Determination of Parameters of Adaptive Law for the Control of an Off-grid Power System

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Abstract: The paper presents the results of a study of an off-grid electric power system that contains typical generation and load devices. The aim of the study is to develop an algorithm for selecting the optimal parameters of adaptive control law of the energy characteristics in the off-grid power system at the connection point of a varied load. To this end a simulation experiment was carried out and its results were used to numerically model the off-grid power system. The authors apply a known method of modelling the complex multi-parametric systems represented by the Volterra integro-power series. Standard approaches to the measurement of dynamic performance were applied to identify a transient response of the system.

1 INTRODUCTION

One of the main directions in power engineering is the adoption of components applicable to the implementation of a smart grid concept. The considered system contains the main elements that belong to the isolated (off-grid) systems. This makes it possible to take into consideration the key features of a change in the nature of generation when changing the load parameters.

The input was represented by a symmetrical change in a three-phase load of both active and reactive components. The load changed in a step-wise manner toward an increase (decrease) in the load current. The parameters of the change in the characteristics were taken into account at the connection point of the varied load. The step-wise change in the load occurred in the steady-state operation of the system. Test inputs reached 50% of the level of rated conditions. Since there is an aperiodic component of three-phase currents in the transient conditions a generalized positive-sequence current phasor was measured. Also active and reactive power flows at the connection point of the varied load were taken into account.

2 STATEMENT OF THE PROBLEM

The issues dealing with the selection of operating conditions, network configuration (in terms of sites for placement of generators), and reliability assessment are considered by us in (Voropai, 2012; Suslov, 2013).

The facilities to be considered as generators are: gas turbine plants, wind turbines and solar panels. Also, consideration is given to energy storage devices, since the renewable energy output is stochastic, their use is necessary to provide the required reliability of electricity supply to consumers of the off-grid systems. We consider an isolated (off-grid) system scheme presented in Fig. 1. The experience gained in operating a gas turbine plant reveals some serious problems when tuning the automatic control loops, namely:

1. Lack of a comprehensive approach, because power systems are considered separately from one another.

2. The problem of obtaining common algorithms for the power system control, which is related to the complexity of traditional mathematical tools.

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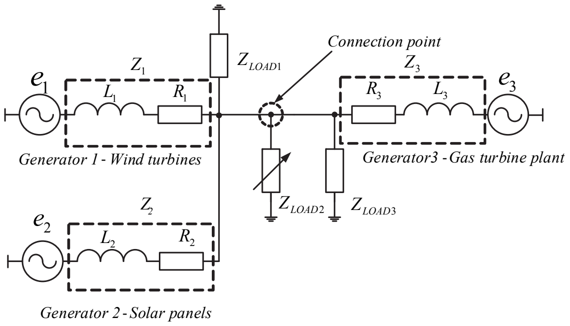

Figure 1: A scheme of an isolated (off-grid) system (e_1, e_2, e_3 - electromotive force of different generators, Z_1, Z_2, Z_3 - internal impedance of the generators, Z_{load1}, Z_{load2} -unchangeable fixed load of consumers, Z_{load3} -variable load,).

We suggest the following approach to solve the above problems. The electricity generating systems are defined by the external structural input-output schemes. The flow chart for the gas turbine plant is presented in Figure 2.

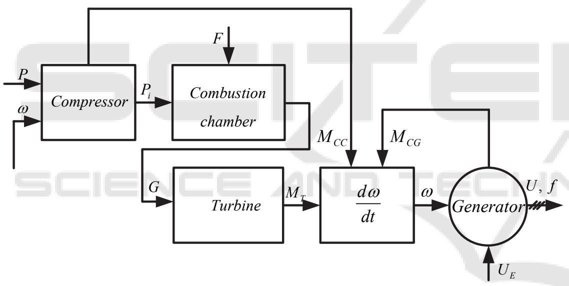

Figure 2: Flow chart for a single-shaft gas turbine plant (U_E-excitation voltage, U – voltage at the generator outlet, f- network frequency, P- air pressure at the compressor inlet, ω - angular velocity, P_i- pressure at the compressor outlet, F – fuel supplied to the combustion chamber, G- gas flow rate, M_{CC}- gas turbine shaft resistance torque created by compressor, M_{CG} - turbine shaft resistance torque created by electric generator).

