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Method of Adaptive Control for Double-Fed Induction Machine

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Abstract: This study presents the solution to the problem of the Double-Fed Induction Generator (DFIG) stable voltage generating in the changing terms of environment. For this in nonlinear multivariable systems such as mathematical model of DFIG, we used the method of observers synthesis for external, parametric and structural disturbances is presented in an additive form. This allows on the basis of disturbances approximation to carry out an evaluation under conditions of uncertainty, leading to adapt to disturbances with a priori unknown structure. The research presents the structure and methods of synthesis of control systems, allowing to solve indicated problem. As a power plant that uses DFIG, used autonomous wind turbine. The control system uses the original nonlinear mathematical model of the DFIG in rotating "dq" coordinates, taking into account non-linear changes in the external internal and structural parameters. For confirm the effectiveness of the problem solution, algorithms realization and created control system research, mathematical computer model in MATLAB was developed.

Key words: Wind power plant, adaptive control, doubly-fed induction machine, non-linear control system, disturbances, approximation

INTRODUCTION

Now a days, one of the actual problems in theory of automatic control is the problem of structural-algorithmic implementation of control systems for objects, running in a priori unstructured environments. The solution of this problem can be accomplished with synthesis of disturbances observers in nonlinear multivariable systems. As an example, consider the DFIG operation in the autonomus wind turbine.

In this case, the parameters of the generated voltage will depend on the environmental conditions, that is from external disturbances. At the same time, the necessity of quality stable voltage generation sets the problem of technological decisions development, allowing to minimize influence of different factors on output voltage quality. Adaptive nonlinear Control System (CS) with disturbance observers for DFIG can permit high speed reaction to wind speed changes and the rate of the connected electrical load, thus, maintaining the stability of the generator output voltage. It becomes possible to design and create a new types of CS for wind turbines.

MATERIALS AND METHODS

Synthesis of nonlinear adaptive CS: The solution of the indicated problem, offered in this study is based on the nonlinear model of DFIG in rotational "dq" coordinates as in the conditions of different disturbances, linearizing appears uneffective (Tolmachev *et al*., 2002; Shefter and Roshdestvensky, 2007; Pshikhopov and Medvedev, 2011a, b). Because coming from the structure of wind power plant, control circuit is a rotor circuit, then primary control objective is feed 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 v_{ds}^{ref} and v_{qs}^{ref} . The classic mathematical model of DFIG does not take into account the nonlinear changes of its parameters, 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 with the subsequent bringing of adjustments in work of CS on the basis of such estimation is a fully solvable task. For this purpose in the standard mathematical model of DFIG, we will add some functions of immeasurable disturbances, f_{d1} and f_{d2} (Eq. 1), accordingly for the stator "d" and "q" axes currents and next, we synthesize control laws:

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

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 where a_1 is a gain of the nonlinear observer. 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 (Eq. 1):

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

Putting Eq. 2 in initial equalization and expressing from him stimulus, we will get:

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

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}:

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

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

Now in accordance with Medvedev (2006), Pshichopov and Medvedev (2011a, b, 2014), we will execute a procedure of synthesis for and disturbances observer 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:

$$f_0 = \frac{L_r\left(V_{qs} - R_s * i_{qs}\right)}{-L_rL_s + L_m^2} + \frac{L_m\left(\omega_r\left(L_ri_{dr} + L_mi_{ds}\right) - R_ri_{qr} + V_{qr}\right.}{-L_rL_s + L_m^2} \tag{5}$$

Putting Eq. 5 in Eq. 1, we will get:

$$\frac{d}{dt}i_{qs} = f_0 + f_{d1} \tag{6}$$

We will enter a macrovariable, reflecting an evaluation error Eq. 7 where $\hat{f}_{d1}$ is an estimation of revolting disturbance:

$$e_{?1} = f_{d1} - \hat{f}_{d1} \tag{7}$$

In accordance with (Medvedev, 2006; Pshichopov and Medvedev, 2011a, b, 2014), we will enter equalization Eq. 8 where $S_{d1}(I_{qs})$ is an arbitrary function which will be determine in the process of observer synthesis, $\hat{z}1$ is a new variable:

$$\hat{f}_{d1} = S_{d1}(I_{qs}) + \hat{z}_1 \tag{8}$$

Thus, with an account of (Eq. 8), it is possible to write Eq. 7 down as:

$$e_{?1} = f_{d1} - S_{d1}(I_{qs}) - \hat{z}_1 \tag{9}$$

A derivative from the error of evaluation Eq. 9 is equal:

$$\dot{e}_{?1} = \dot{f}_{d1} - \frac{\partial S_{d1}}{\partial I_{qs}}(f_0 + f_{d1}) - \dot{\hat{z}}_1 \tag{10}$$

