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The system of nonlinear adaptive control for wind turbine with DFIG

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Abstract

This paper presents a problem solution of the stable voltage generating in the changing terms of environment for the double-fed induction generator (DFIG). For this, in nonlinear multivariable systems, such as mathematical model of DFIG, the method of observer's synthesis for external, parametric and structural disturbances was used. This allows, on the basis of disturbances approximation, to carry out an evaluation under conditions of uncertainty, leading to disturbances adaptation with a priori unknown structure. The work presents a synthesis method of control system, allowing to solve indicated problem. Stand-alone wind turbine used as a power plant with DFIG. The control system uses the original nonlinear mathematical model of the DFIG in rotating "dq" coordinates, taking into account non-linear changes in the parameters. To confirm the effectiveness of the problem solution, mathematical computer model was developed. The paper also presents the results of full-scale simulation.

Keywords: wind power plant, adaptive control, doubly-fed induction machine, non-linear control system.

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1. Introduction

Nowadays, one of the actual problems in wind power generation is a problem of technological solutions development for electricity quality, generated in the changing conditions of the environment, at the same time increasing the availability and effectiveness of wind turbines. In particular, such technological solutions are dedicated wind turbine power structure and control system of the equipment in it. The structure will determine the circle of power supply problems, solved with the help of wind turbines, will form the requirements for the equipment used, will determine the scope and the total cost of wind energy complex. The control system will ensure the interaction between the individual nodes in wind turbine, supporting its effectiveness at a high level. Thus, the key moments of the indicated problem solution is the wind turbine structure development and functioning algorithms synthesis for its control system.

2. Methods of stabilization and structural requirements

For stand-alone wind turbines, the parameters of the generated voltage will depend on the environmental conditions, that is, from outside disturbances. Considering the various stabilization methods of the generated voltage wind turbine, we will note that the requirements for the quality of any energy source are some of the basic in the design of various types of such sources. More acutely than usual the problem of generated voltage stabilization is in the development and study of electrical engineering complexes with a variable mechanical torque on a shaft, and as a consequence with variable shaft rotation speed of the generator, which include wind energy systems.

Papers [1-5] describe the control of a powerful grid wind power plants. Its power, however, is much less then total connected grid power. On this basis a conclusion is drawn about inexpediency of various types voltage stabilization methods, because on the output terminals of the generator

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will always be voltage with parameters of power grid, connected to a wind turbines, and researches focus on the produced power control.

Note, that this approach is applicable only to systems with the level of renewables not more than 25%. The increase of this share impact on the grid by produced voltage will be more essential and becomes critical, if the power of wind turbines comparable to the capacity of the network, or if the wind turbines operate on a stand-alone load. Given this, research in the field of quality improvement for produced electric power are promising.

It can be noted that at present the common methods of DFIG output voltage stabilization for stand-alone wind power plants can be divided into two directions:

(i) The first direction includes methods, approaches and technological solutions aimed to maintain the rotation frequency of the generator's shaft in a valid range. Typically, propeller rotational speed of a grid-connected wind turbine is constant. This is achieved by installing rotating propeller blades, wind turbine lowering system from under the wind, and the multiplier with variable gear ratio on the generator shaft. With the change in the blades slope relative to the wind, the carrying power also changed, and hence its component, acting in the direction of propeller rotation. The main advantages of these mechanical stabilization systems are the lack of transforming devices, maintaining good uniformity of speed propeller, and as a consequence quality of generated voltage. However, functioning in a certain range of speeds, low efficiency due to the partial use of the available wind energy, and energy loss in mechanical converters limits the use of such stabilization systems.

(ii) The second direction, allowing qualitative electric power generation of wind turbine, includes technological solutions, providing stability of the produced output voltage due to the conversion of already generated voltage. This method is widely used in autonomous power supply systems. A classic decision consists in setting of converting device in the output circuit of a generator. The main advantage of such stabilization systems is a very high output voltage quality, depending on the converting device model in a generator output circuit. In this case, the consumer receives quality sine voltage, in a form which does not manifest the influence of external disturbances, such as, for example, variable frequency of shaft rotation. However, the presence in the generator output circuit expensive transforming devices, which cost is up to half of the total wind energy systems cost, energy losses in them, and the application of highly specialized generator restricts the usage of such systems of stabilization.

Therefore, at present, the output voltage stabilization is achieved either by control over the speed of the wind turbine, which leads to a complication of the mechanical part of the system and reduced efficiency, or by converting the generated energy, which greatly increased the total cost of wind energy systems. This implies that the optimal solution for the formulated problem is the method that combines the advantages of two classic stabilization ways and without their drawbacks. This can be achieved by influencing on mechanic-electric energy conversion process directly in the wind turbine generator, during electricity generation, which will provide stable voltage at its output without using expensive converters in a wide range of wind speeds.

Thus, we can formulate the requirements to the structure of wind turbines, which ensure:

(i) The external influence on mechanic-electric energy conversion process directly in the generator, during power generation. This becomes possible if the turbine structure will contain AC generator with wound rotor circuit, which in this case will be the excitation circuit. Using this we can influence on the total magnetic flux of the AC machine, and, consequently, on the generated voltage parameters. The calculation of the excitation voltage parameters will be made by the control system, with adaptation property to the external and parametric perturbations, such as unstable speed of generator shaft rotation and the changes of a connected load.

(ii) Effective operation in a wide range of wind speeds. The structure should ensure the conversion of all available wind energy into electricity with minimal losses.

