Tuning the Regulators of Wind-Diesel Power Plant Operating on the DC-bus

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Abstract**—*The present work focuses on the development of control systems of wind-diesel power plant with DC-bus, which provide generation static stability for a given operation conditions. The article describes the operating modes of generating units and conversion devices, by which the maximum power output and static stability of the wind-diesel system are realized. Independent controllers setting for each generation source is proposed, making possible a modular extension of the hybrid power plant. The controllers are tuned for wind and diesel generation sources. Two optimization methods are used: linear and modular. By quality indicators analysis of the transients and logarithmic frequency responses the optimal structure and parameters of the regulators are selected. The regulators developed are implemented and used for existing power equipment. The control systems test experimental data obtained confirm the adequacy, reliability and performance of the developed solutions.*

Keywords-wind-diesel power plant; parallel operation; static stability; control system; regulator.

I. INTRODUCTION

Nowadays, autonomous power supply systems, built on the basis of wind-diesel power plants are widespread. That leads to need for the researches related to the optimization of structure and parameters, control and regulation of various operating modes of power equipment [1].

Given the location of the object of autonomous power supply, rated capacity, wind power resources and the graphs of electrical loads of consumers, the way of coupling of diesel and wind power installations through converters on the DC-bus is preferable [2]. The power conversion is followed by inversion to form output voltage and current.

Autonomous power supply systems, created on the basis of renewable energy power installations, are quite complex technical systems, consisting of a series of interconnected heterogeneous objects, characterized by non-linear characteristics and stochastic character of physical processes in them.

Provided the structural stability of the system, it tends to establish a mode if the certain operation conditions are formed. However, DC-bus parallel operation of wind and diesel power plants requires additional research on the static stability of the operating mode. The subject of this article is tuning the regulators of wind-diesel power plant and investigating its dynamical characteristics.

II. OPERATING MODES OF POWER EQUIPMENT

To ensure the static stability it is necessary to stabilize the voltage on the DC bus using diesel power plant or energy storage in the discharge mode. Wind power plant is considered to be appropriately connected to the DC-bus as a controlled current source [2].

One of the most difficult tasks in assessing the stability of autonomous power supply systems for decentralized consumers is to optimize the regulation loops of wind-diesel power plants due to the complexity of mathematical description. Moreover the control systems are described by nonlinear differential equations of higher order [3].

Taking into account the complexity of the mathematical description of the physical processes occurring in the system “diesel engine – synchronous generator – load” the diesel engine and the synchronous generator are considered to be represented by two aperiodic units in the block diagram. This assumption does not violate the general physical meaning and corresponds to the assigned tasks.

The circuit of wind-diesel power plant operating on a common DC-bus is depicted in Fig. 1.

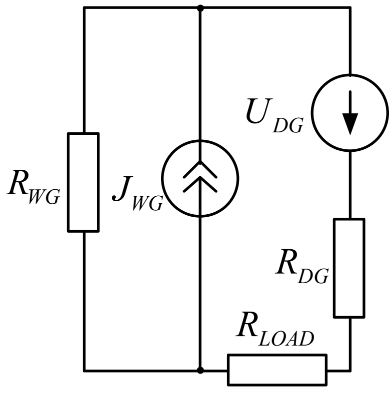

Figure 1. Wind-diesel power plant circuit

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The wind generator possesses the properties of the current source J_{WG} with its total resistance R_{WG} connected in parallel to it. The diesel generator with its internal resistance R_{DG} provides the constant value of voltage U_{DG} on the DC-bus connected to the load R_{LOAD}. Both wind generator and diesel generator have their own control systems tuned by appropriate way.

The way of tuning is defined by the requirements to meet the originally specified quality indicators. The main quality indicators are steady-state value of output and transient response time. The first indicator defines the control error, the second – system's performance.

III. DEVELOPMENT OF CONTROL SYSTEM FOR DIESEL POWER PLANT

For the development of automatic control system for diesel power plant the data from experiments conducted on laboratory equipment is used. Diesel power plant block diagram is shown in Fig. 2. The initial settings of the system allow to get the voltage value on the DC-bus of only 407,5 V instead of required 600 V.

