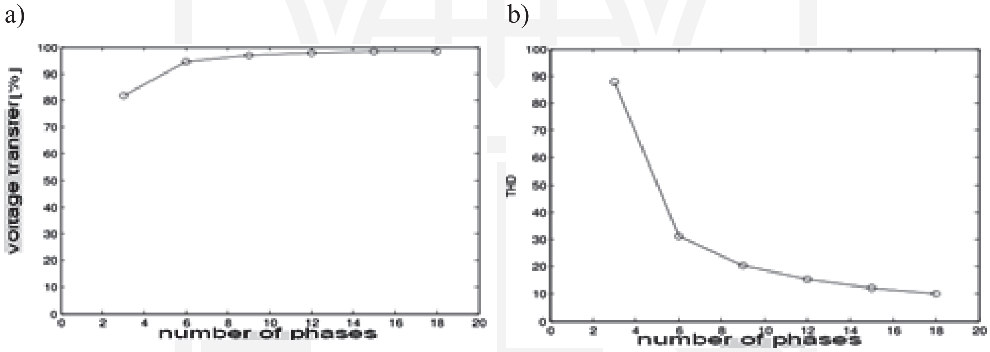

Fig. 3. Voltage transfer (a) and THD (b) as the function of the number of phases in MC square structure

The proposed multiphase structures (3x12, 12x12) have several advantages over the simple 3x3 structures – the voltage transfer of the MC increases, output voltage distortion and the rating of the switching elements decreases as its dimensions increase (Fig. 3). Moreover, in the proposed control procedure, the switching occurs between two adjoining input phases which minimize commutation problems. A square structure of the MC was chosen (the number of input phases is equal to the number of output phases) since for a proposed control scheme it enables a continuous current flow (currents without ‘0’ periods) in all input and output phases. If the structure is not square and the simultaneous connection of two input phases into one output phase (or opposite) is not allowed due to a short circuit restriction at a certain instant, only the same number of input and output phases are connected, i.e. all phases from the side with the lesser number of phases and not all phases from the side with the greater number of phases. This leaves some phases unconnected resulting in zero current periods.

In order to maximize MC power transfer and to minimize produced disturbances, it is necessary to switch on at a certain instant all possible switches without the creation of short circuits.

The investigated MC based grid connector structures include multiphase matrix arrangements (3x3, 3x12, 12x12) and transformers. The multiphase MC showed much better performance than three phase versions. The performance assessment was done for a much higher input frequency than output frequency and included voltage transfer, order of generated harmonics and THD coefficient.

It is worth noticing that for the investigated input frequency and 12x12 structure, the order of harmonics is close to the one produced by a 48 level converter which is a very complicated structure.

3. Simulation parameters and structure of the models

The performance of the proposed control scheme for a different structure of energy conversion paths was investigated using MATLAB/Simulink software and compared. The variations in the models included variations to the MC structure, generator and transformer models.

The models of the elements of the energy conversion systems (transformers, filters, equivalent models of power systems and power lines) were build using standard Simulink Libraries. The model of the permanent magnet generator (its electrical part) was developed using standard machine equations and taking several simplifications and assumptions such as sinusoidal distribution of the flux in the machine air gap into consideration, omitting mutual stator inductances and assuming phase shift of the N phase windings by $2\pi/N$:

$$\mathbf{U} = \omega \cdot \Psi \cdot \begin{bmatrix} \sin \vartheta \\ \sin\left(\vartheta - {}^{2\pi}\!/_{N}\right) \\ \\ \sin\left(\vartheta - {}^{2(N-1)\pi}\!/_{N}\right) \end{bmatrix} - R_G \cdot \mathbf{I} - L_G \frac{\mathrm{d}}{\mathrm{d}t}\mathbf{I} \tag{2}$$

where:

U and **I** – matrixes of the generator voltages and currents (1xN),
Ψ – magnitude of the flux,
ϑ – actual position of a flux with respect to the first winding (the position of the rotor),
R_G, L_G – resistance and reactance of the generator.

The mechanical equation of rotor movement can be then expressed as:

$$J\frac{\mathrm{d}\omega}{dt} = T_m - T_e - D \cdot \omega \tag{3}$$

where:

J – moment of inertia,
T_m – mechanical torque applied to the rotor,
D – friction coefficient,
T_e – electrical torque.