(iii) The lowest total cost compared with other structures. This can be achieved by applying a new method of AC generator output voltage stabilization, characterized by the absence of converting devices in the output generator circuit. The cost also can be reduced by use a series-produced AC machines as generator.

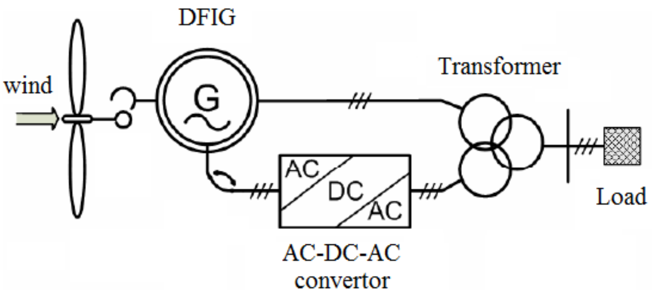


Figure 1. The proposed structure of wind turbine with DFIG

Given the above requirements, now we choose the most suitable AC wind turbines structure.

Such structure is variable-speed, with a limited range of speed propeller configuration, a feature of which is the use of DFIG and 30% of the nominal generator power frequency converters in the rotor circuit, shown in figure 1. Here the stator is connected to the load directly, while the frequency converter controls the frequency of the voltage in the circuit rotor and influence on its rotation speed. The power of the frequency converter and the maximum permissible current in rotor windings are determines the range of working speeds, usually ±30% of simultaneous, and in some models with liquid cooling coils up to ± 40%.

Moreover, the frequency converter allows a smooth connection to a power network or the load and reactive power compensation in over synchronous speed. Also less nominal power and, as a result, the price of the frequency converter becomes attractive from the economic point of view.

The control system structure of wind turbines, is shown in figure 1, should allow an implementation of the main idea in real time, to achieve these advantages. The main idea of the proposed method is in AC voltage with some amplitude and frequency, feeding on phase-wound DFIG rotor, which at the current disturbances will provide the voltage parameters on the output generator terminals always relevant to your needs.

Implementation of the proposed idea is adaptive nonlinear control system (CS) of wind turbines with DFIG, that allow high speed respond to the disturbances change, such as wind speed, the value of connected electrical load and internal parameters of the generator, thereby maintaining the stability of the output voltage.

However, in the process of structural-algorithmic CS support implementation for wind turbines with a DFIG, occurs one of the most important problems in control theory for today - the problem of structural-algorithmic implementation of control systems for objects, running in a priori unstructured environments. This problem have a solution with the help of observers synthesis for perturbations in nonlinear multivariable systems, one example of which can serve a DFIG in the stand-alone wind turbine with structure shown on figure 1.

Thus, synthesizing an adaptive fast CS and using the proposed structure of wind turbine on the DFIG basis, it becomes possible to design and construct wind turbines with new characteristics.

3. Nonlinear CS synthesis

3.1. The control laws of nonlinear CS

The solution of the indicated problem, offered in this paper, is based on the nonlinear model of DFIG in rotational "dq" coordinates, as in the conditions of different disturbances linearizing appears ineffective [1-5].Coming from the structure on figure 1, control circuit is a rotor circuit, so then primary control objective is in feeding on it control voltage of some parameters, at that DFIG output voltage remains unchanging and corresponds to set, without depending on influences. As it applies to a model, it is necessary to get the control values of voltages on the "dq" rotor axes V_{dr} and V_{qr}, at the well-known required stator voltages ${}_{ds}^{ref}$ and V_{qs}^{ref} . The classic mathematical model of DFIG does not take into account the nonlinear changes of its parameters [16, 17], such as winding inductances, changes of winding resistances from temperatures etc., accepting their permanent that is not quite right. Meantime, in real DFIG such changes have an influence on control quality, so the synthesis of control system, which is taking into account such nonlinear disturbances, is an actual task. The disturbances, arising up from nonlinear character of the control object, are difficult to mathematical description. However, valuation of these disturbances is a fully solvable task, with the further correction of CS work, based on such estimation. For this purpose, in the standard mathematical model of DFIG we will add some functions of immeasurable disturbances [18-20], f_{d1} and f_{d2} (equation (1)), accordingly for the stator "d" and "q" axes currents, and next we synthesize control laws.

$$\left[\begin{array}{l} \frac{d}{dt}i_{qs}=\frac{L_r(V_{qs}-R_s*i_{qs})}{-L_rL_s+L_m^2}+\frac{L_m(\omega_r(L_ri_{dr}+L_mi_{ds})-R_ri_{qr}+V_{qr}}{-L_rL_s+L_m^2}+f_{d1}; \\ \frac{d}{dt}i_{ds}=-\frac{L_r(V_{ds}-R_si_{ds})}{-L_rL_s+L_m^2}+\frac{L_m(\omega_r(L_ri_{qr}+L_mi_{qs})-R_ri_{dr}+V_{dr}}{-L_rL_s+L_m^2}+f_{d2}; \\ \quad \frac{d}{dt}i_{qr}=-\frac{L_m(V_{qs}-R_si_{qs})}{-L_rL_s+L_m^2}-\frac{L_s(\omega_r(L_ri_{dr}+L_mi_{ds})-R_ri_{qr}+V_{qr}}{-L_rL_s+L_m^2}; \\ \quad \frac{d}{dt}i_{dr}=-\frac{L_m(V_{ds}-R_si_{ds})}{-L_rL_s+L_m^2}-\frac{L_s(\omega_r(L_ri_{qr}+L_mi_{qs})-R_ri_{qr}+V_{qr}}{-L_rL_s+L_m^2}; \end{array}\right] \tag{1}$$

