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Simulation and experimental examinations of voltage inverter and synchronous generator synchronization system with the use of VisualDSP++ 5.0 environment

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This study describes the operation of the programming algorithm used to synchronize the machine VSI inverter with the rotating synchronous generator. Presented algorithm which bases on the Radix–2 Fourier transform allows to synchronize the inverter with the machine with variable in wide range rotating speed. This study presents the results obtained with use of the simulation software and the auxiliary software created with the use of VisualDSP++ 5.0 development environment and exemplary results of an algorithm operation in the laboratory test stand.

KEYWORDS: synchronous generator, machine inverter, Radix–2 FFT, synchronization, DSP, real–time

1. Synchronization of synchronous generator with machine inverter

1.1. Introduction

Due to the practical reasons, the most commonly used alternators in the industry and shipbuilding are the synchronous self–excited generators. In order to improve the effectiveness of generators and the Diesel engines driving them, it is pursued to create the control system, which is able to control both, the drive side, as well as the work of electric generators. The conjoining of elements which control these units allows to save the fuel significantly. In order to maximize opportunities of the modern combustion engines it is required to provide their work with variable rotating speed in wide range. The self–excited alternator generates the voltage already when it starts to rotate, what makes necessary to obtain the information about the parameters of this voltage in order to execute the proper machine inverter control program and with the generator synchronization process. In the presented system, the measurement of actual values of phase voltage is executed by the FPGA system which cooperates with DSP, there is no direct information about the resulting voltage frequency. This parameter, as one of the most important, shall be determined in the real–time system on the basis of parameters. In the offered algorithm, the method of voltage frequency determination is executed in the DSP processor interrupts within the time of 150 μs. Before the actual software of the inverter which cooperates with the machine, it was necessary to test the created algorithm with the use of VisualDSP++ 5.0 development environment to eliminate the possible errors and problems with e.g. memory leak. The VisualDSP++ environment has a very reach set of tools which allow to analyze the code and its inspection with the use of inbuilt signal's processor simulator of the Analog Devices company, which were used during creation of the rotating generator's frequency determination function.

1.2. The concept of the cooperation system consisted of transistor inverter and the synchronous generator working with the variable shaft's speed

The presented system consists of bidirectional inverter with the DC intermediate circuit and the synchronous generator with a power of 6 kVA. The inverter powers the DC intermediate circuit and controls the voltage value. This control is necessary to distribute the power between generators and drive motors. As in the case of the power grid, it is required to synchronize the inverter with the machine which rotates with unknown speed. One of the synchronization conditions is the equality of the generator's and inverter's frequency. Due to the easy adjustment of the frequency, the generator during its operation is synchronized with the machine inverter. The fulfilment of the synchronization conditions is provided by the safe connection of two sources of energy without the occurrence of unfavorable phenomenon such as high equalizing currents flow. After the synchronization process, the synchronous generator's control system controls the inverter in the decoupled manner, i.e. the values of i_{sq} active current and i_{sd} idle current are controlled independently. In case of self–excited generator, the value of idle current is set to zero and the value of active current results from the regulation loop of the DC control.

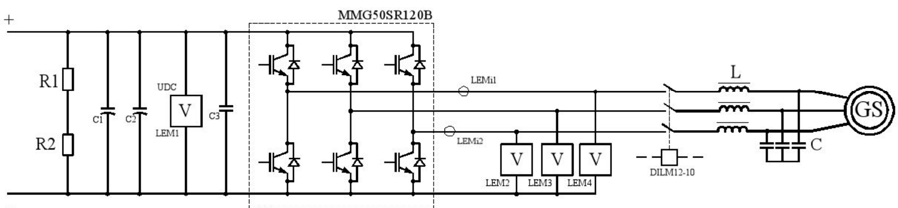

Fig. 1. The connection diagram of the machine inverter and synchronous generator (GS) system [3]

The analyzed system consists of the three–phase's inverter bridge additionally equipped with the measurements of the U_{DC} intermediate circuit voltages and phase voltages measured by the LEM2, LEM3 and LEM4 converters. The synchronous generator is connected with converter with the LC filter and with the contactor which switches the generator on the inverter's rails with the fulfilment of condition to obtain on terminals the minimum voltage necessary to proper operation of the DC regulation system.

The self–excited generator used for experiments generates on the terminals the alternating voltage and this voltage powers the rectifier bridge through the three–phase transformer. The rectified constant voltage powers the excitation circuit of the generator through the brushes and slip rings. The entire system of voltage regulator is built inside the generator's terminal board.