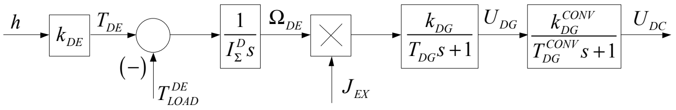

Figure 2. Block diagram of the diesel power plant

Transfer functions of the block diagram depicted in Fig. 2 and their parameters are: k_{DE} is the transfer coefficient of diesel engine, h – fuel supply value, T_{DE} – output torque on the diesel engine shaft, T^{DE}_{LOAD} – load torque applied to the shaft; $W^{DE}_{MECH}(s)=\frac{1}{I^D_\Sigma s}$ – transfer function of diesel engine mechanical system, where I^D_Σ – total moment of inertia; Ω_{DE} – angular rotation frequency of the diesel engine's shaft, J_{EX} – excitation current of the generator; $W_{DG}(s)=\frac{k_{DG}}{T_{DG}s+1}$ – transfer function of the generator, where k_{DG} – transfer coefficient of the generator, T_{DG} – time constant, taking into account inductivity and active resistance of generator's windings; U_{DG} – output voltage of diesel generator; $W^{CONV}_{DG}(s)=\frac{k^{CONV}_{DG}}{T^{CONV}_{DG}s+1}$ – transfer function of the generator's converter, where k^{CONV}_{DG} – transfer coefficient of the generator's converter, T^{CONV}_{DG} – time constant, taking into account the electromagnetic inertia of converter's elements; U_{DC} – voltage on the DC-bus.

Taking into consideration the standard diesel power plant speed control, assume that the angular rotation frequency Ω_{DE} of the diesel engine is constant. Synchronous generator excitation current J_{EX} of diesel power plant regulates the output voltage of diesel generator U_{DG} which is converted into the voltage on the DC-bus U_{DC}. Therefore the control system must be developed to maintain the voltage on the DC-bus within the prescribed limits. Block diagram of the voltage loop with regulator is shown in Fig. 3.

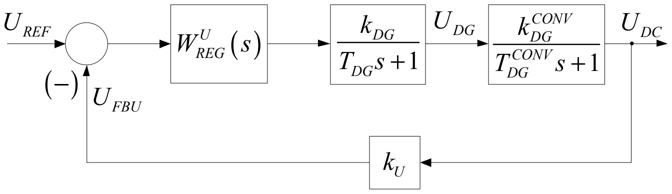

Figure 3. Block diagram of the diesel power plant voltage loop

In control theory there are three ways to optimize control loops: linear, modular and symmetrical optimums developed by Kessler [4]. During the process of regulators tuning the control system is supposed to be linear with zero initial conditions.

Choice of the desired open loop transfer function is determined by the requirements demanded to the control system, namely the response speed of control loop and accuracy.

Consider the tuning of the system on linear and modular optimums. The desired open loop transfer functions are defined by the next expressions:

$$W^{LO}_{DES}(s)=\frac{1}{4\cdot T_\mu\cdot s\cdot\left(T_\mu\cdot s+1\right)}, \tag{1}$$

$$W^{MO}_{DES}(s)=\frac{1}{2\cdot T_\mu\cdot s\cdot\left(T_\mu\cdot s+1\right)}, \tag{2}$$

where T_μ – small uncompensated time constant. In the case under consideration $T_\mu = T^{CONV}_{DG}$.

According to (1) and (2) the next transfer functions of output voltage regulators of diesel power plant were derived:

$$W^{LO}_{REGU}(s)=\frac{1}{4\cdot T^{CONV}_{DG}\cdot k^{CONV}_{DG}\cdot s}=\frac{k^{LO}_{REGU}}{s}, \tag{3}$$

where $k^{LO}_{REGU}=\frac{1}{4\cdot T^{CONV}_{DG}\cdot K^{CONV}_{DG}}$,

$$W^{MO}_{REGU}(s)=\frac{1}{2\cdot T^{CONV}_{DG}\cdot k^{CONV}_{DG}\cdot s}=\frac{k^{MO}_{REGU}}{s}, \tag{4}$$

where $k^{MO}_{REGJ}=\frac{1}{2\cdot T^{CONV}_{DG}\cdot K^{CONV}_{DG}}$,

T^{CONV}_{DG} is the time constant of diesel generator's converter, K^{CONV}_{DG} – its transfer coefficient, k^{LO}_{REGU}, k^{MO}_{REGU} – voltage regulator's transfer coefficients when the current loop is tuned on linear and modular optimums respectively.