We will consider equalization $\dot{e}+a_1e=0$, reflecting requirements to the transients of close system in case of disturbances occurring, such as for example change of wind speed or connected power load. Let error $e=V_{ds}-V_{ds}^{ref}=R_ni_{ds}-V_{ds}^{ref}$, where R_n - the resistance of power load, V_{ds}^{ref} is the required d-axes voltage, then, with an account of equation (1), we will get derivative $\dot{e}$:

$$\dot{e}=\frac{d}{dt}i_{dsR_n}=-R_n(\frac{L_r(V_{ds}-R_si_{ds})}{-L_rL_s+L_m^2}+ \\ +\frac{L_m(\omega_r(L_ri_{qr}+L_mi_{qs})-R_ri_{dr}+V_{dr}}{-L_rL_s+L_m^2}+f_{d2})\cdot \tag{2}$$

Putting equation (2) in initial equalization, and expressing from him stimulus, we will get:

$$-R_n(\frac{L_r(V_{ds}-R_si_{ds})}{-L_rL_s+L_m^2}+\frac{L_m(\omega_r(L_ri_{qr}+L_mi_{qs})-R_ri_{dr}+V_{dr}}{-L_rL_s+L_m^2}+ \\ +f_{d2})+a_1(R_ni_{ds}-V_{ds}^{ref})=0; \\ V_{dr}=-\frac{1}{L_mR_n}(f_{d2}L_rL_sR_n+f_{d2}L_m^2R_n-R_nL_rV_{ds}+R_sL_rR_ni_{ds}- \\ -L_rR_n\omega_rL_mi_{qr}-\omega_rL_m^2i_{qs}R_n-R_nL_mR_ri_{dr}-a_1L_rL_sR_ni_{ds}+ \\ +a_1L_m^2R_ni_{ds}+a_1V_{ds}^{ref}(L_rL_s-L_m^2)). \tag{3}$$

By analogy, knowing that error on the axis of "q" is $e=V_{qs}-V_{qs}^{ref}=R_ni_{qs}-V_{qs}^{ref}$, we get V_{qr} :

$$V_{qr}=\frac{1}{L_mR_n}(-f_{d1}L_rL_sR_n+f_{d1}L_m^2R_n+R_nL_rV_{qs}-R_sL_rR_ni_{qs}- \\ -L_rR_n\omega_rL_mi_{dr}-\omega_rL_m^2i_{ds}R_n+R_nL_mR_ri_{qr}+a_1L_rL_sR_ni_{qs}- \\ -a_1L_m^2R_ni_{qs}+a_1V_{qs}^{ref}(-L_rL_s+L_m^2)). \tag{4}$$

Values of the required voltages V_{ds}^{ref} and V_{qs}^{ref} set through Park-Gorev transformations from “abc” coordinates to “dq”:

$$\begin{aligned}
&V_{ds}^{ref} = \frac{2}{3} * (V_{as} * \sin(\omega t) + V_{bs} * \sin(\omega t - \frac{2\pi}{3}) + V_{cs} * \sin(\omega t + \frac{2\pi}{3}))\\
&V_{qs}^{ref} = \frac{2}{3} * (V_{as} * \cos(\omega t) + V_{bs} * \cos(\omega t - \frac{2\pi}{3}) + V_{cs} * \cos(\omega t + \frac{2\pi}{3}))\\
&V_{as} = A * \sin(\omega^{ref} t);\\
&V_{br} = A * \sin(\omega^{ref} t - \frac{2\pi}{3})\\
&V_{cr} = A * \sin(\omega^{ref} t + \frac{2\pi}{3})
\end{aligned} \tag{5}$$

Where the ω is angular rotation speed of the “dq” coordinates, i.e. in our case it is equal to 0, $V_{as,} V_{bs,}, V_{cs}$ - instant required generator output voltage in “abc” coordinates, A - the desired amplitude of the generator output voltage, ω^{ref} is required angular frequency.

Note that $\omega^{ref} = 2\pi F^{ref} + p\omega_r$, i.e. frequency control of the generated voltage occurs when calculating the required voltage, and further considered in the synthesis of control voltages of the rotor. Here F^{ref} is required frequency voltage; p is the number of pole pairs, ω_r - mechanical angular rotation speed of the rotor.

Instantaneous values of control voltages in phases A, B and C of the rotor are calculated via the Park-Gorev inverse transform:

$$\begin{aligned}
&V_{ar} = V_{dr} * \sin(\omega t) + V_{qr} * \cos(\omega t)\\
&V_{br} = (V_{dr} * \sin(\omega t - \frac{2\pi}{3}) + V_{qr} * \cos(\omega t - \frac{2\pi}{3}))\\
&V_{cr} = (V_{dr} * \sin(\omega t + \frac{2\pi}{3}) + V_{qr} * \cos(\omega t + \frac{2\pi}{3}))
\end{aligned} \tag{6}$$

Thus, calculating the reference voltage (equation (5)), changing with generator shaft rotation speed change, and substituting it into equation (3) and equation (4), control laws on axes “d” and “q” become known.

