Technique of a Wind-diesel Power System Formation for a Stand-alone Consumer Using a Cost-efficiency Criterion: Systems Approach

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***Abstract*—The paper is devoted to developing a technique of a hybrid Wind-Diesel Power System (WDPS) formation for a stand-alone Power Consumer (PC) that takes into account the functional, economic, operational and environmental performance indicators. The technique creates a model for the system operation by modeling the wind as a correlated random process using the Monte Carlo method and using an economic (cost) model for the purchase, deployment, maintenance, and operation of the system, including possible state financial incentives, and recycling the excess power generated by a Wind turbine Generator (WG). The basic characteristics of the WDPS that are selected at the phase of its formation are the installed power of the WG, the storage battery capacity, the installed power of the diesel generator, the coefficient of the storage battery recharge level and the diesel generator switch on/off commands forming algorithm. As an example, we consider a WDPS formation for a PC located in the Dikson settlement in Krasnoyarsk Krai, Russian Federation. To calculate the unit cost of 1 (kWh) of power using WDPS, a general model was developed consisting of Monte-Carlo simulation functional and empirical economic models, as well as a computer program implementing these models. The calculation results show that the WDPS deployment project is economically competitive only if state financial support is received and an auxiliary system for recycling excess power generated by the WG is used. The practical application of the developed methodology as a decision support system in the renewable energy industry is discussed.**

***Index Terms*—wind-diesel power system, stand-alone consumer, wind turbine generator, functional model, cost model, renewable energy**

I. Introduction

Hybrid WDPSs for stand-alone PCs that are discussed in this article are one of the applications of renewable energy systems. In a system like that a traditional Diesel Power System (DPS) is supplemented by a Wind Power System (WPS). WDPS is especially relevant for providing power supply to consumers without access to an electrical grid. Private households, small airports, relay stations, satellite receivers and other PCs that are located in the remote regions is just a sample of consumers for this technology. The use of a WDPS provides a partial replacement of the power generated by a Diesel Generator (DG) with renewable wind power from a wind turbine generator (WG). A WDPS can be developed for PC as a new system or as a modernization of an existing DPS.

There are multiple reasons that hinder wider use of the WDPSs [1, 2]. Those reasons include significant costs for delivery and deployment of WPS components, complexities of service maintenance of the WDPS operating in remote areas and in difficult meteorological conditions, etc. [3]. We believe that one of the main deterrent factors to wider WDPS acceptance is the lack of a WDPS design methodology that uses widely available components and provides a convincing evidence of the resulting system effectiveness with respect to its functional, economic, operational and environmental characteristics. Many factors [4, 5] influence those indicators: projected power needs of a customer, wind characteristics at the place of system operation, functional characteristics of the WDPS components, the costs of deploying and maintaining the system, possible financial state incentives for the WDPS project [6], a method for recycling the excess power generated by a WG during prolonged periods of strong winds, etc.

Among the listed factors, predicting functional indicators is particularly methodically difficult [7], because WDPS is a nonlinear dynamic system and wind is essentially non-Gaussian and strongly correlated in time random process. Practically the only way to assess the functional performance indicators of a WDPS is a system simulation approach [7, 8].

Recently, the deployment of wind farms, including both offshore and onshore, has been widely discussed [9, 10]. One of the interesting research questions is to take into account the influence of the spatio-temporal correlation of wind speed in the area of the wind farm location on the efficiency indicators of the power system [11, 12]. It should also be noted that offshore wind turbines require additional costs for deployment and maintenance [13]. Systems of this type are not considered in this article.

The aim of this paper is to develop a technique of a WDPS formation for providing power to a stand-alone consumer by modeling WDPS as a nonlinear stochastic

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dynamic system and taking into account its functional, economic, operational and environmental performance indicators.

The technique proposed in the paper is based on the key principles of system analysis, namely: system decomposition, creation of a functional flowchart, determination of key performance indicators, development of adequate models for evaluation indicators, formation of a preference criterion, solving an optimization problem as a nonlinear programming problem, formulation of recommendations.

The application of the technique is demonstrated by an example of a WDPS formation for use in the settlement of Dikson, located in the northern part of the Krasnoyarsk Krai of the Russian Federation. The input data for the example is presented in Appendix A. The technique can serve as a basic component of the Decision Support System (DSS) adopted by companies engaged in the development or sale of WDPS to consumers who plan to modernize the existing DPS by supplementing it with a WPS or develop a new WDPS.

The rest of the paper is structured as follows. Section II presents the functional block diagram of the WDPS with a description of its subsystems and functional interactions between them. The WDPS performance indicators are formulated in Section III. The functional model of the system with a list of simplifying assumptions and a mathematical description of subsystem's models is presented in Section IV. Section V describes the economic model of the WDPS. Section VI presents the results of solving the WDPS analysis and formation problems for a specific example. Section VII concludes the paper by listing the main results of the work.