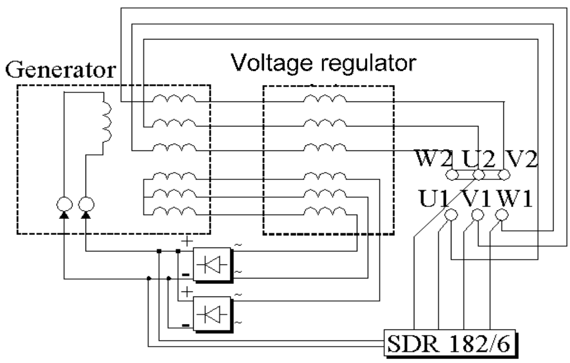

Fig. 2. The BTP3 synchronous generator's voltage regulator system [2]

Chosen for tests synchronous generator is not designated to the long–term parallel cooperation with other sinusoidal alternating voltage generators what results from, e.g. variability of the output's voltage value which depends on the, e.g. winding temperature and the receiver's circuit power factor and changes within the range from ±5 % (cold winding, $\cos\varphi = 0{,}8$) to ±10 % (hot winding, $\cos\varphi = 1$).

In case of the examined generator, there is a possibility to regulate the voltage on terminals within the range of approx. ±10% by changing the width of air gap in the transformer's core, however the generator must be switched off in this moment.

As it can be seen on the waveforms registered by the oscilloscope, the waveforms of the actual value of voltage generated by generator are not the perfect sine wave, additionally the interferences resulting from operation of other power electronics devices can be seen in the real system.

In the present system it is assumed that the range of rotating speed detected by the algorithm shall be within the range from 10 Hz to 50 Hz. In practice, the first of these values is usually greater and is about 20 Hz. Due to the interferences, the commonly used in shipbuilding method of detecting of the frequency by measuring the time between exceeding the null value may be insufficient. In modern systems which use the converters, the FFT of voltage signal of chosen phase method is often used. In the high level programming languages libraries, the FFT are implemented as a basic methods used to analyze signals.

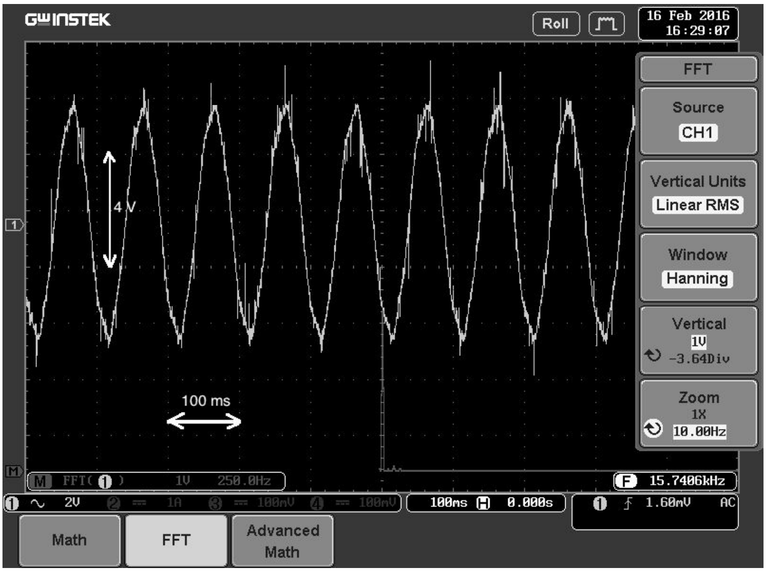

Fig. 3. Recorded waveforms of a single phase of a BTP3 synchronous generator for a rotating speed corresponding to 10 Hz and to frequency spectrum

In the presented system used to detect the generator's frequency was used the ready library contained in the trans.h file. This is a file normally attached to the VisualDSP++ 5.0 environment which contains several versions of FFT functions which handle data vectors with different amounts of samples. The implemented function which executes the FFT uses the Cooley–Tukey algorithm in its simplest form, also known as a R2 DIT FFT.