In the process of study the transient responses, logarithmic frequency characteristics are obtained. The main quality indicators are estimated.

The typical transient response curve for the diesel power plant control system tuned on linear optimum is shown in Fig. 4.

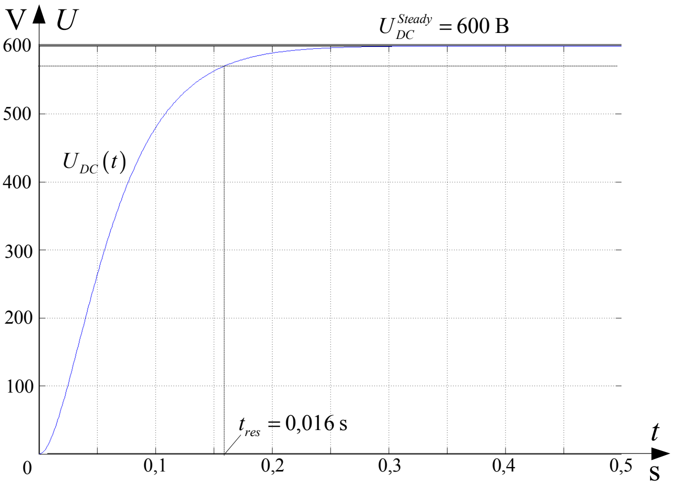

Figure 4. Typical transient response curve for the diesel power plant control system

The results of tuning the regulator of diesel power plant shown in Table 1.

TABLE I. QUALITY INDICATORS OF THE CONTROL SYSTEM OF DIESEL POWER PLANT

Quality indicator	**System investigated**		
	Initial system	***Linear optimum***	***Modular optimum***
Steady-state voltage, V	600	600	600
Transient response time, s	1.5	0.016	0.007
The first peak time, s	-	-	0.011
Rise time, s	-	-	0.008
Overshooting, %	-	-	4.3
Modulus bandwidth, rad/s	1.98	192	415
Phase bandwidth, rad/s	34.4	300	423
Phase stability margin, deg	-	76.3	65.5
Transfer coefficient of regulator	-	74.85	149.7

Analyzing the optimization methods the modular optimum should be used if high response speed in necessary, whereas the linear optimum is the smooth response in needed without overshooting. Both optimums provide allowable control error, quite high stability phase margin and relatively high response speed.

IV. DEVELOPMENT OF CONTROL SYSTEM FOR WIND POWER PLANT

Wind power plant is complicated enough to control because of stochastic change in wind speed. So to control the operating modes of wind power plant it is proposed to regulate the electrical load [5].

According to the power balance on the DC-bus, the current supplied by wind power plant can be regulated via power converter of the wind generator. To develop automatic control system for wind power plant the calculation data of the wind turbine Abatec-2000 and the experimental data on the synchronous generator with permanent magnets are used.

Initial block diagram of the wind power plant is shown in Fig. 5.

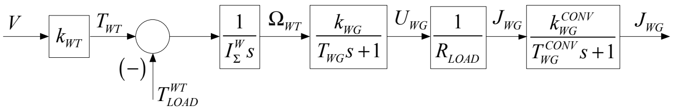

Figure 5. Block diagram of the wind power plant

Transfer functions of the block diagram depicted in Fig. 5 and their parameters are: k_{WT} is the transfer coefficient of wind turbine, V – velocity of wind, T_{WT} – output torque on the wind turbine shaft, T_{LOAD}^{WT} – load torque applied to the shaft; $W_{MECH}^{WT}(s) = \frac{1}{I_\Sigma^W s}$ – transfer function of wind turbine mechanical system, where I_Σ^W – total moment of inertia; Ω_{WT} – angular rotation frequency of the wind turbine's shaft, U_{WG} – output voltage of the generator; $W_{WG}(s) = \frac{k_{WG}}{T_{WG}s+1}$ – transfer function of the generator, where k_{WG} – transfer coefficient of the generator, T_{WG} – time constant, taking into account inductivity and active resistance of generator's windings; U_{WG} – output voltage of wind generator; $W_{WG}(s) = \frac{k_{WG}^{CONV}}{T_{WG}^{CONV}s+1}$ – transfer function of the generator's converter, where k_{WG}^{CONV} – transfer coefficient of the generator's converter, T_{WG}^{CONV} – time constant, taking into account the electromagnetic inertia of converter's elements; J_{WG} – output current of wind power plant.

