WIND POWER STATION MODEL WITH LOAD VARIABLE IN TIME AND SPACE

Epshtein, Georgy L., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*
Sytov, Evgeny S., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*

ABSTRACT

The article presents the results of development and research of a mathematical model of wind power station connected to the electric system and multi-level, mobile load. It is assumed that the load is variable in time and location. The response of the system to various perturbations is studied, the technique of selection of parameters for automatic control of external rotor resistance is considered, the necessity of introducing a voltage stabilization circuit is justified. The advantages of the power supply circuit using a wind power station in the presence of wind power fluctuations are shown.

Keywords: wind power station, asynchronous generator, mathematical model, mobile load, recuperation.

Background. *The feature of simulated AC system is that, depending on load level, there are three modes of operation: the use of entire capacity of the wind power station for power supply load; transmission of generated power in the network and load; transfer of all power into the network. To this we must add that in case of mobile load in the electric circuit there arise variable parameters, including changing of the power factor in the load circuit. The supplied wind power may be exposed to noticeable fluctuations. Hence there is a need to solve a task of ensuring proper quality in the system's functioning both in terms of acceptable values of efficiency and acceptable transient characteristics.*

The system consists of an air turbine, mechanical multiplier transmitting torque to the shaft of the asynchronous generator with wound rotor, compensating capacity, power transformer and power lines connecting the generator to the general power grid and load. It includes also devices of protection, automatic control of external rotor resistances, the angle of attack of air turbine blades, and the apparatus for measurement of electric power and speed of generator's shaft.

The solution of this task is based on mathematical modeling of transients in the system. Questions about wind power plants operating in the power system or stationary load, are considered in [1, 2].

Objective. *The objective of the authors is to consider a model of a wind power station with load, which is variable in time and space.*

Methods. *The authors use general scientific and engineering methods, modeling, comparative analysis, mathematical apparatus.*

Results.

Mathematic modeling

In the development of a mathematical model data and recommendations given in [3–5] were taken into account.

Asynchronous generator with wound rotor

The equation of motion:

$$2H\frac{d\omega_r}{dt}=\left(\frac{P_t-D\left(\omega_r-\omega_0\right)}{\omega_r}-M_e\right), \qquad (1)$$
$$M_e=\psi_{fd}\,i_{12}-\psi_{fq}\,i_{11}.$$

In (1) there are following notations:

P_t is power developed by an air turbine;

M_e is an electromagnetic moment of an asynchronous generator;

ω_r, ω_0, Ω_s (in (2) below) are actual rotation speed, nominal rotation speed in relative units and synchronous rotation speed in rad / s;

H is inertia constant in view of reduced masses of an air turbine and a gear;

D is a coefficient taking into account the change of additional losses in deviation of rotation speed from the nominal value;

ψ_{fd}, ψ_{fq} are orthogonal components of flux linkage of rotor and stator windings;

i_{11}, i_{12} are orthogonal components of the stator current.

Differential equations of electromagnetic processes:

$$\frac{d\psi_{fd}}{dt}=\frac{\left(1+s\right)\psi_{fd}+L^{'}i_{11}}{T_{01}}+\left(1-\omega_r\right)\Omega_s\psi_{fq},$$
$$\frac{d\psi_{fq}}{dt}=-\frac{\left(1+s\right)\psi_{fq}+L^{'}i_{12}}{T_{01}}-\left(1-\omega_r\right)\Omega_s\,\psi_{fd}. \qquad (2)$$

In (2) there are following notations:

L' is transient inductance;

T_{01} is time constant of the rotor circuit;

s is a saturation ratio of the magnetic circuit.

The time constant, and the saturation ratio are variable values and are calculated according to the formulas:

$$T_{01}=\frac{r_2T_0^{'}}{r_2+R_{ext}},$$
$$\psi=\sqrt{\psi_{fd}^2+\psi_{fq}^2},\quad s=\begin{cases}0,\ \psi\le a_s,\\ \dfrac{b_s\left(\psi-a_s\right)^2}{\psi},\ \psi>a_s.\end{cases} \qquad (3)$$

In (3) there are following notations:

R_{ext} is variable external resistance;

r_2 is resistance of the rotor winding;

T_0' is time constant of the rotor winding;

a_s, b_s are parameters of the saturation curve of the magnetic circuit.

Control system of external rotor resistances

Correction circuit of the feedback channel:

$$\frac{dx_1}{dt}=\frac{k\left(\omega_0-\omega_r\right)-y_1}{T_2},\quad y_1=x_1+\frac{kT_1}{T_2}\left(\omega_0-\omega_r\right), \qquad (4)$$

where k, T_1, T_2 are parameters of transfer function of the correction circuit.