The flow chart for the solar panel is demonstrated in Figure 3. The flow chart for the wind turbine plant is shown in Figure 4.

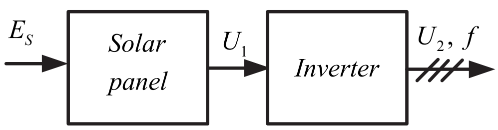

Figure 3: Flow chart for solar panel (E_S – solar energy, U_1 – voltage at the solar panel outlet).

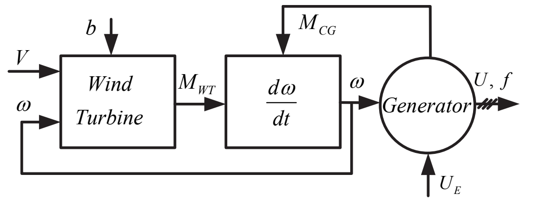

Figure 4: Flow chart for the wind turbine plant *(V*- wind speed, *b* – attack angle*, M_{WT}*- engine torque, created by wind turbine).

Each of the generators has their specific features to be taken into account in designing the automated control system. For example, gas turbine plant makes it possible to completely control input parameters but has quite high inertia. Generation from solar panels is deterministic due to the lack of inertia.

Generation from wind power plants is a vivid example of stochastic operation of generators. At the same time, apart from the random change in the input data such a generation is subject to inertia.

Figure 5 presents a subsystem of the wind turbine module which is described by a system of algebraic equations, where the input signals are represented by wind speed *V*, attack angle of turbine blade *b*, current coordinate of angular velocity ω depending on the shaft resistance torque.

Inertia of the rotating parts in the wind turbine is taken into account by the equation of dynamics

$$\frac{d\omega}{dt} = \frac{M_T - M_C}{J_\Sigma}, \qquad (1)$$

where M_T - turbine generator shaft torque, M_C - resistive torque created by generator, J_Σ - total inertia torque. Generally speaking, the analysis of dynamic characteristics of wind power unit is based on the methods using differential equations. Most of the researches are devoted to the specification of characteristics of individual components of wind turbine (He, 2009; Li, 2011), specification of various coefficients (Manyonge, 2012) or consideration of a mechanical part of the turbine as an *N*-mass system (Bhandari, 2014).

Traditionally, the theory of modelling the control systems employs differential equations with constant coefficients. These equations are obtained by linearizing the nonlinear differential equations with variable coefficients of the most typical operating conditions of a certain system (Saadat, 2010, Ogata, 2010). This is explained by the presence of a nondeterministic system with distributed parameters.

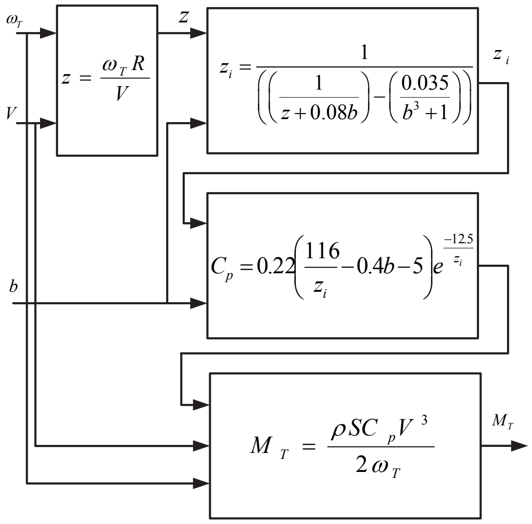

Figure 5: A subsystem of the wind turbine scheme (C_m - torque coefficient, ρ - air density, V - wind speed, m/s; S - blade-swept area, R - wind wheel radius, m, $C_P = \frac{2P}{\rho V^2 S}$ - coefficient of wind energy use, $Z = \frac{\omega R}{V}$ – specific speed).

In practice, the initial data are known with some error. In this case, as a rule, solutions to the inverse problem turn out to be unstable with respect to an error in the initial data. Therefore, to construct stable methods we use the theory of ill-posed problems (Kabanikhin, 2011).

Thus, all traditional methods are convenient for the research and analysis of power system operation but are hardly suitable for the implementation of an adaptive response of a control system to the real-time disturbances.