Block diagram of the current loop of the wind power plant is shown in Fig. 6.

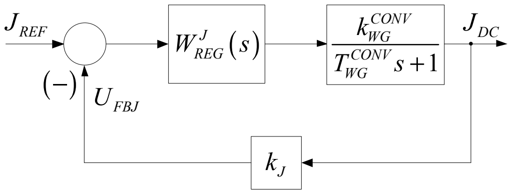

Figure 6. Block diagram of the wind power plant current loop

For linear and modular optimums in accordance with (1) and (2) the transfer functions of corresponding regulators are defined respectively:

$$W_{REGJ}^{LO}\left(s\right)=\frac{1}{4\cdot T_{WG}^{CONV}\cdot k_{WG}^{CONV}\cdot s}=\frac{k_{REGJ}^{LO}}{s}, \qquad (5)$$

where $k_{REGJ}^{LO}=\frac{1}{4\cdot T_{WG}^{CONV}\cdot K_{WG}^{CONV}}$,

$$W_{REGJ}^{MO}\left(s\right)=\frac{1}{2\cdot T_{WG}^{CONV}\cdot k_{WG}^{CONV}\cdot s}=\frac{k_{REGJ}^{MO}}{s}, \qquad (6)$$

where $k_{REGJ}^{MO}=\frac{1}{2\cdot T_{WG}^{CONV}\cdot K_{WG}^{CONV}}$,

T_{WG}^{CONV} is the time constant of wind generator's converter, K_{WG}^{CONV} – its transfer coefficient, k_{REGJ}^{LO}, k_{REGJ}^{MO} – current regulator's transfer coefficients when the current loop is tuned on linear and modular optimums respectively.

The results of numerical experiments using the model developed for tuning controllers are summarized in Table 2.

TABLE II. QUALITY INDICATORS OF THE CONTROL SYSTEM OF WIND POWER PLANT

Quality indicator	System investigated		
	Initial system	***Linear optimum***	***Modular optimum***
Steady-state value, A	3.873	4.74	4.74
Reference current, A	4.74	4.74	4.74
Control error, A	0.867	0	0
Control error, %	18.29	0	0
Transient response time, s	0.005	0.016	0.007
The first peak time, s	-	-	0.0105
Rise time, s	-	-	0.00787
Overshooting, %	-	-	4.32
Modulus bandwidth, rad/s	598	191	423
Phase bandwidth, rad/s	-	299	423
Phase margin, deg	-	76.3	65.5
Transfer coefficient of regulator	-	183.23	366.46

Analyzing the data obtained (Table 2) the tuning of wind power plant control loop on both optimums ensures accurate output current corresponding to the reference one and relatively high response speed, which is, however, slightly different from the performance of initial open loop system.

V. EXPERIMENTAL STUDY

To confirm the developed solutions a series of experiments of wind-diesel power plants operation on a common DC bus are carried out. For diesel generator the three-phase bridge rectifier is used. Stabilization of the output voltage is provided by voltage regulator tuned on modular optimum developed. For wind generator the controlled rectifier is used. The current loop is also tuned on the modular optimum.

Fig. 7 and 8 show the oscillograms of currents and voltage on DC-bus respectively for operating modes of the system under varying load power and quite small change in wind generator output power.