3.2. Synthesis of observer

Now, in accordance with [8, 9, 13-15], we will execute a procedure of observer synthesis for f_{d1} and f_{d2} disturbances, influencing on currents in stator windings, because from their values depends the value of DFIG output voltage. For procedure of synthesis simplification we will enter denotation:

$$f_0 = \frac{L_r(V_{qs} - R_s * i_{qs})}{-L_r L_s + L_m^2} + \frac{L_m(\omega_r(L_r i_{dr} + L_m i_{ds}) - R_r i_{qr} + V_{qr}}{-L_r L_s + L_m^2} \tag{7}$$

Putting equation (7) in equation (1), we will get:

$$\frac{d}{dt} i_{qs} = f_0 + f_{d1} \tag{8}$$

We will enter a macro variable, reflecting an evaluation error, where $\hat{f}_{d1}$ is an estimation of revolting disturbance:

$$e_{\text{н}1} = f_{d1} - \hat{f}_{d1}. \tag{9}$$

In accordance with [8, 9] we will enter equalization equation (10), where $S_{d1}(I_{qs})$ is an arbitrary function, which will be determined in the process of observer synthesis, $\hat{z}_1$ is a new variable:

$$\hat{f}_{d1} = S_{d1}(I_{qs}) + \hat{z}_1. \tag{10}$$

Thus, with an account of equation (10), it is possible to write equation (9) down as:

$$e_{\text{н}1} = f_{d1} - S_{d1}(I_{qs}) - \hat{z}_1. \tag{11}$$

A derivative from the error of evaluation (11) is equal:

$$\dot{e}_{\text{н}1} = \dot{f}_{d1} - \frac{\partial S_{d1}}{\partial I_{qs}}(f_0 + f_{d1}) - \dot{\hat{z}}_1. \tag{12}$$

For providing of estimation asymptotic convergence, we will demand, that the error $e_{\text{н}1}$ submitted to the decision of equalization [21-25]:

$$\dot{e}_{\text{н}1} + a_{1\text{н}} e_{\text{н}1} = 0. \tag{13}$$

Putting equalizations (11) and (12) in equalization (13), we will get:

$$0 - \frac{\partial S_{d1}}{\partial I_{qs}}(f_0 + f_{d1}) - \dot{\hat{z}}_1 + a_{1\text{н}}(f_{d1} - S_{d1}(I_{qs}) - \hat{z}_1) = 0. \tag{14}$$

If we choose the function $S_{d1}(I_{qs})$ so, that equalization (14) did not depend on not measureable disturbance of f_{d1}, then expression (14) will be an asymptotic observer. Thus the estimation of not measured disturbance f_{d1} will be determined in accordance with equation (10). So, right part of equation (14) did not depend on not measureable disturbance f_{d1} , and we will equate all elements containing this parameter to the zero. As a result, we will come to the next equalization:

$$-\frac{\partial S_{d1}}{\partial I_{qs}} f_{d1} + a_{1\text{н}} f_{d1} = 0. \tag{15}$$

Solving equalization (15) relatively from $\frac{\partial S_{d1}}{\partial I_{qs}}$, find:

$$\frac{\partial S_{d1}}{\partial I_{qs}} = a_{1\text{н}}. \tag{16}$$

Thus, from(16) we will define $S_{d1}(I_{qs})$:

$$S_{d1}(I_{qs}) = a_{1\text{н}} I_{qs}. \tag{17}$$

We will put equation (15) and (17) in (14), so we get:

$$-a_{1\text{н}} f_0 - \dot{\hat{z}}_1 - a_{1\text{н}}^2 I_{qs} - a_{1\text{н}} \hat{z}_1 = 0. \tag{18}$$

We will express a new variable $\dot{\hat{z}}_1$ from equation (18):

$$\dot{\hat{z}}_1 = -a_{1\text{н}} \hat{z}_1 - a_{1\text{н}}^2 I_{qs} - a_{1\text{н}} f_0. \tag{19}$$

Using equation (10) and (17), we can define equalization of observer:

$$\hat{f}_{d1} = a_{1\text{н}} I_{qs} + \hat{z}_1. \tag{20}$$

Equalizations (17) and (18) are observer equalizations for disturbance, operating on a "q" axis current. Because f_{d1} disturbance is not measureable, then instead of it its estimation $\hat{f}_{d1}$ is used in equation (1). Applying analogical procedure for a current on the axis of "d", we will get:

$$\hat{f}_{d2} = a_{2\text{н}} I_{ds} + \hat{z}_2. \tag{21}$$

$$\overset{\wedge'}{z}_2 = -a_{2\text{н}} f_0 - a_{2\text{н}}^2 I_{ds} - a_{2\text{н}} \hat{z}_2 \tag{22}$$

These disturbances estimations are used in close control system, built on preset systems principle with indirect adaptation to disturbances. Equation (3) and equation (4) are equalizations of voltage regulator with the estimation of disturbances.