The electrical torque is defined by the following equation:

$$T_e = p \cdot \frac{\delta}{\delta\vartheta} \mathbf{\Psi} \cdot \mathbf{I} \tag{4}$$

where $\mathbf{\Psi}$ – matrix of machine fluxes.

What for the stated assumptions results in the formula:

$$T_e = \omega \cdot \Psi(\sin\vartheta \cdot i_1 + \sin\left(\vartheta - \frac{2\pi}{N}\right) \cdot i_2 + \ldots + \sin\left(\vartheta - \frac{2(N-1)\pi}{N}\right) \cdot i_N) \tag{5}$$

The models of the multiphase transformers were developed using standard Simulink models and proper winding arrangements.

The speed of the generators in the presented simulation result was chosen in such a way that no inter-harmonic components are present in the current, voltage and torque waveforms

4. Simulation results of µT with 3x3 matrix converter

Several structures of the device were investigated and figure 4 shows the structure based on a 3x3 structure and transformer.

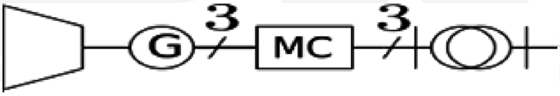

Fig. 4. Structure of 3x3 conversion device

Figures 5a) to 5c) illustrate selected results of simulations for a 3x3 structure. The waveforms of current, voltage and torque were chosen for the investigation.

The advantage of this structure is the use of typical elements (three phase generator MC and transformer) which result in the low cost of the connecting device.

The figures below show converter waveforms. All harmonics in the presented spectra were given with respect to the dominating one.

This device, however simple, produces a highly distorted generator current that results in a ripple in the generator torque. This highly distorted current will cause high losses in the generator core that will decrease the efficiency of the energy conversion. The generation unit output voltage, although not shown in this paper, also contains high level contents of high order harmonics and its shape is not acceptable.