Also, such systems can be described by the system of linear differential equations in the neighbourhood of operation point (Salamanca, 2010, Chenx, 2011) and by the system of differential equations written in the normal Cauchy form (steady-state) (Al-Jufout, 2010; Wang 2013, 2014)

We believe that the study can involve a known mathematical modelling approach in which any dynamic system is represented as a “black box” (Fig.6). In the case, where the output y(t) continuously depends on inputs x(t), the model of nonlinear dynamic system can be represented by Volterra integro-power series (Volterra, 1959).

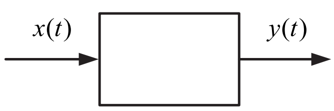

Figure 6: The “input-output” system.

The studies show that wind power plant has the greatest impact on the output value y(t). And the larger the share of wind generation in the off-grid system, the greater this impact is. The qualitative character of this impact is demonstrated in Fig.7. Here it was assumed that gas turbine plant and photovoltaic cells share the rest of generation in halves.

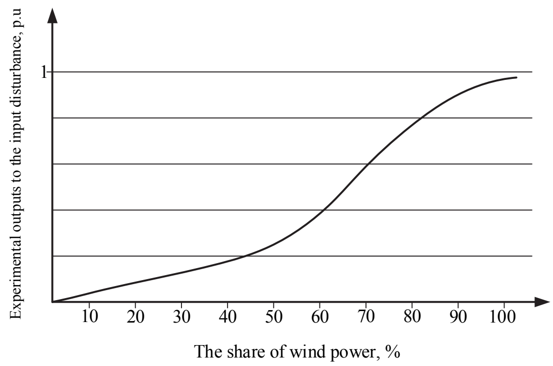

Figure 7: The qualitative character of the impact.

Thus, it is reasonable to consider the problem of the off-grid system modeling on the example of a wind power plant.

3 ABOUT A NEW APPROACH TO THE MATHEMATICAL DESCRIPTION OF THE WIND POWER PLANT DYNAMICS

The Volterra integro-power series (Doyle, 2002; Rugh, 1981; Venikov, 1982; Pupkov, 1976) are widely used in mathematical modeling of complex nonlinear dynamic systems. The nonlinear dynamic systems and their properties are fully characterized by multidimensional weight functions, i.e. Volterra kernels. In this case the problem of constructing a mathematical model of a nonlinear dynamic system lies in the identification of Volterra kernels on the basis of data obtained from the experimental research into an input-output system (Giannakis, 2001).

In this research we employ an approach (Apartsyn, 2013) based on the physically implemented test inputs. The main distinction of this approach lies in the fact that the initial problem is reduced to solving special integral equations which can be explicitly solved.

In this research we have developed and implemented new algorithms for the construction of integral models represented by Volterra polynomials with vector input

$$y(t)=\sum_{n=1}^{N}\sum_{1\le i_1,\dots,i_n\le 2}\int_0^t\dots\int_0^t K_{i_1,\dots,i_n}(t,s_1,\dots,s_n)\prod_{k=1}^{n}x_{i_k}(s_k)ds_k$$

in the cases which are the most important for applications, $N=2,3$. The research is a continuation of (Suslov, 2015).

In (Solodusha, 2015) the authors show that the problem of the Volterra kernels identification in the quadratic Volterra polynomial

$$y_{quad}(t)=\int_0^t K_1(t,s_1)x(s_1)ds_1+ \quad (2)$$

$$+\int_0^t\int_0^t K_2(t,s_1,s_2)\prod_{i=1}^{2}x(s_i)ds_i\ ,\ t\in[0,T]$$

can be solved by using only two integral equations

$$y^\alpha(t,\omega_1,\omega_2)-\alpha\int_0^{\omega_1}K_1(t,s_1)ds_1+ \quad (3)$$

$$+\alpha\int_{\omega_1}^{\omega_1+\omega_2}K_1(t,s_1)ds_1=3y^\alpha(t,\omega_1,0)-$$

$$-3y^\alpha(t,0,\omega_1+\omega_2)+y^\alpha(t,\omega_1+\omega_2,-\omega_2)-$$

$$-7\alpha\int_0^{\omega_1}K_1(t,s_1)ds_1-5\alpha\int_{\omega_1}^{\omega_1+\omega_2}K_1(t,s_1)ds_1,$$