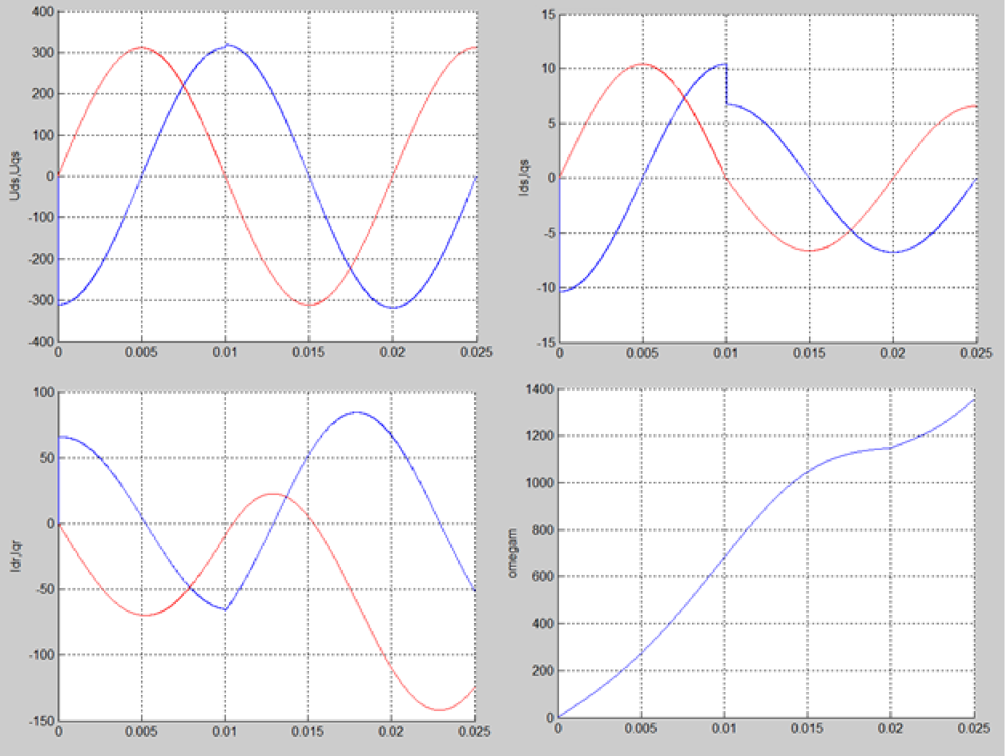


Figure 2. Charts of the CS with observer operational results at variable disturbances, clockwise: voltage “dq” stator, currents “dq” stator, shaft rotation speed, currents “dq” rotor.

4. Computer simulation

MATLAB was chosen as an appropriate computer simulation tool. Note that the main idea of the proposed method is the nonlinear unaccountable disturbances inclusion into model and estimation of such disturbances, and on the basis of this estimation to make a correction when working adaptive control system. The model of adaptive nonlinear control system consist of two m-file, the first of which describes used constants and variables, specify the conditions of calling the built-in MATLAB functions, processed the results and built the required graphics. The second file is an m-file to calculate the right parts of the differential equations, described by formulas (3) ,(4), (19) and (22), in accordance with the syntax and call rules of these functions in MATLAB. Let disturbances be the change of electric load and frequency of DFIG shaft rotation.

So, let's set the required parameters of the generated voltage amplitude 220*√2 volts and frequency of 50 Hertz. Let at time 0.01 second, the electric load has changed, and at the time 0.02 - frequency of shaft rotation. Figure 2 shows 4 charts, allowing to evaluate the quality of adaptive nonlinear control system with the observer. We see that the form of a voltage stator in “dq” axis is smooth, without strong distortions that is a result of adaptive control systems with observer operation. At time 0.02 second, we asked the change in the mechanical moment on the generator shaft, which corresponds to increased wind and the shaft rotation speed also gradually began to increase, which is reflected on the corresponding graph.

The currents of the rotor, which is also the stimulation and control currents, has changed their form, in particular the amplitude and frequency, depending on external disturbances, which is a consequence of adaptive control system operation, and the most appreciable break curve is observed at the moment of time 0.01 seconds, that is corresponds to a spike load. As the shaft rotation speed varies smoothly, and control system, adapting, also changes the voltage, and therefore the rotor currents smoothly.

Figure 3 shows 3-phase output DFIG voltage. See, that in time, when abruptly changed disturbance of load, we have a deformation of output voltage sine wave, however, the duration of the distortion is so small, and it itself is so insignificant, that we can talk about almost instant adaptation of the system. Note, that in real conditions getting this quality of transients with so impressive instantaneous changes in load will not succeed, but even getting similar in the waveform in figure 3, is a good result.

As for changing the rotation speed of the shaft, his influence on the shape of the output voltage is not even viewed at high magnification, which is a consequence modeling in ideal conditions, and most likely during actual operation, such an abrupt change will be visible in the waveform of the generated voltage.

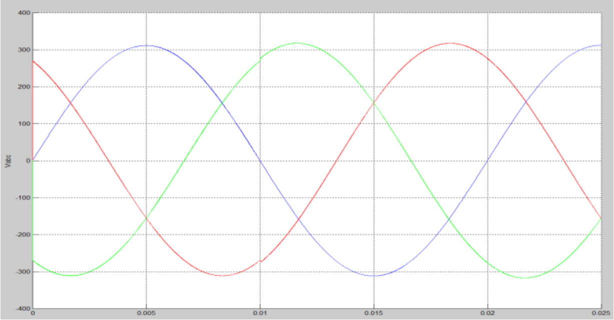


Figure 3. 3-phase output DFIG voltage.

Now refer to figure 4, where curves illustrated asked AC disturbance load and assessment of observer.

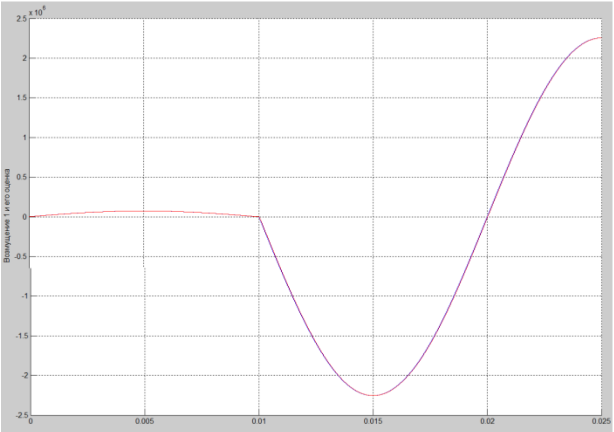


Figure 4. Load disturbance (red) and it’s estimation (blue) by observer.