For providing of estimation asymptotic convergence, we will demand, that the error e_{H1} submitted to the decision of equalizatione where a_{1H} is a gain of the d-axis nonlinear observer:

$$\dot{e}_{H1} + a_{1H}e_{H1} = 0 \tag{11}$$

Putting Eq. 9 and Eq. 10 in Eq. 11, we will get:

$$0 - \frac{\partial S_{d1}}{\partial I_{qs}}(f_0 + f_{d1}) - \dot{\hat{z}}_1 + a_{1?}(f_{d1} - S_{d1}(I_{qs}) - \hat{z}_1) = 0 \tag{12}$$

If we choose the function $S_{d1}(I_{qs})$, so that, equalization Eq. 12 did not depend on not measureable disturbance of f_{d1}, then expression Eq. 12 will be an asymptotic observer. Thus, the estimation of not measurand disturbance f_{d1} w ill be determined in accordance with Eq. 8.

So that, right part of Eq. 12 did not depend on not measureable disturbance f_{d1}, we will equate all elements containing this parameter, to the zero. As a result, we will come to the next equalization:

$$-\frac{\partial S_{d1}}{\partial I_{qs}} f_{d1} + a_{1H} f_{d1} = 0 \tag{13}$$

Solving equalization Eq. 13 relatively from $\frac{\partial S_{d1}}{\partial I_{qs}}$, find:

$$-\frac{\partial S_{d1}}{\partial I_{qs}} = a_{1H} \tag{14}$$

Thus, from Eq. 14, we will define $S_{d1}(I_{qs})$:

$$S_{d1}(I_{qs}) = a_{1H} I_{qs} \tag{15}$$

We will put Eq. 13 and 15 in Eq. 12, so, we get:

$$-a_{1H} f_0 - \hat{z}_1' - a_{1H}^2 I_{qs} - a_{1H} \hat{z}_1 = 0 \tag{16}$$

We will express a new variable $\hat{z}_1$ from Eq. 16:

$$\hat{z}_1' = -a_{1H} f_0 - a_{1H}^2 I_{qs} - a_{1H} \hat{z}_1 \tag{17}$$

Using Eq. 8 and 15, we can define equalization of observer:

$$\hat{f}_{d1} = a_{1H} I_{qs} + \hat{z}_1 \tag{18}$$

Equation 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 Eq. 1. Applying analogical procedure for a current on the axis of “d”, we will get:

$$\begin{gathered} \hat{z}_2' = -a_{2H} f_0 - a_{2H}^2 I_{ds} - a_{2H} \hat{z}_2 \\ \hat{f}_{d2} = a_{2H} I_{ds} + \hat{z}_2 \end{gathered} \tag{19}$$

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

RESULTS AND DISCUSSION

Computer modelling: For computer simulation and analysis of the proposed control system, it is necessary to choose the most suitable package of computer modeling. This package is a software product MATLAB. Note that the main idea of this 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 is 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 Eq. 3 , 4, 17 and 19 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 V and frequency of 50 Hz. Let at time 0.01 sec, the electric load has changed and at the time 0.02- frequency of shaft rotation. Figure 1 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 axis dq is smooth without strong distortions that is a result of adaptive control systems with observer operation. At time 0.02 sec, 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 sec that is corresponds to a spike load. As the shaft rotation speed varies smoothly and control system, adapting, also chainges the voltage and therefore the rotor currents smoothly. Figure 2 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 Fig. 2 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