Differentiating circuit of the perturbation channel on electric power:

$$\frac{dx_2}{dt}=-\frac{y_2}{T_{dp}},\quad y_2=x_2+\frac{k_{dp}}{T_{dp}}\omega_rM_e, \qquad (5)$$

where k_{dp}, T_{dp} are parameters of the transfer function of the real differentiating circuit.

The output stage of external resistance control:

$$\frac{dx_3}{dt}=\begin{cases}\dfrac{y_1+y_2+R_0-x_3}{T_{2R}},\quad x_3\in\left(R_{\min},R_{\max}\right),\\ 0,\quad x_3=R_{\min}\wedge\dfrac{dx_3}{dt}<0\vee x_3=R_{\max}\wedge\dfrac{dx_3}{dt}>0,\end{cases} \qquad (6)$$
$$R_{ext}=\max\left(R_{\min},\min\left(x_3,R_{\max}\right)\right),$$

where T_{2R}, R_0, R_{min}, R_{max} are parameters of the transfer function of the output stage.

The control system of the angle of attack of air turbine blades

Correction circuit of the speed deviation channel:

$$\frac{dx_4}{dt}=\frac{k_{pw}\left(\omega_r-\omega_0\right)-y_4}{T_{2w}},\quad y_4=x_4+\frac{k_{wp}\,T_{1w}\left(\omega_r-\omega_0\right)}{T_{2w}},\qquad (7)$$

$$y_{41}=\max\left(-bpr,\min\left(y_4,bpr\right)\right),$$

where k_{pw}, T_{1w}, T_{2w}, bpr are parameters of the transfer function of the correction circuit.

The mechanism of rotation of the air turbine blades:

$$\frac{dx_5}{dt}=\begin{cases} y_{41}, & y_{41}\in\left(0,90\right),\\ 0, & y_5=0\wedge\dfrac{dx_5}{dt}<0\vee y_5=90\wedge\dfrac{dx_5}{dt}>0,\end{cases}$$

$$y_5=\frac{\pi}{180}\max\left(0,\min\left(x_5,90\right)\right),\qquad (8)$$

$$\frac{dx_6}{dt}=\frac{\cos(y_5)-x_6}{T_{aw}},\quad P_m=P_{wind}(\mathrm{t})\,x_6,$$

where T_{aw} is time constant of the transfer function of the blades' rotation mechanism.

In the external circuit wind power station is present in the form of a source of integrated EMF

$$E_d=-\frac{L_l}{L_2}\psi_{fq},\ E_q=-\frac{L_l}{L_2}\psi_{fd},\ E=E_d+jE_q\qquad (9)$$

with serial impedance Z_p and compensating capacity Z_c.

Transformer and power line connecting to an external power grid, are represented by impedance Z_{line}. The voltage on busbars of the remote power system V_{net} is unchanged.

Load is simulated through serial connection of active resistance R with current $I_4(t)$ and time-varying impedance $Z_{load}(t)$. Selecting various options of dependence of serial impedance on time, it is possible to simulate movement of the load in space.

Below there are equations in a complex form for calculating currents in the external circuit.

$$\begin{pmatrix} Z_p & 0 & -Z_{LINE} & 0\\ Z_p & Z_C & 0 & 0\\ 0 & -Z_C & 0 & Z_{LOAD}+R\\ 1 & -1 & 1 & -1\end{pmatrix}\begin{pmatrix} I_1\\ I_2\\ I_3\\ I_4\end{pmatrix}=$$

$$=\begin{pmatrix} E-V_{NET}\\ E\\ 0\\ 0\end{pmatrix},\quad I_1=i_{11}+ji_{12}.\qquad (10)$$

Designating complex voltage on the capacity through V_c, from the equations (10) we get:

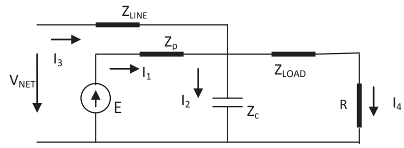
$$\mathrm{Y}=\frac{1}{Z_p}+\frac{1}{Z_{LINE}}+\frac{1}{Z_C}+\frac{1}{Z_{LOAD}+R},\quad V_C=\frac{1}{\mathrm{Y}}\left(\frac{E}{Z_p}+\frac{V_{NET}}{Z_{LINE}}\right),\qquad (11)$$

$$I_1=\frac{E-V_C}{Z_p},\ I_2=\frac{E-V_C}{Z_C},\ I_3=\frac{V_{NET}-V_C}{Z_{LINE}},\ I_4=\frac{V_C}{Z_{LOAD}+R}.$$