Here electrical load disturbance varies according to given above change, and its estimation by the observer similarly changing, and shapes of the two curves are nearly identical. This suggests that the observer estimates disturbances correctly and makes the necessary adjustments in CS work.

When analyzing the results of nonlinear adaptive CS with observer modeling, it can be noted that this control system solved the indicated above control problems. The advantages of this CS are the high quality of the generated voltage, and also the estimation of nonlinear disturbances with the subsequent adjustment of the control voltage, current, in this particular example, for the current of the stator “dq” axis. The disadvantage is the high demands for the computing power of microprocessor system, on which you'll create this CS. It should also be noted that in real conditions, an inverter cannot instantly change the shape of the control voltage that will affect performance. These issues require further implementation of full-scale experimental studies.

5. Experimental modelling

Experimental verification of theoretical principles set out above, is the main proof of the correctness of the calculations and proposed methods to solving problems of the study. One of the main difficulties faced during the experiments, is the fact that when performing theoretical calculations are based on the model of the real electrical facilities. These models are built and are subject to certain assumptions, as the simulation involves the use of abstraction and idealization that is naturally absent in real objects. This leads to getting in general cases, results, close to the rated [11].

The main objective of the experiment is to test theoretical statements (confirmation a proposed method of stabilization), as well as broader and deeper studying of a theme of scientific research.

To perform experiments it is necessary to create the schema like on figure 5. The basic elements of the scheme is the DFIG, battery or a DC power source, power inverter with amplitude and frequency control channels, and phase active load. To simulate the rotation generator’s rotor under the action of wind flow will be used a DC motor rigidly connected with rotor of the generator. Also for the formation of the feedback it is necessary to use a voltage, rotation speed and frequency of the output generator voltage and its circuit sensors. It is also advisable to add to the output circuit of the generator and field circuit three-pole switches. The control system can be performed, for example, on PC using software product LabVIEW, as this package formalizes phase of the control systems algorithm creation, describing the algorithm in the form of a flowchart, which is very convenient.

Experimental confirmation of the theoretical results is performed using the equipment of the Department of Electrical engineering and mechatronics of Russia’s SFU. There is an educational stand of firm "Educational technology", "Electric machines", intended to hold practical lessons on the courses "Fundamentals of electrical engineering and electronics", "Theory of electrical circuits and fundamentals of electronics", "Electric machines", "Electric drives".

This stand has a block structure that allows configuring it under specific experimental research, remote control of the some blocks that allows creating a closed control system. Also it includes all necessary elements of figure 5, except controlled through the channels of frequency and amplitude 3-phase inverter, which greatly impedes the performance of the experiments. Therefore, his work will be to replace synchronous generator, regulating the frequency of shaft rotation and the excitation voltage, it is possible to achieve generation of alternating voltage with required amplitude and frequency to perform experiments. On this basis, the total electrical connection diagram will look like on figure 5.

Now refer to figure 5. Note that negative mechanical torque of propeller turbine under the influence of an air stream simulates a DC motor "M2". Accordingly, the wind turbine is DFIG "G3", with rigidly fixed rotor to the rotor of the machine "M2". Load "A2" by tripolar switch "A3" connected to the stator windings of "G3", while on the rotor through a switch A4 is receiving AC three-phase voltage of excitation from synchronous generator "G6", which is driven by DC machine "M1". Power sources "G1" and "G9" feed a necessary voltage on DC machines "G2" and "G5", exciter of synchronous machines "G8", and auxiliary units of the stand.

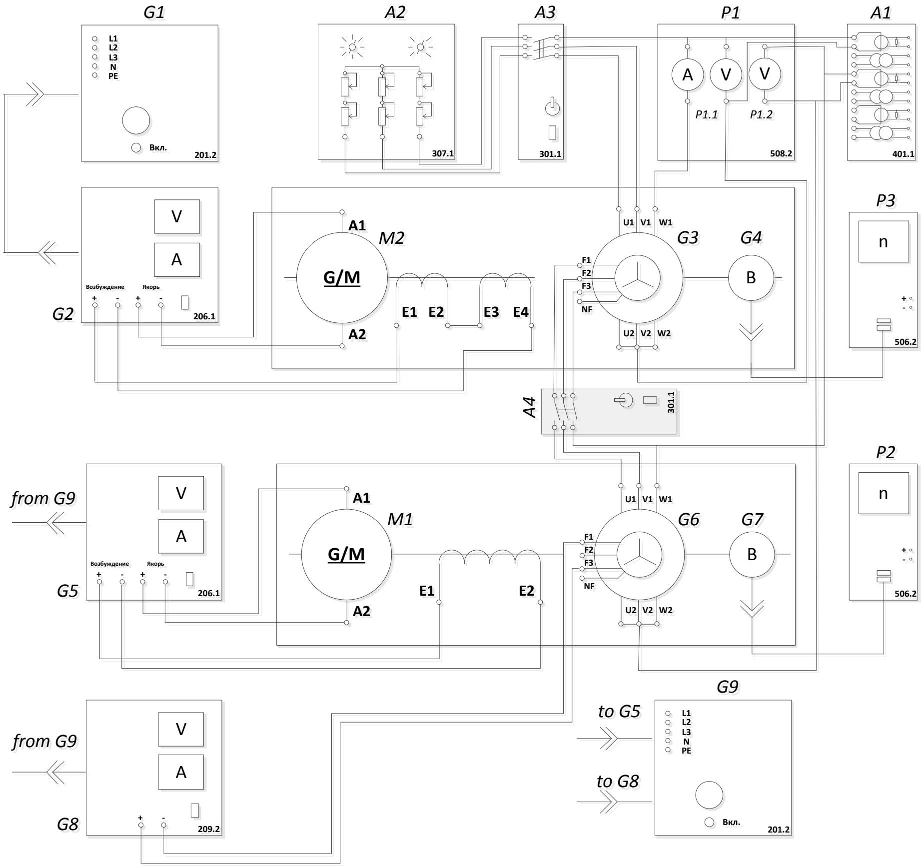


Figure 5. Electrical wiring.