$$\alpha\int_0^{\omega_1}K_1(t,s_1)ds_1-\alpha\int_{\omega_1}^{\omega_1+\omega_2}K_1(t,s_1)ds_1+ \quad (4)$$

$$+\alpha^2\int_0^{\omega_1}\int_0^{\omega_1}K_2(t,s_1,s_2)ds_1ds_2-$$

$$-2\alpha^2\int_0^{\omega_1}\int_{\omega_1}^{\omega_1+\omega_2}K_2(t,s_1,s_2)ds_1ds_2+$$

$$+\alpha^2\int_{\omega_1}^{\omega_1+\omega_2}\int_{\omega_1}^{\omega_1+\omega_2}K_2(t,s_1,s_2)ds_1ds_2=y^\alpha(t,\omega_1,\omega_2).$$

The output $y^\alpha(t,\omega_1,\omega_2)$ in the right-hand side of (3), (4) is a response of the reference dynamic system (1) to the test inputs

$$x^\alpha_{\omega_1,\omega_2}=\alpha(e(t)-2e(t-\omega_1)+e(t-\omega_1-\omega_2)), \quad (5)$$

where $t,\omega_1,\omega_2\in[0,T]$, $e(t)$ is the Heaviside function:

$$e(t)=\begin{cases}0,\ t<0,\\ 1,\ t\ge 0.\end{cases}$$

In order to improve the accuracy of modelling we will consider a modification of this algorithm for the case of cubic Volterra polynomial. Let us consider a combined cubic model

$$y_{cub}(t)=\int_0^t K_1(t,s_1)x(s_1)ds_1+ \quad (6)$$

$$+\int_0^t\int_0^t K_2(t,s_1,s_2)\prod_{i=1}^{2}x(s_i)ds_i+$$

$$+\int_0^t\int_0^t\int_0^t \hat{K}_3(s_1,s_2,s_3)\prod_{i=1}^{3}x(t-s_i)ds_i\ .$$

Using the above approach it is easy to see that the condition of form (3) and outputs of the reference dynamic system to the test inputs $x^{\alpha_i}_{\omega_1\omega_2}(t)$, $\alpha_i\ne 0$, $i=1,2$, $\alpha_1\ne\alpha_2$ of form (5) make it possible to completely identify the kernels $K_1,K_2,\hat{K}_3$. For example, the restoration of kernel K_1 is reduced to solving the integral equation

$$\int_0^{\omega_1}K_1(t,s_1)ds_1=f_1(t,\omega_1), \quad (7)$$

where

$$f_1(t,\omega_1)=\frac{\begin{vmatrix}f^{\alpha_1}(t,\omega_1) & \alpha_1^3\\ f^{\alpha_2}(t,\omega_1) & \alpha_2^3\end{vmatrix}}{\begin{vmatrix}\alpha_1 & \alpha_1^3\\ \alpha_2 & \alpha_2^3\end{vmatrix}}, \quad (8)$$

$$f^{\alpha_i}(t,\omega_1)=\frac{1}{2}\left(y^{\alpha_i}(t,\omega_1,0)-y^{\alpha_i}(t,0,\omega_1)\right)$$

As applied to the model

$$y_{cub}(t)=\int_0^t K_1(t,s_1)x(s_1)ds_1+ \quad (9)$$

$$+\int_0^t\int_0^t \hat{K}_2(s_1,s_2)\prod_{i=1}^{2} x(t-s_i)ds_i +$$
$$+\int_0^t\int_0^t\int_0^t \hat{K}_3(s_1,s_2,s_3)\prod_{i=1}^{3} x(t-s_i)ds_i$$

we obtain, that for the unique restoration of $K_1, \hat{K}_2, \hat{K}_3$ it is sufficient to have outputs of a dynamic system to the test inputs $x^{\alpha_i}_{\omega_1\omega_2}(t)$, $\alpha_i \neq 0$, $i=1,2$, $\alpha_1 \neq \alpha_2$ of form (4) and condition $f_2(t,\omega_1) = f_2(t-\omega_1,-\omega_1)$.