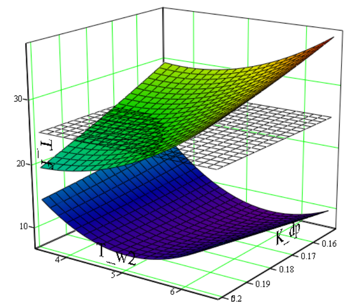
Selection of control parameters

Preliminary calculations have shown that the greatest impact on dynamics of external resistance control systems is produced by a gain coefficient of the differentiating circuit in the power measurement channel k_{dp} and time constant in the correction circuit in the rotation frequency measurement channel T_2.

To select the values of these parameters, calculations were made under conditions of a perturbation along wind speed abd under perturbation in the receiving power system in the form of a temporary undervoltage. As the main criterion of quality of transients regulation time t_{fv} was used. As a result of calculations regression dependences of regulation time on parameters of the control system were built.



Pic. 1. Electric circuit of the system.



Pic. 2. The position of the response surfaces for disturbances under wind load (bottom) and voltage (upper) plane – maximum value of transition process time.

On the receiving grid the following dependence was obtained for conditions of perturbation in the form of a single gust and operation of the wind power station

$$t_{fw}=121{,}899-327{,}942\bullet k_{dp}-33{,}305\bullet T_{2w}+$$
$$+47{,}908\bullet k_{dp}\bullet T_{2w}+305{,}167\bullet k_{dp}^2+2{,}365\bullet T_{2w}^2.$$

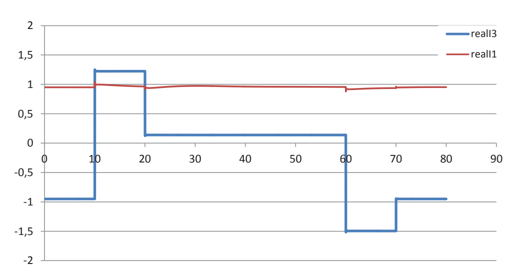
Stationary minimum point of this dependence is outside the allowable area and is equal to $k_{dp}^{*}=-0{,}075$, $T_{2w}^{*}=-7{,}801$. Minimizing within allowable boundary gives $k_{dp}=0$, $T_{2w}=6{,}5$.

In case of perturbation in the receiving power system dependence of time regulation on parameters takes a form:

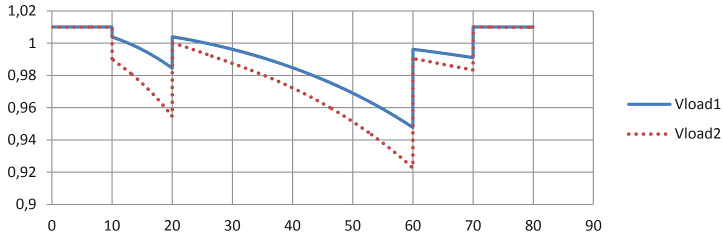
$$t_{fe}=106{,}64-455{,}625\bullet k_{dp}-13{,}93\bullet T_{2w}+$$
$$+26{,}867\bullet k_{dp}\bullet T_{2w}+462{,}417\bullet k_{dp}^2+1{,}26\bullet T_{2w}^2.$$

In this case, stationary minimum point is outside the allowable area and is equal to $k_{dp}^{*}=0{,}481$, $T_{2w}^{*}=0{,}399$. Minimizing within the allowable area gives $k_{dp}=0{,}2$, $T_{2w}=3{,}5$.

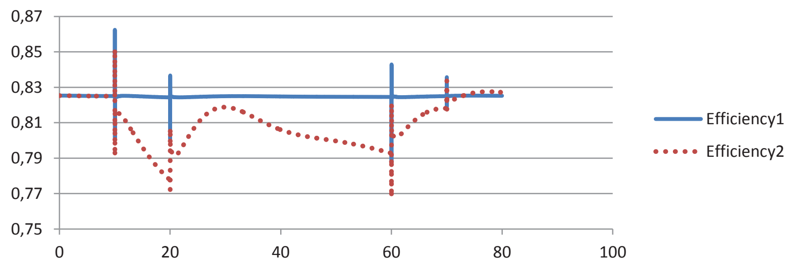
At various perturbations conflicting results were obtained, requiring thus multi-criteria optimization:



Pic. 3. Material components of currents I_3 reall3 and I_1 reall1; time – in seconds, current – in relative units.



Pic. 4. The voltage under load in stabilization of the generator's voltage Vload1 and without stabilization of the generator's voltage Vload2; time – in seconds, voltage – in relative units.