2. Implementation of FFT algorithm in a simulation software of visual DSP++5.0 environment

The radix–2 DIT algorithm is a very popular, but not the fastest form of the Cooley–Tukey algorithm. The prime feature of used DIT algorithm is, that this algorithm divides the N–points data vector resulting from DFT input signal into smaller N/2–points vectors.

$$X_r = \sum_{l=0}^{N-1} x_l e^{-\frac{2\pi i}{N}}, \qquad r \in \{0,1,\ldots,N-1\} \tag{1}$$

With the new indication $W_n = e^{-\frac{i2\pi}{N}}$ we obtain:

$$X_r = \sum_{l=0}^{N-1} x_l W_N^{rl}$$

To use the FFT algorithm in the software it is necessary to divide the input data x_n string into two parts, in which the elements are indexed even and odd what allows to divide the equation (1) into two parts:

$$X_r = \sum_{n=0}^{\frac{N}{2}-1} x_{2n} e^{-\frac{2\pi i(2n)r}{N}} + \sum_{n=0}^{\frac{N}{2}-1} x_{2n+1} e^{-\frac{2\pi i(2n+1)r}{N}} \tag{2}$$

After substituting respectively $y_n = x_{2n}$ oraz $z_n = x_{2n+1}$ we obtain:

$$Y_r = \sum_{k=0}^{\frac{N}{2}-1} y_k W_{\frac{N}{2}}^{rk}, \qquad r \in \{0,1,\ldots,N/2-1\}$$

and

$$Z_r = \sum_{k=0}^{\frac{N}{2}-1} z_k W_{\frac{N}{2}}^{rk}, \qquad r \in \{0,1,\ldots,N/2-1\}$$

As can be seen the summands are the same as in the equation (1) after replace N by N/2. Another parts of DFT shall be divided recursively to reach two–point DFT strings on the understanding that the length of transform is a power of 2.

To create and test functions of C++ language which uses the FFT algorithm, the functions of debugger contained in the IDE VDSP++ were used.

This function after checking the accuracy of its operation was implemented directly in the software of DSP processor. To check the accuracy of the software operations the measurements with the digital oscilloscope were executed, what resulted in obtaining of data of exemplary input voltages waveforms. As it is shown on the Fig. 3, the waveforms of voltages coming from the synchronous generator consist interferences which result, i.e. from the conduction of machine inverter's backward diodes.

The obtained data in a text form were attached to the simulating software as a float type vector, from which the data are taken for calculations. The software runs in an infinite loop and counters are set so that the algorithm shifts the data after each ending of the data in the vector.

Due to the practical reasons, the presentation of algorithm's operation accuracy for one input vector of rfft512 function was limited to 512 measurement samples.

Implemented to the tested software values of phase voltage coming from the oscilloscope's measurement can be watched in a form of time waveforms. The

VisualDSP++ 5.0 has an ability to create the analysis of FFT resulting from the given waveform and the exemplary effect of the FFT function operation is shown in a Fig. 4.

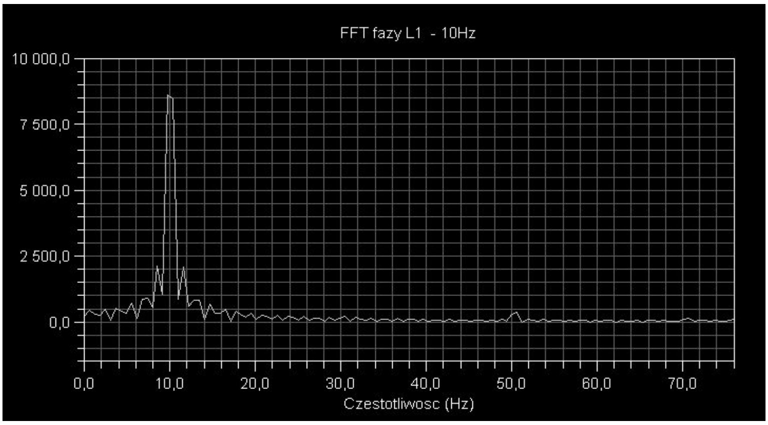

Fig. 4. The time waveform of the L1 phase of generator implemented into the testing software

The function which detects the frequency of fundamental harmonic is generated in the DSP processor interrupt, which communicates with FPGA and reads, i.e. values of A/D converters and exposes the converter's controls. To use the inbuilt rfftN it is required to prepare the vector with data coming from measurements executed in a real time. Due to the high speed of signals processing it is necessary to reduce data. The reduction is executed by choosing only some of samples which are written to the input vector of rfftN function. This solution makes that the part of information about the frequency spectrum of tested voltage is lost, but due to the necessity of detection of low frequencies this simplification is reasoned and doesn't affect the accuracy of generator's voltage frequency detection in a planned range.