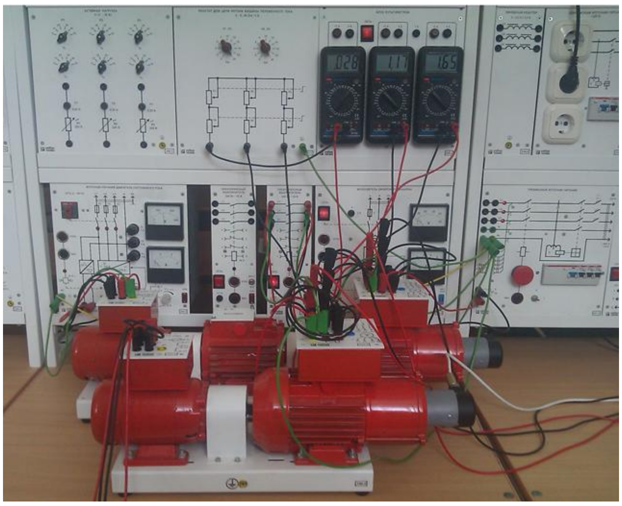


Figure 6. General view of the stand.

Having considered the options of separate blocks of electric circuit used in this experiment, we present a general view of the stand. He is shown in figure 6.

See that the block structure of the stand allows to conveniently assembling blocks respectively ongoing experience. In the foreground one can see the analyzed DFIG in a dual-control with DC motor, on the background is the synchronous generator driven by a DC motor. The torque on the generator rotor from DC motor is transmitted via the hand wheel.

To perform full-scale simulation of the above described control system on the existing equipment is not possible, mainly due to the lack of three-phase inverter, controlled on channels of frequency and amplitude. Its replacement by the synchronous generator, even with the possibility of automatic regulation of shaft rotation frequency and voltage excitation will not be equivalent [12].

Therefore, for experimental modeling simplify proposed control system, and bring stabilization of the frequency and amplitude to two formulas [12]:

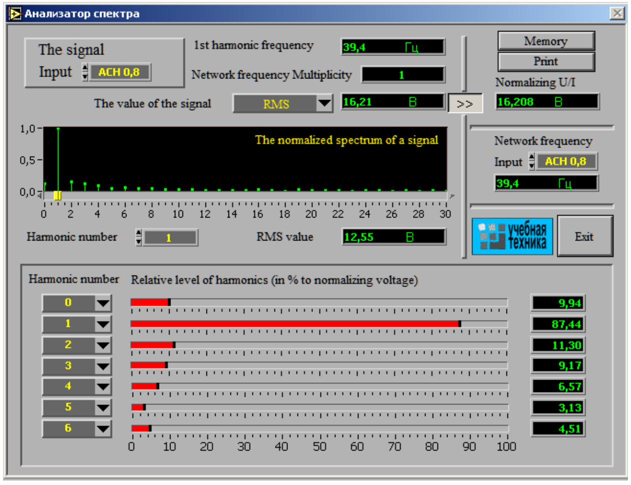
$$f_{ext} = f_{stat} - f_{sh} \cdot p \tag{23}$$

$$U_R = U_s \cdot \frac{f_{stat} - f_{sh} \cdot p}{f_{stat}} \cdot \frac{(R_L + R_{L0}(K2_0 - 1))}{R_L} \tag{24}$$

Here U_s is a required stator voltage, f_{ext} is the frequency of the excitation voltage, f_{stat} is required frequency of a stator voltage, f_{sh} is a shaft rotation frequency, p – pole pairs, R_L is value of electric load, R_{L0} is the resistance of the windings, $K2_0$ the transformation coefficient.

Formulas (23) and (24) are obtained on the basis of the substitution procedure of DFIG.

So, after making the necessary wiring diagram, and sighting the description of its all elements, let’s proceed to execution of the experiment. Get the shaft up to 800 rpm, and set the load at 40 ohms per phase. In the frequency analyzer we select inputs, corresponding to the voltage of excitation and stator voltage. The program window and calculated in this case parameters is shown in figure 7 and 8.



Анализатор спектра

The signal

Input: АСН 0,8

1st harmonic frequency: 39,4 Гц

Network frequency Multiplicity: 1

The value of the signal: RMS 16,21 В

Normalizing U/I: 16,208 В

Network frequency

Input: АСН 0,8

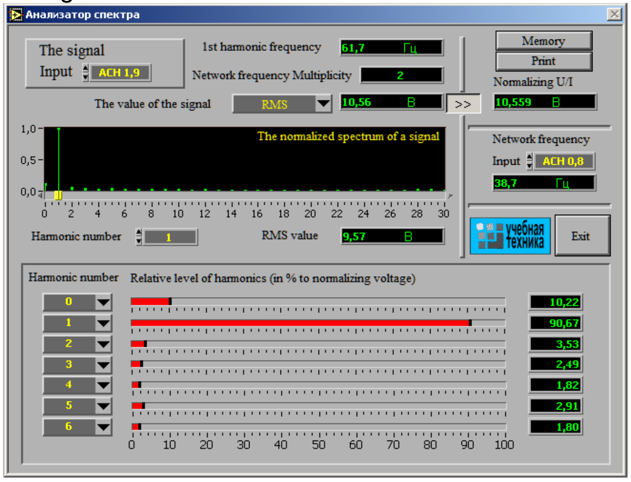
39,4 Гц

Harmonic number: 1

RMS value: 12,55 В

Harmonic number	Relative level of harmonics (in % to normalizing voltage)
0	9,94
1	87,44
2	11,30
3	9,17
4	6,57
5	3,13
6	4,51

Figure 7. Harmonic composition of the excitation voltage.