Pic. 5. The efficiency of the wind power installation in stabilization of the generator's voltage Efficiency1 and without stabilization of the generator's voltage Efficiency2; time – in seconds.

$$\min_{K_{dp},T_{w2}}\{t_{fw}(k_{dp},T_{2w}),t_{fe}(k_{dp},T_{2w})\}\,. \qquad (12)$$

We have used an approach [6], in which one of the criterion function is left as a target, and the other criterion is restricted, for example $t_{fe} < 25$. We get a constrained optimization task with a single criterion:

$$t_{fw}(k_{dp},T_{2w})\to\min\,,\; t_{fw}(k_{dp},T_{2w})\le 25\,. \qquad (13)$$

The solution of this task: $k_{dp}^{*}=0,185$, $T_{2w}^{*}=5,031$, $t_{fe}=8,567$ sec.

The parameter selection method is illustrated in Pic.2.

Features under movable load

It is assumed that the load appears on the 10th second from the start of simulation, after which it is removed from the wind power station and changes on 20th and 60th seconds. On the 70th second load becomes zero. In case of load movement inductive reactance of the power line increases. On the 60th second load goes to the recovery mode and stops on the 70th second.

Pic. 3 shows time variation of material components of the current I_3 in the line connecting wind power station to the power grid, and the current of the generator I_1. The material component of generator current is almost unchanged throughout the simulation period as a result of the rotation controller. In the range from 0 to 10 sec realI_3 is negative, that in accordance with the direction selected in Pic. 1 indicates the transfer of all generated power to the grid. When switching on the load, realI_3 becomes positive. The power, supplied from the grid, is added to the generator's power and goes to the load. When the load power reduces, realI3 becomes a little bit positive, because the load is almost entirely powered by the generator of the wind power station. After transition of the load in the recovery mode regenerative power returns to the grid, summed with asynchronous generator's power.

Pic. 4 shows change in voltage under load versus time (and hence the distance from the reference position). As the distance from the starting position increases, there is a growth in inductive resistance of the line and increase in the reactive component of the current at a constant power load. The maximum voltage drop reaches 9% of the original level, which may adversely affect the operation of the load equipment. At acceleration stage it reaches 5%. In order to reduce this undesirable effect voltage stabilization on the asynchronous generator has been introduced.

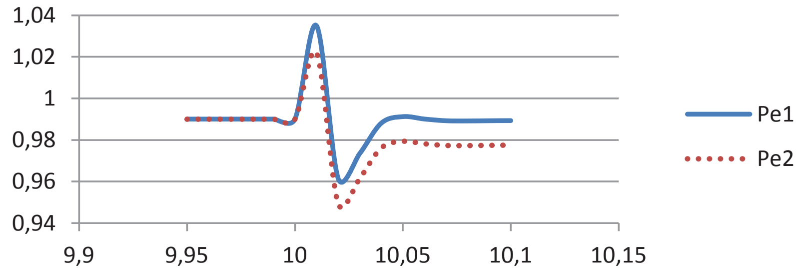
Voltage stabilization was achieved by changing conductivity of the shunt capacitance Y_c in the voltage deviation function at the output of the generator from the set point. The equation of static voltage regulator has a form

$$\frac{dY_C}{dt}=\frac{k_V\left(V_0-V\right)-Y_C+Y_C^0}{T_V}, \qquad (14)$$

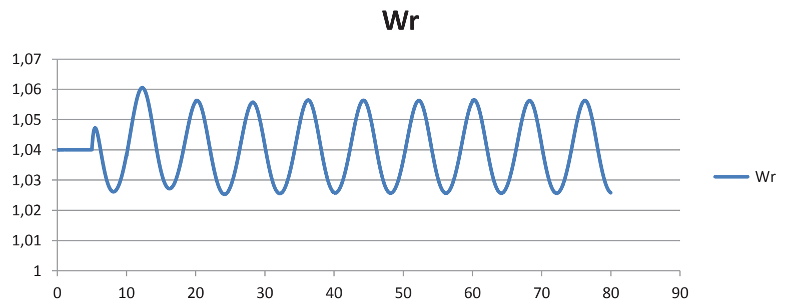
where Y_c^0 is nominal conductivity, V is voltage at the generator's output, V_0 is voltage set point, k_V, T_V are parameters of the controller.

As shown in Pic. 4, the maximum voltage drop is less than 6%, voltage drop on the acceleration segment was less than 2,5%.