In case of data processing in a real time, the data entered to the buffer called Vector are multiplied by the Hann window function [4] to avoid so–called spectrum's "leakage" which is visible at the beginnings and ends of measurements. The relevant part of software's code is as follows:

$$\text{Vector }[i]=0.54-0.46*\cos(2*\text{PI}*i/(NUM\_POINTS-1)) \tag{3}$$

where: *NUM_POINTS* is the number of points subjected to FFT, i – the number of iteration of executed code.

In practice, to search the frequency of fundamental harmonic of sinusoidal voltages or undistorted voltages, it is sufficient to use the time rectangular window.

As a result, the rfftN function enters to vectors the output values in a complex form (real_2, imag_2), therefore, to find the maximum value it is necessary to determine the module in accordance to the relations taken from the code of software written in C language:

```
float real_2 = (real_output[i])*(real_output[i]);
float imag_2 = (imag_output[i])*(imag_output[i]);
real_input[i] = sqrtf(real_2 + imag_2);
```

where: *real_output* and *imag_output* are the vectors which contain the function's values determined by the rfftN function, *real_input* is the vector which contains calculated values of modules.

In the next step the table which contains modules is recursively scanned and during this period of time the sought maximum value of generator's voltage frequency band and the frequency which corresponds to it is stored. After finding the number of a basic frequency band it is necessary to calculate the frequency value using this formula:

*Frequency = sample*Fs/(NUM_POINTS/COKTORA)*

where: *sample* is the number of a band relevant for the fundamental harmonic, *Fs* is a sampling frequency and COKTORA is a value which reduces the number of stored samples.

3. Implementation of FFT algorithm in experimental system and exemplary results of software's operations

The experimental system consists of PC with installed software, which cooperates with converter via USB interface. The converter is equipped with Analog Devices ADSP–21363 signal processor and FPGA system of Altera company. The tests were executed with a constant and varying in time rotating speed of synchronous generator. The measurement system was recording the data coming from voltage converter, which have been entered to the matrix during the interrupt subroutine execution. During the interrupt, the measurements of generator's rotating frequency were also executed. The generator used for test was powered by asynchronous cage motor. The cage induction machine was driven by vector inverter.

3.1. Tests results for set generator's rotating speed

The executed tests of experimental software covered, i.e. algorithm's accuracy examination in the steady state. The values of rotating speed of asynchronous machine were set in the vector inverter which controlled this machine, and then the values of amplitude and frequency of voltage generated by the L1 phase of generator were recorded.

As it is shown on the Fig. 5, the voltages waveforms were multiplied by the rates of Hann time window, what resulted in significant change of their shape.

The Hann window is a linear combination of modulated rectangular windows and smooths out any discontinuities and thereby reduces artefacts in the spectrum.

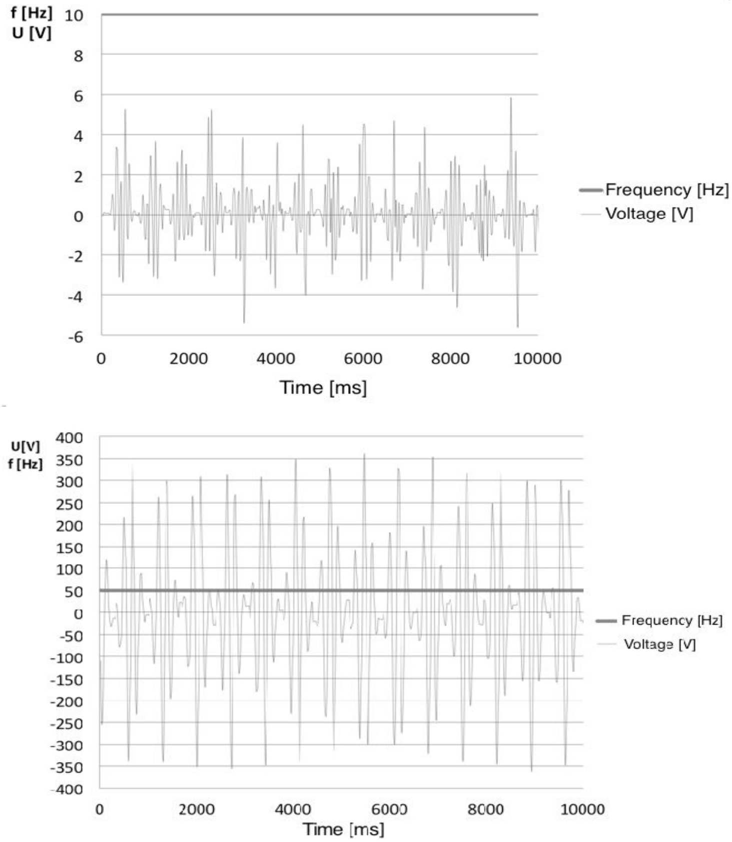

Fig. 5. The exemplary waveforms of voltages and frequencies recorded by the experimental system