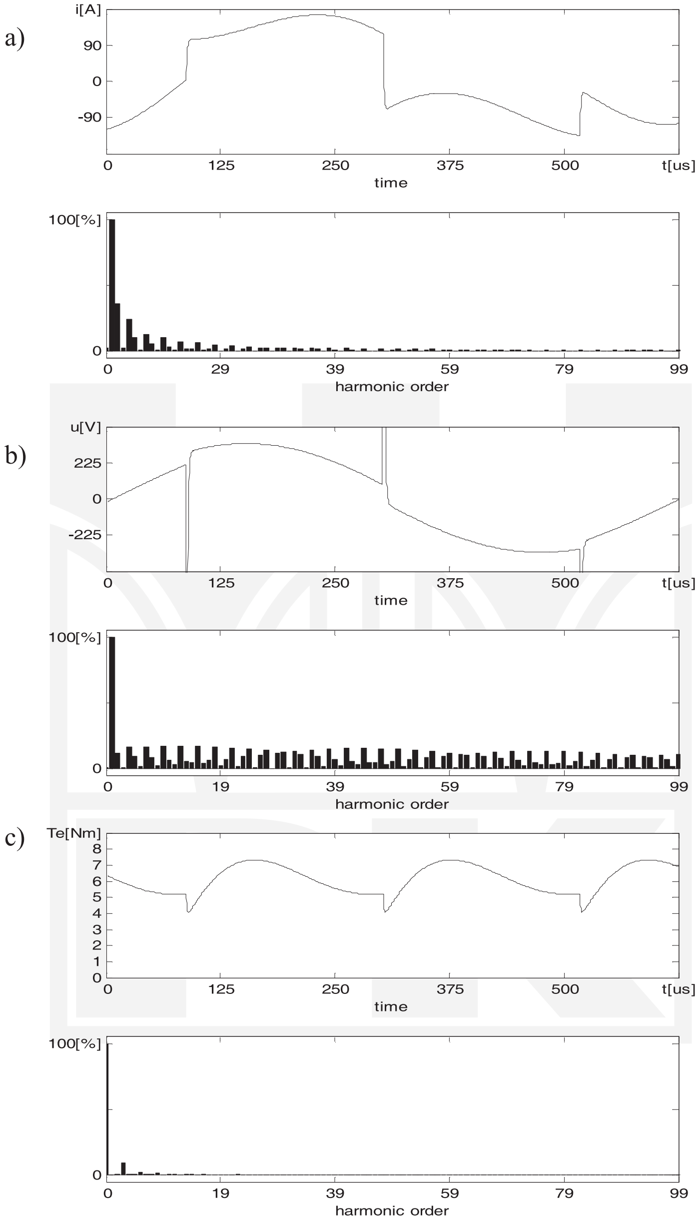

Fig. 5. Current (a), voltage (b) and electromagnetic torque of the generator (c) of µT with 3x3 MC

5. Simulation results of µT with 3x12 matrix converter

This device consists of the 36 switch MC structure (3x12) of a typical three phase generator and a non-typical 12x3 transformer.

Fig. 6. Structure of 3x12 conversion device

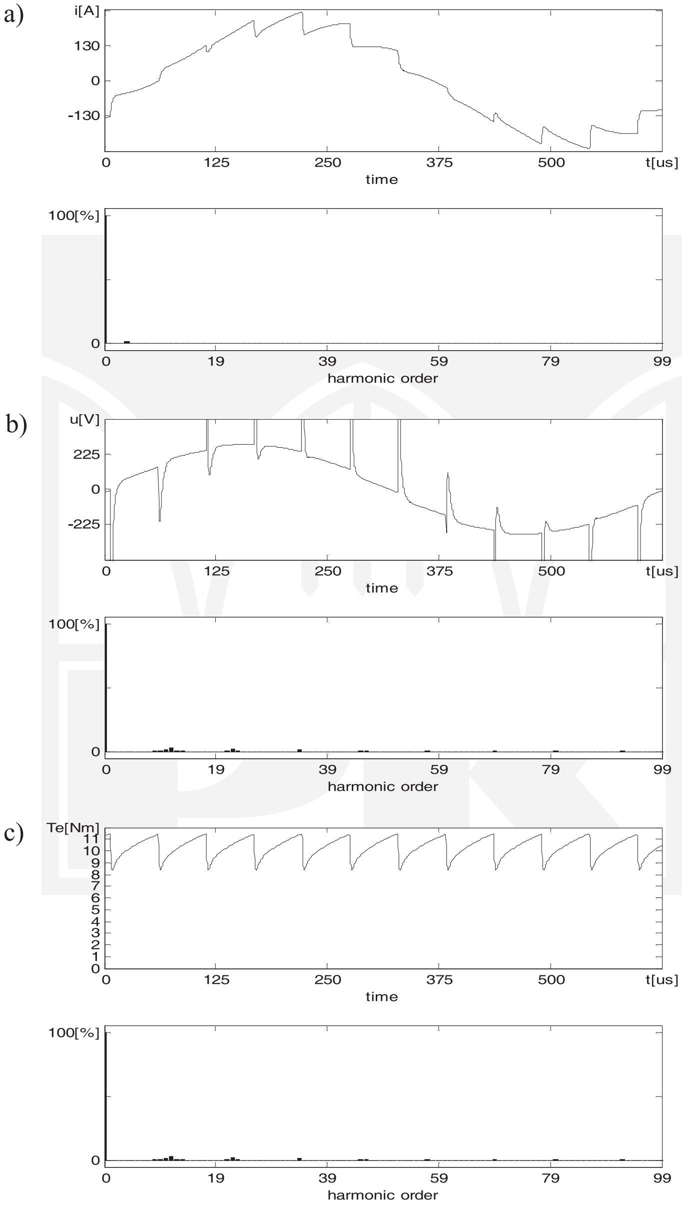

Fig. 7. Current (a), voltage (b) and electromagnetic torque of the generator (c) of μT with 3x12 MC

The disadvantages of this structure include rapid changes in the currents of the switches which results in rapid changes and over-voltages in generator output voltages.

4. Simulation results of μT with 12x12 matrix converter.

Fig. 8. Structure of 12x12 conversion device

The proposed structure is square and results in non ‘0’ periods in converter currents i.e. for a proposed control 12 switches are always in the ‘on’ state.