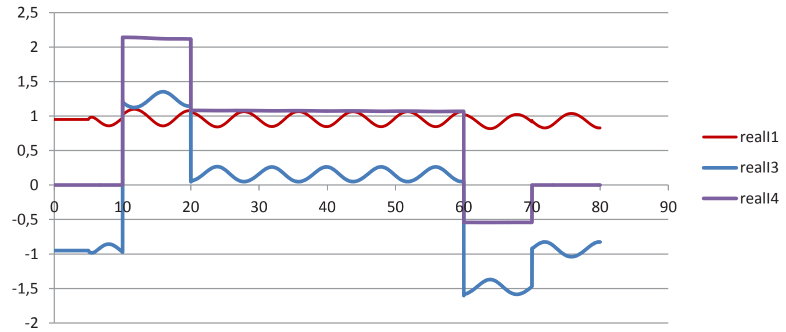
Pic. 5 shows that voltage stabilization increases efficiency of the wind power station in the mode of power supply load. Without stabilization efficiency becomes at the end of disperse phase of at least 78%, with stabilization – not less than 82.5%.



Pic. 6. The electric power of the generator in case of generator's voltage stabilization Pe1 and without stabilization of the generator's voltage Pe2; capacity – in relative units, time – in seconds.



Pic. 7. The relative rotation frequency of the generator, time – in seconds.



Pic. 8. Material components of the generator's current reall1, grid current reall3, load current reall4; time – in seconds.

Note that vertical bars on the graph of efficiency are conditioned by rapid transients of electrical power, see Pic. 6.

During operation of wind power installations it is necessary to take into account volatility of wind load of the air turbine represented in modeling by single-frequency harmonic oscillation of wind power. As a result of disturbance fluctuations of rotation frequency of the generator occur, shown in Pic. 7. Deviation of sliding from the nominal value of 0,04 does not exceed 0,02.

Wind power fluctuations cause fluctuations of currents of the generator and the power system (Pic. 8). These fluctuations are in antiphase. Therefore, the load current does not suffer fluctuations.

Conclusion. *The developed mathematical model of the wind power station with a load variable in time and space allows to select the parameters of control systems of rotor resistance and the angle of rotation of air turbine blades in order to maintain the desired rotation frequency. With the help of mathematical calculations such characteristics of the system are defined as efficiency, the greatest decrease in voltage under load movement, rotation frequency deviation under wind power fluctuations.*

The simulation results confirm feasibility of automatic voltage regulation on power bus lines. The greatest voltage drop under load decreases and efficiency of a wind power installation increases. With modern data transmission features voltage stabilization is possible directly on the load during its movement. Such options are noteworthy as introduction of the load current into the law of voltage regulation, and controlled longitudinal compensation of inductive resistance of the line from the power station to the load.

The advantages of the supply circuit «power system – wind power station – load» are shown, which provides stable load current and small generator rotation frequency deviations in wind power fluctuations. At the same time peak loads are removed due to power of the power system, and in case of no load or its transition to recovery mode power from the wind power station and from load is transmitted to the power system.

REFERENCES

1. Wind Power in Power Systems. Ed. by Thomas Ackermann. Royal Institute of Technology Stockholm, Sweden John Wiley & Sons, Ltd, 2005, 691 p.

2. Stiebler, M. Wind Energy Systems for Electric Power Generation. Springer-Verlag, Berlin, 2008, 293 p.

3. Miller, N. W., Price, W. W., Sanchez-Gasca, J. J. Dynamic Modeling of GE1.5 and 3.6 Wind TurbineGenerators. Version 3.0. GE-Power Systems Energy Consulting, 2003, pp. 1977–1983.

4. Miller, N. W., Price, W. W., Sanchez-Gasca, J. J. Modeling of GE Wind Turbine-Generators for Grid Studies (Version 3.4b); GE Energy, 2005, 67 p.

5. Akhmatov, V. V. Induction Generators for Wind Power. Multi-Science Publishing Company, Ltd., 2007, 258 p.

6. Sytov, E. S. A dynamic model of wind power station. Abstracts of X-th international scientific-practical conference of students and young scientists «Trans-Mech-Art-Chem» [*Dinamicheskaja model' vetroelektrostancii. Tezisy X-j mezhdunarodnoj nauchno-prakt. konferencii studentov i molodyh uchenyh «Trans-Mech-Art-Chem»*]. Moscow, MIIT publ., 2014, pp. 192–193.

Information about the authors:
Epshtein, Georgy L. – Ph.D. (Eng.), associate professor of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, egl413@gmail.com.
Sytov, Evgeny S. – Ph.D. student at the department of Applied Mathematics-1 of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, eusytov@gmail.com.

Article received 29.02.2016, accepted 21.04.2016.