3.2. Experimental tests result for the variable rotating speed of asynchronous generator

During the system's designing it was assumed, that the synchronization process may be started also at the time of dynamic change of generator's rotating speed. This question hasn't yet occurred in conventional synchronous generator's systems due to the constant generator's rotating speed. The measurements were executed in a similar way as in the steady generator's rotating state.

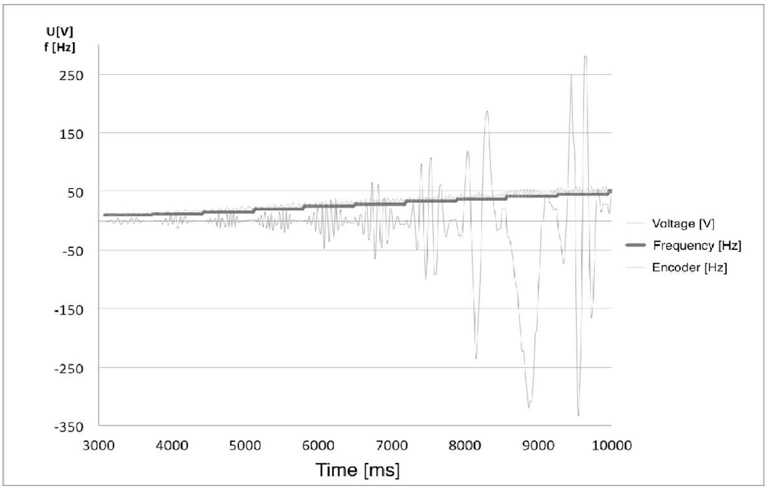

Fig. 6. Change of the generator's rotating speed and recorder values of L1 phase frequency and voltage

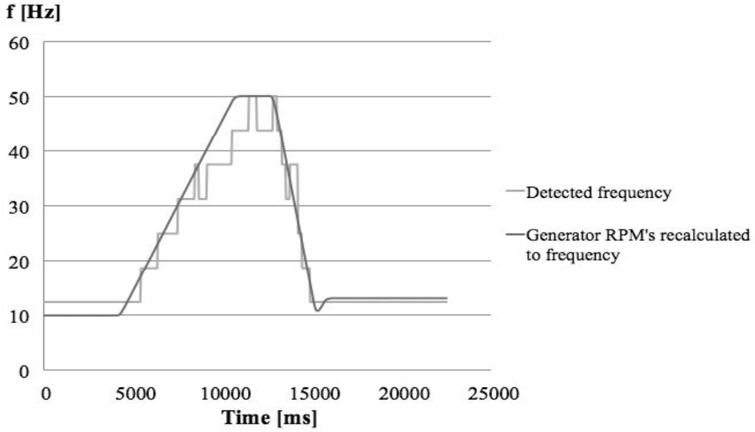

Fig. 8. Experimental results of frequency detection in real–time setup with 512 points

The rotating speed of generator was smoothly increased from 10 Hz to 50 Hz. The stepping readings of frequency and delay resulting from the necessity of samples acquisition and their processing can be noticed. The time required to perform the FFT algorithm for the set of 4096 samples, from which only 512 is selected, is 615ms, what is a pretty large value and limits the range of use of proposed method to synchronize the electromechanical systems with low changing speed of the rotation speed. In the further tests there were 1024 points acquired for every calculation period. Every second sample was put into input FFT vector 512 points long. Total number of points was 512 so resolution

6.5 Hz per FFT bin was achieved and minimal time needed for frequency calculation was roughly 154 ms.

4. Conclusions

The VisualDSP++ 5.0 environment provides the ability to create the executable code for the family of ADSP processors and thanks to the inbuilt signal processors simulator and debugger allows to test the code in a real time. Additional functions, such as a preview of vectors and matrixes content and the signal's analysis tools make this software very useful in creating the new code for signal processors. The presented algorithm for searching of synchronous generator's frequency has been written and tested in the VisualDSP++ 5.0 environment. After starting the described function in the generator's control real system, it emerged that the determined frequency values practically do not differ from the real ones. This allowed to use this software as one of elements served for real–time synchronization of machine inverter with rotating excited generator.

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