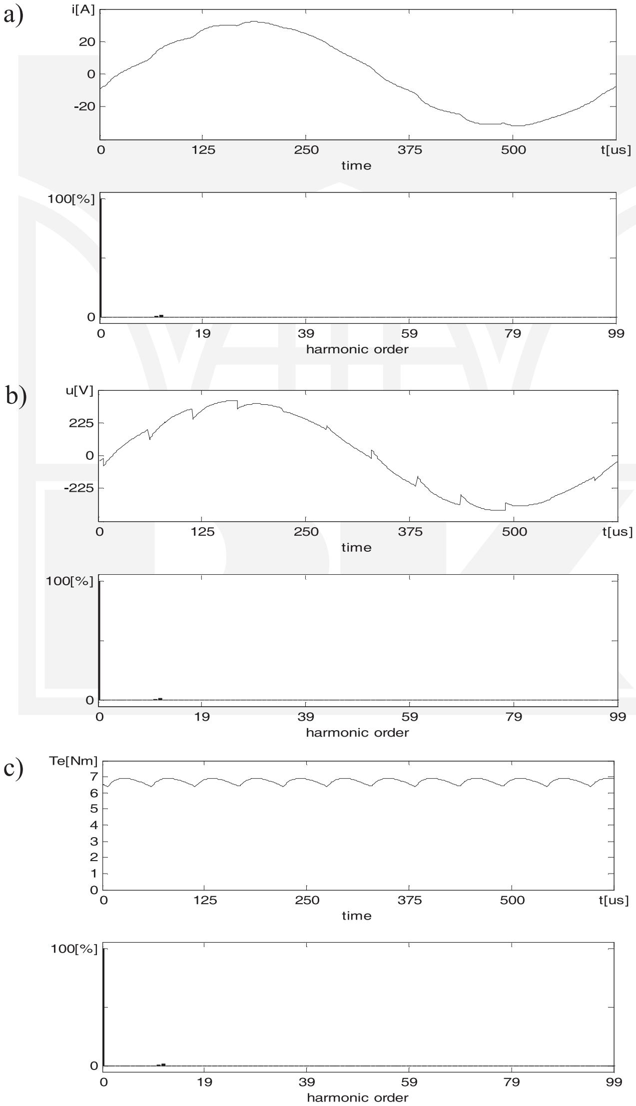

Fig. 9. Current (a), voltage (b) and electromagnetic torque of the generator (c) of μT with 12x12 MC

For this structure, the shape of the generator current and voltage is closer to the sinusoidal shape than for the previously considered structures what results in almost constant machine torque (Fig. 9c)). Thus, the expected machine losses are also smaller than for previously considered structures. However, the constructions of the generator and transformer are not typical and 144 switches are required to build the converter matrix.

5. Conclusions

This work shows a study of the implementation of MC as part of microturbine – grid connection devices. The paper includes the comparison of three different connector structures based on the comparison of generator currents, their terminal voltages and electromagnetic torque. A 3x3 structure achieves a fairly good performance if output voltages are considered (not shown in this research), but the shape of the input current influencing the electromechanical torque is not acceptable. Moreover, the sudden change between input phases (only three input phases) when creating output voltage, creates high over-voltages on converter switches. The current rating of the switches has to be relatively high since all power is transferred through only three phases and nine switches (three switches are working at any one time).

The 3x12 MC based structure shows much better properties than the 3x3 version (lower ripple in generator current and torque), but there are still large overvoltages visible in the generator terminal voltages

The best performance of the 12x12 MC working with a 12 phase generator and a 12x3 transformer is not a surprise, however, it requires special construction of a 12 phase generator and a 12x3 transformer as well as a large 144 element matrix hardware which is expensive when building a prototype. The alternative is a structure containing a 3 phase generator, two 12x3 transformers and a 12x12 MC structure. The problem lays within the construction of a high frequency 3x12 transformer which has to minimize its core losses, thus, this is not the same transformer as a transformer coupling a 12x12 MC to the grid.

It can be noted that the simulations were performed for a 1600 Hz input frequency and if this frequency decreases (speed of the turbine decreases), the advantage of multiphase structures over three phase ones increases.

The currents and the voltages at the grid side of the interconnection device were not analyzed in this paper which concentrated only on the influence of the MC on the generator working conditions.

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