In this case the problem of identification, for example, of kernel K_1, can be reduced to equation (9) with the right-hand side of (8), where

$$f^{\alpha_i}(t,\omega_1) = \frac{1}{2}\left(y^{\alpha_i}(t,\omega_1,0) - y^{\alpha_i}(t-\omega_1,-\omega_1,0)\right)$$

4 CASE STUDY

Based on the developed algorithms we constructed a quadratic model of form (2) and a cubic model of form (9). The identification involved the studied system outputs (Fig.1) to the test inputs of form (5).

The input is considered to be a change in the character of load power, and the outputs are represented by the power system parameters. The parameters were calculated for the connection point demonstrated in Fig.1. A generalized vector of a three-phase load current was used as a parameter. The rest of the parameters were active and reactive power at the connection point.

Figures 8-10 present the outputs of the reference model (Fig. 1) to the input disturbances

$$S\ (t,\omega) = 10(e(t) - e(t-\omega)),$$

where S - total load power.

These data were employed to restore transient characteristics in the integral models. The accuracies of quadratic and cubic models were compared in the description of the studied off-grid electricity supply system. The time of the transient process is T=0.2 sec., which corresponds to real values of the transient process time in the electric power systems. The computational experiment demonstrated the advantages of cubic model versus quadratic one.

Figure 11 illustrates the typical outputs of active

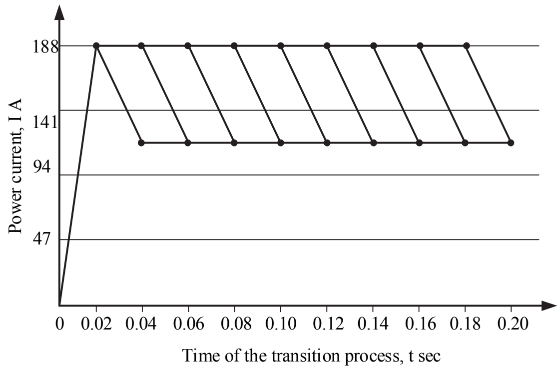

Figure 8: Values of power current at the connection point.

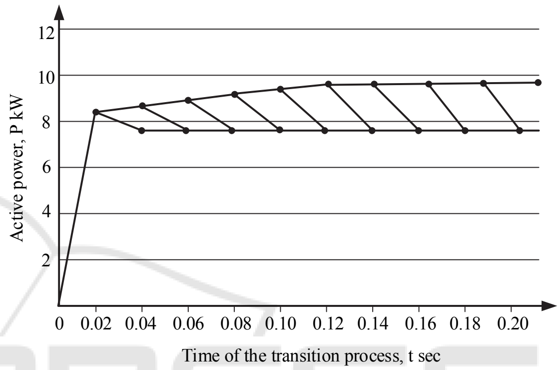

Figure 9: Values of active power at the connection point.

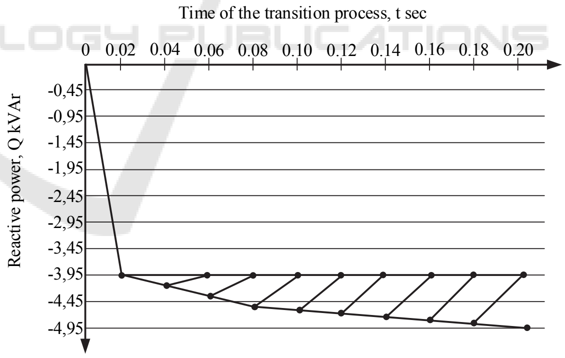

Figure 10: Values of reactive power at the connection point.

power at load shedding. They were obtained using quadratic and cubic models. Curve 1 denotes a steady-state value; curves 2 and 3 were obtained using quadratic and cubic models, respectively; curve 4 stands for an accurate value obtained using the reference model.

Curve 3 illustrates an effect of the inclusion of additional terms, i.e. an essential nonlinear character of the studied output.