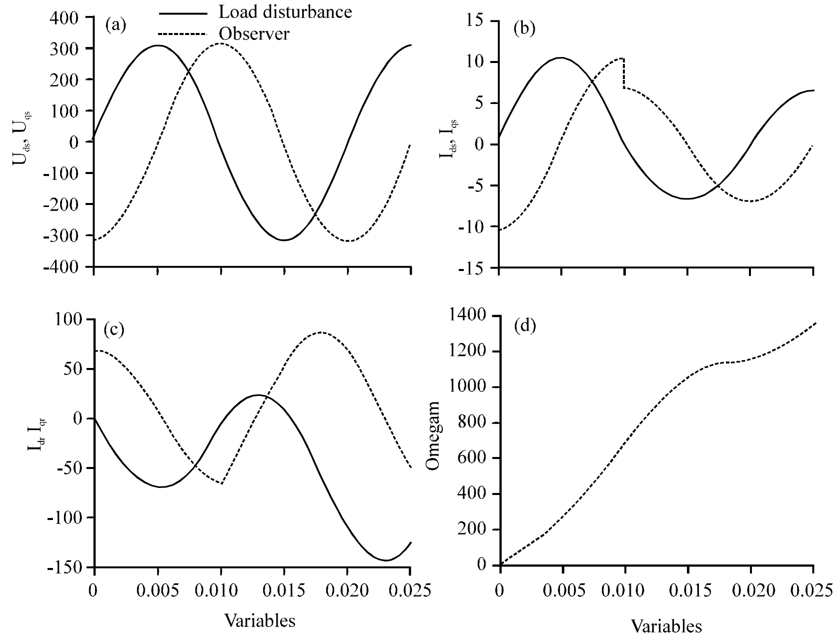

Fig. 1: Charts of the CS with observer operational results at variable disturbances, clockwise: voltage "dq" stator, currents "dq" stator, shaft rotation speed, currents "dq" rotor

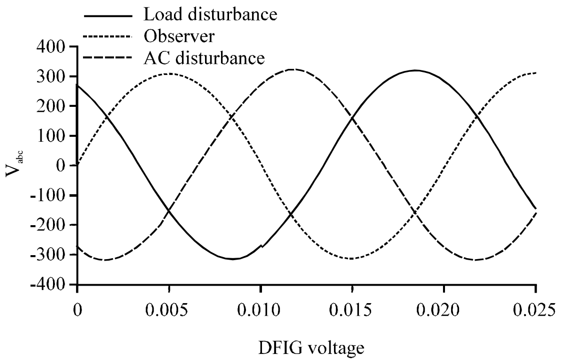

Fig. 2: 3-phase output DFIG voltage

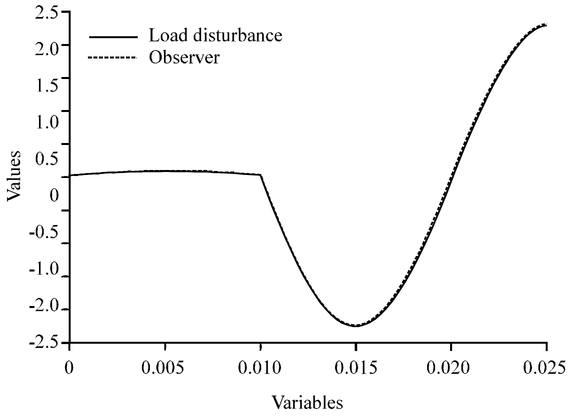

Fig. 3: Load disturbance (red) and it's estimation (blue) by observer

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.

Now refer to Fig. 3 where curves illustrated asked AC disturbance load and assessment of observer. Here electrical load disturbance varies according to given above chainge and its estimation by the observer similarly changing and shapes of the two curves are nearly identical. This suggests that the observer estimates a 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.

CONCLUSION

Thus, by the given above method of synthesis, we got DFIG control system with ability to adapt oneself to the influencing on the control object nonlinear unmeasureable external and self-reactance disturbances. A control law is synthesized on the basis of DFIG mathematical model in “dq” coordinates with nonlinear unmeasureable self-reactance and external disturbances of generator being added. Arising up from nonlinear character of control object, such disturbances are difficult yield to mathematical description, however, determination of these disturbances with the subsequent bringing of adjustments in CS operate on the basis of such estimation is the decided task. An observer estimating such disturbances is synthesized for this purpose and on the basis of this estimation bringing in adjustment in work of CS.

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