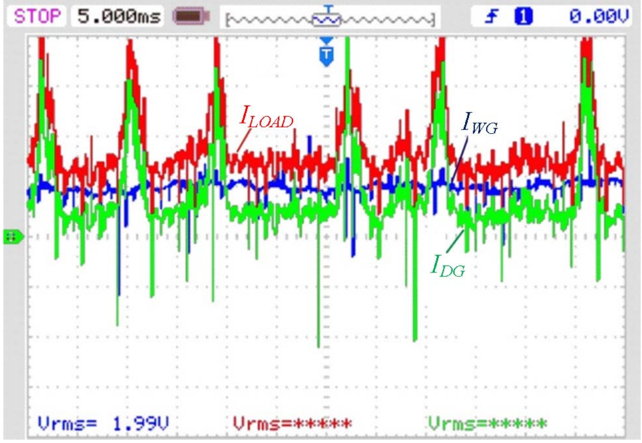

Figure 7. Current oscillograms on the DC bus

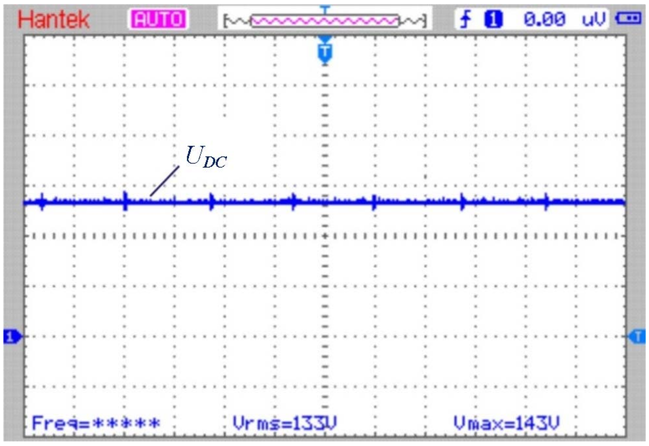

Figure 8. Voltage oscillogram on the DC bus

In the mode investigated, the load power is changed and the power generated by wind generator varies slightly. That is due to some restriction of the wind power plant physical model use, which is implemented by electromechanical couple – "DC motor – synchronous generator with permanent magnets" (Fig. 9).

Figure 9. Physical model of wind power plant

Electric load power variation occurs within the range from 0.5 to 2.0 kW, and the power variation in the wind turbine is within 0.5 kW. Waveforms of the currents (Fig. 7) show that when the output power of wind generator is changed, the output current of diesel generator is varying to provide the current balance on the DC-bus.

The inertia of the control loops is mainly due to electromagnetic and electromechanical time constants of the synchronous generator and diesel engine. That leads to the fact that the power generated on DC-bus has a pulsating character. According to the voltage waveform on the DC-bus demonstrated in Fig. 8 the system provides almost complete damping of power oscillations.

VI. DEVELOPMENT PROSPECTS

As has been previously mentioned, the main goal of this work is to tune the regulators of wind-diesel power plant and to investigate the plant's dynamical characteristics. This work can be divided into three stages.

The first stage is creating the models of diesel and wind power plants with regulators separately, their consolidation into one wind-diesel power plant and investigating the performance of the system developed. The result of this stage is to obtain the parameters for the regulators of voltage and current which maintain appropriate voltage and current on the DC-bus.

The second stage is to confirm the developed solutions by experiments on physical models based on electromechanical couple "DC motor – synchronous generator with permanent magnets" and diesel-generator. The power equipment mentioned is installed in laboratory of Institute of Power Engineering of National Research Tomsk Polytechnic University.

During the third stage the modifying of both numerical and physical models of wind-diesel power plant will be performed. As a result of the third stage the clarification of regulators' parameters is planned in order to tune the regulators of the real wind-diesel power plant which is installed and used in the laboratory.

VII. CONCLUSION

Tuning the regulators of wind-diesel power plant was carried out according to control theory.

The circuit topology of the developed system (Fig. 1) provides the ability to operate both wind and diesel power plants on a common DC-bus.

Durations of transient responses in both cases are the same for a given optimum. This is due to identity of power converters' parameters. Consequently, it is necessary to adjust both wind power plant control loop and diesel one on the same optimum. Total load current is directly dependent on the load. If the wind generator's output power is low, this is compensated by the diesel generator, providing the constant load current.

As a result of a series of experiments performed it is found that for all operating modes of collaborative operation of wind and diesel power plants on a common DC-bus the voltage variation does not exceed 5 V (less than 1%). That provides the inverter by high quality voltage.

The control systems for parallel operation of diesel and wind power plants developed allow to provide the static stability in the process of control. At constant controllers' settings the quality indicators are quite acceptable.

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