Анализатор спектра

The signal

Input: АСН 1,9

1st harmonic frequency: 61,7 Гц

Network frequency Multiplicity: 2

The value of the signal: RMS 10,56 В

Normalizing U/I: 10,559 В

Network frequency

Input: АСН 0,8

38,7 Гц

Harmonic number: 1

RMS value: 9,57 В

Harmonic number	Relative level of harmonics (in % to normalizing voltage)
0	10,22
1	90,67
2	3,53
3	2,49
4	1,82
5	2,91
6	1,80

Figure 8. Harmonic composition of the stator voltage.

Because of the strong distortion presence in the input and output voltage, in figures 7 and 8 expressed in the form of high values of the relative harmonics level, in the calculation we will use not the current value of the signal but the RMS of the main harmonic. These distortions are especially visible in the waveform, shown in figure 9.

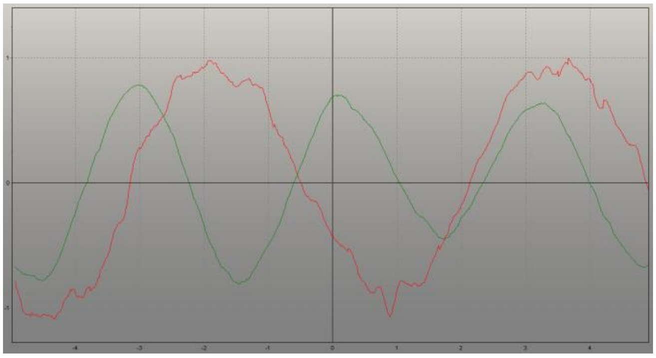


Figure 9. Waveforms of excitation (light) and stator (dark) DFIG voltage.

So, let's calculate the excitation DFIG voltage using data of figures 7 and 8:

$$U_R = U_s \cdot \frac{f_{stat} - f_{sh} \cdot p}{f_{stat}} \cdot \frac{(R_L + R_{L0}(K2_0 - 1))}{R_L} = \\ = 9{,}57 \cdot \frac{39{,}4}{61{,}7} \cdot \frac{(40 + 40(1{,}67 - 1))}{40} = 10 \cdot 0{,}567 \cdot 1{,}67 = \\ = 10{,}2. \qquad (25)$$

See that the calculated value of 10.2 volts slightly different from those obtained experimentally - 12.5 volts. When performing this part of the experiment, fluctuations of RMS value and frequency of the excitation and stator voltage was marked, therefore, the deviation of the calculated value of 2.3 volts from experimental could be considered as a good result.

To test the control law (23), also refer to the following figures 7 and 8. Let’s calculate manually, what frequency of the voltage should be feed on the rotor circuit at 800 rpm to get on the stator voltage with frequency of 61.7 Hz. Insert the necessary data in (23). Will receive:

$$f_{ext} = f_{stat} - f_{sh} \cdot p = 61{,}7 - \frac{800}{60} \cdot 2 = 35{,}03 \qquad (26)$$

Figure 7 shows the actual frequency of the rotor circuit voltage. It is equal to 39.4 Hz at manually calculated 35,03 Hz. The difference in 4,37 Hz explained by the fact, that at the time of measurement DFIG shaft rotation frequency was not exactly equal to 800 rpm, as exhibited by analogue measuring instrument of rotation frequency with the error. In addition, the vibration of the generator shaft “G6” has caused fluctuations in the frequency of the excitation voltage that caused such a discrepancy between experimental data and analytical calculations. Considering that, in these conditions, experimental studies of such deviation in 4,37 Hz from settlement can be considered a good result, confirming adequacy of the control law (23).

Analysing the obtained data during the experiment, it was found that the calculated analytically values of excitation voltage at a certain rotation frequency of the DFIG shaft and the load, almost coincided with the values of these quantities obtained experimentally. That, given the negative effects associated with the replacement of the controlled converter on a AC machine, is an excellent result and confirms the theoretical calculations. Despite the fact that the regulation was carried out manually, the obtained data proved the efficiency of the control laws (23) and (24) that at presence in the laboratory controlled by amplitude and frequency channel converter with a high probability will implement a closed CS and get the best results.

Conclusion

The paper proposed a synthesis method that delivers DFIG control system with ability to adapt oneself to the nonlinear immeasurable external and self-reactance disturbances influencing on the control object. A control law was synthesized on the basis of DFIG mathematical model in "dq" coordinates, with nonlinear immeasurable self-reactance and external disturbances of generator being added. Due to nonlinearity of the control object, such disturbances are difficult to describe mathematically. In this paper a work around was proposed by defining the values of these disturbances with subsequent adjustments to the CS work, based on such evaluation. An observer for estimating such disturbances was synthesized, which brings a correction to the CS work on the basis of this estimation. The method was proved using the full-scale computer simulation.

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