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

STUDIUM UKŁADU PRZYŁĄCZENIA SZYBKOOBROTOWEGO UKŁADU GENERACYJNEGO, BAZUJĄCEGO NA PRZEKSZTAŁTNiku MATRYCOWYM DO SYSTEMU ELEKTROENERGETYCZNEGO

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


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

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

1. Introduction

The high parameters steam and gas miniturbines and microturbines becoming an interesting option for small co-generation plants. The plant typically consists of high speed gas fueled turbine and generating unit including transmission for speed reduction and heat recovering system or medium or high parameters boiler with high speed steam turbine, transmission (gear box), generator and heat exchanger to extract energy form the steam. The power range of such system starts from 20-30 kW and goes up to 10 MW. Usually the speed of the gas turbines ranges from 16 to 60 thousand rpm. The speed of steam turbines (usually single stage turbines are used for small co-generation) depends on the parameters of the steam and on turbine power  and ranges from 6 to 12 thousand rpm. For all this arrangements the combined cycle of work allows to achieve high efficiency over 80%. The cogeneration unit structure usually includes the transmission decreasing the revolutions to match generator synchronous speed. For gas turbines generators with synchronous speed 3000rpm are used whereas for steam turbines the four pole generators with 1500rpm speed are utilized. Typical performance of such unit can be shown for example for Capstone C-65 microturbine with electrical efficiency 29% for nominal load 65kW 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 by high speed generator and electronic unit able to convert high frequency alternating current into 50 Hz one.
The removal of the gear box and straight forward coupling of the turbine into generator will decrease energy losses and will provide better reliability of the mechanical part of the system. The changes will contain not only the generator (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 50 Hz grid frequency: structure based on AC-DC-AC conversion or structure based on straight forward 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 ones. Recently, due to its simplicity, the Matrix Converter (MC) has received a lot of attention. The main problems in large scale industry application are complexity of control schemes, large amount of low order harmonics in converter currents and their non-continuity.

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

\[
V_{outm}(t) = \sum_{n=1}^{N} k_{(n,m)} V_{nN}
\]

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],[6],[7] and was chosen from among other possible algorithms developed by authors. The algorithm, as opposed to other algorithms found in literature, uses all fragments of the input sinusoids to create the shape of the output ones whereas gross algorithms described in literature utilize only the parts of the input sinusoids which are close to the peaks of the waveforms [8][9][10]. The method of output waveform creation used by the proposed control technique can be clearly seen in Fig. 2 for 3x3 MC structure and in Fig.2.3 for 12x1 MC structure. Any output phase can be connected at a certain instant to any input phase what creates ties not only for voltages but also for converter currents [11].

The proposed multiphase structures (3x12, 12x12) have several advantages over the simple 3x3 one: the voltage transfer of the MC increases, output voltage distortion and the rating of the switching elements decreases as its dimensions increase (Fig. 4 and Fig. 5). Moreover in the proposed control procedure the switching occurs between two adjoining input phases what minimize commutation problems. The square structure of the MC was chosen (the number of the input phases is equal to the number of the output phases) since for a proposed control scheme it enables 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 short circuit restriction at a certain instant only the same number of the input and output phases are connected i.e. all phases from the side with lesser number of phases and not all phases from the side with 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 the 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 ones. The performance assessment was done for much higher input frequency then output one and included voltage transfer, order of generated harmonics and THD coefficient (Fig. 2-5).

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

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

Fig. 4. Voltage transfer as the function of the number of phases in MC square structure

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

3. Simulation parameters and structure of the models

The performance of the proposed control scheme for different structure of energy conversion paths was investigated using MATLAB/Simulink software and compared. The variations in the models included variations to MC structure, generator and transformers 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. Model of the permanent magnet generator (its electrical part) was developed using standard machine equations and taking under consideration several simplifications and assumptions such as sinusoidal distribution of the flux in the machine air gap, omitting mutual stator inductances and assuming phase shift of the N phase windings by \( \frac{2\pi}{N} \):

\[
U = \omega \cdot \Psi \cdot \begin{bmatrix}
  \sin \theta \\
  \sin \left( \frac{2\pi}{N} \right) \\
  \sin \left( \frac{2(N-1)\pi}{N} \right)
\end{bmatrix}
- R_s \cdot I - L_s \cdot \frac{dI}{dt}
\]

Where: \( U \) and \( I \) – matrices of the generator voltages and currents (1xN), \( \Psi \) – magnitude of the flux, \( \theta \) – actual position of a flux with respect to the first winding (the position of the
The mechanical equation of rotor movement can be then expressed as:
\[ J \frac{d\omega}{dt} = T_m - T_e - D \cdot \omega \]  \hspace{1cm} (3)

Where: $J$ – moment of inertia, $T_m$ – mechanical torque applied to the rotor, $D$ - friction coefficient and $T_e$ – electrical torque.
The electrical torque is defined by the following equation:
\[ T_e = p \cdot \frac{\delta}{\delta \theta} \Psi \cdot I \]  \hspace{1cm} (4)

Where: $\Psi$ – matrix of machine fluxes

What for the stated assumptions results in the formula:
\[ T_e = \omega \cdot \Psi (\sin \phi \cdot i_1 + \sin \left( \phi - \frac{2\pi}{N} \right) \cdot i_2 + \ldots + \sin \left( \phi - \frac{2(N-1)\pi}{N} \right) \cdot i_N) \]  \hspace{1cm} (5)

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

4. Simulation results
Several structures were investigated and below there were shown some results of the simulations for most promising structures.

4.1. Microturbine with 3x3 MC

This device, however simple, produces highly distorted generator current what results in ripple in generator torque. This highly distorted current will cause high losses in the generator core what will decrease the efficiency of the energy conversion. The generation unit output voltage, however not shown in this paper, also contains high level contents of high order harmonics and its shape is not acceptable.
4.2. Microturbine with 3x12 MC

This device operates 36 switches structure typical three phase generator and 12x3 transformer.

![Structure of 3x12 conversion device]

The disadvantages of this structure are caused by rapid changes in the current of the switches what results in rapid changes and overvoltages in generator output voltages.

4.3. Micro Turbine with 12x12 MC

The proposed structure is a square one what results in non „0” periods in converter currents i.e. for a proposed control always 12 switches are in “on” state

![Structure of 12x12 conversion device]

For this structure the shape of the generator current and voltage is closest to the sinusoid than for the previously considered structures what results in almost constant machine torque (Fig. 17) and will not produce additional machine losses. However, the construction of the generator and transformer is not typical and 144 switches is required to build converter matrix.
5. Conclusions

The work shows the implementation of MC as part of microturbine – grid connection devices. The paper includes the comparison of three different connector structures based on comparison of generators currents, their terminal voltages and electromagnetic torque. 3x3 structure achieves quite good performance if output voltages are considered (not shown in this research), but the shape of the input current influencing 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 time).

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

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

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

6. Bibliography


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