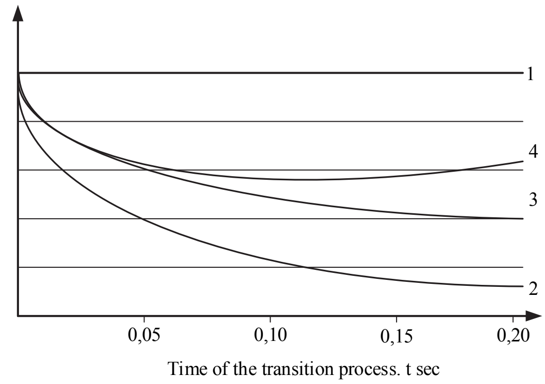

Figure 11: System outputs.

5 PARAMETER OPTIMIZATION IN TEST INPUTS (5)

Let in (5) $\alpha > 0$. The extreme problem of choosing α^* for some standard mathematical model is formulated in (Apartsyn, 2013). Let us consider by analogy the optimal (in some or other sense) choice of α in (4) to identify the kernels K_1 and K_2 in (1).

We choose some α from a range $[-B,B]$. Take the set

$$X(B,T)=\{x_{\omega}^{\beta}(t)=\beta\cdot(e(t)-e(t-\omega)),\\ \beta\in[-B,B], 0\le\omega\le t\le T\} \qquad (10)$$

as a class of the admissible inputs $x(t)$.

As the system response value at the end of the considered transient process ($t=T$) plays an important role in applications, the criterion of model accuracy has the form

$$\max_{x_{\omega}^{\beta}(t)\in X(B,T)} |y_{et}^{\beta}(T,\omega)-y_{quad}^{\alpha,\beta}(T,\omega)| \to \min_{\alpha\in[0,B]},$$

where $y_{quad}^{\alpha,\beta}(T,\omega)$ is response (2) to the input $\Delta S_{\omega}^{\beta}(t)$ (10). Actually, the difference $y_{et}^{\beta}(T,\omega)-y_{quad}^{\alpha,\beta}(T,\omega)$ is some function of the parameters α,β,ω.

Then

$$\alpha^*=\arg\min_{\alpha\in[0,B]}\left\{\max_{\substack{\omega\in[0,T]\\ \beta\in[-B,B]}}\left|N(\alpha,\beta,\omega)\right|\right\}, \qquad (11)$$

where

$$N(\alpha,\beta,\omega)=y_{et}^{\beta}(T,\omega)-y_{quad}^{\alpha,\beta}(T,\omega).$$

We present the results of mathematical modeling that were obtained using the software (Gerasimov, 2015).

The set $X(B,T)$ of such inputs as $\Delta S_{\omega}^{\beta}(t)$; $\beta\in[0,B]$, $B=50\%S_0$; $T=0.2$ sec. was taken as admissible. The calculations showed that

$$\omega_{\max}=T, \quad \beta_{\max}=\left\{B,\approx\frac{B}{2}\right\}.$$

The calculations demonstrate that the value $\alpha^*\approx 0.9B$, at $B=50\%S_0$.

The plot of the function $|N(\alpha^*,\beta,\omega)|$ with $B=50\%S_0$, $T=0.2$ sec. is given in Fig. 12.

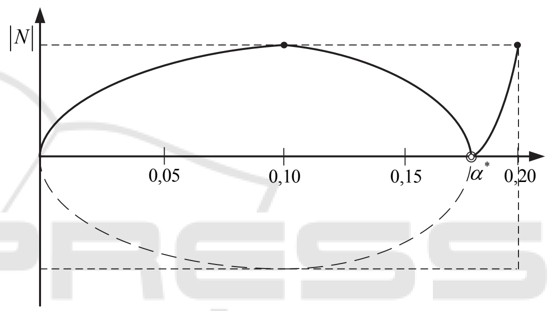

Figure 12: The plot of the function $|N(\alpha^*,\beta,\omega)|$.

Analysis of the results obtained for the reference model (1) enables us to recommend that for the identification of Volterra kernels the parameter α of test inputs (5) be chosen in the range $0.75B\div 0.9B$.

6 CONCLUSIONS

Consideration is given to a model of an off-grid system represented as a quadratic segment of the Volterra integro-power series on the basis of a reference model. The reference model is represented by an isolated electric power system, which contains several electricity sources, storage systems, and the shunt- and series-connected devices (active elements) that allow an on-line change in the energy parameters of the system. A system of algorithms is developed to control the most characteristic operating conditions of the power system, which can be used for on-line technical implementation.

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