II. Functional Block Diagram of the WDPS

The WDPS consists of a wind power and diesel power subsystems, with the power sources being a WG and a DG respectively, see Fig. 1. Nomenclature is presented in Appendix B. In addition, the WDPS includes: an energy storage device - a Storage Battery (SB), a controller that controls the operation of the system, an inverter that converts the direct current generated by the WG or extracted from the SB, into alternating current for the PC active loads. Often the controller and inverter are combined into a joint subsystem called as a Controller-Inverter (CI). The power P^*_{PC}, demanded by the PC active loads is the main control input of the WDPS, the power P_{PC}, received by the PC is the main output of the system. In addition, a wind speed and amount of a Diesel Fuel (DF) are inputs from the Wind Model (WM) and Diesel Fuel Storage System (DFSS), respectively. The excess power generated by the WG and entering the Energy Recycling System (ERS) is additional output of the WDPS.

With a random wind and a limited SB capacity, there could be time periods when the power $P_{WG}(t)$ generated by the WG is less than the power $P^*_{PC}(t)$, requested by the PC active load, i.e. $\Delta P_{WS}(t) = \left(P_{WG}(t) - P^*_{PC}(t)\right) \le 0$, and the SB is drained to the minimum level $Q_{SB,\,min}$. In such a situation, a control command to switch on the DG $u_{DG}(t) = 1$ is formed.

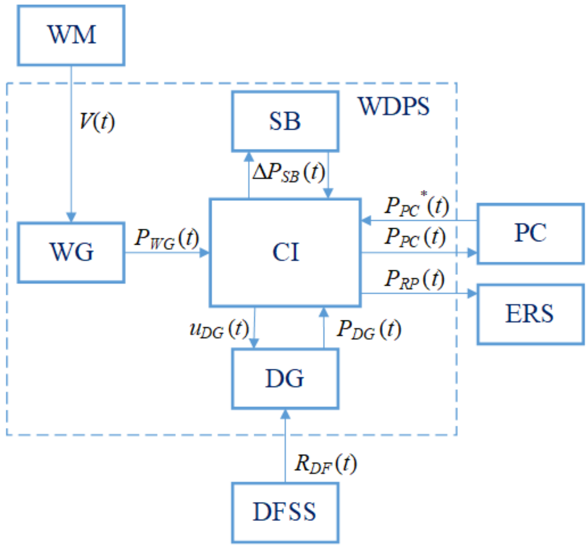

Figure 1. Functional block diagram of the WDPS for a stand-alone consumer.

Alternatively, situations are possible when $P_{WG}(t) = P^*_{PC}$, the SB is fully charged, and an excess of power occurs, then $P_{RP} = \Delta P_{WS}$. To improve the economic efficiency of the system, excess power can be recycled somehow, for example, it could be used in the PC's hot water supply or heating systems.

At the phase of the WDPS formation, the following basic characteristics are selected: the installed power of the WG $\tilde{P}_{WG}$, the SB capacity Q_{SB}, the installed power of the DG $\tilde{P}_{DG}$, the coefficient of the SB recharge level K_{LR}, the DG switch on/off commands forming algorithm u_{DG}.

III. Performance Indicators of the WDPS

At the early design phase of the WDPS for stand-alone PC, various indicators of its performance should be considered. The key ones are functional, economic, operational, and environmental indicators.

The main functional indicator is the total energy E_{PC} received by the PC during the system's lifetime T.

As an economic indicator it makes sense to consider a predicted relative unit cost of 1 (kW h) delivered to the consumer by the WDPS relative to the unit cost when only the DPS is used: $\bar{c}_{WDPS} = c_{WDPS} \cdot c^{-1}_{DPS}$.

Ecological indicator is the power substitution coefficient which is a ratio of the energy provided to the consumer by WPS $E_{WPS,PC}$ during the lifetime T relative to the total energy E_{PC} provided to the consumer during the same period, i.e. $K_{PS} = E_{WPS,PC} \cdot E^{-1}_{PC}$.

Operational indicators are an average monthly frequency of the DG switching-on n_{DG} and an energy recycling coefficient $K_{RP} = E_{WPS,RP} \cdot E^{-1}_{WPS}$, which is a ratio of the total recycled energy to the total energy generated by the WG during the lifetime T.

The indicators K_{PS}, n_{DG} and K_{RP} are estimated using the functional model of the WDPS. A simplified WDPS economic model is proposed for predicting $\bar{c}_{WDPS}$. Indicators c_{DPS} and c_{WDPS} are calculated using both functional and economic models of the WDPS.

IV. THE FUNCTIONAL MODEL OF THE WDPS

The WDPS functional model is developed under the following simplifying assumptions:

- the total power of active PC loads is constant in time, i.e. $P_{PC}^{*}(t) = \text{const}$;
- seasonal variations of wind speed characteristics are not considered, i.e., wind speed is assumed to be a stationary random process;
- the inertia of the WG as a dynamic system is not taken into account, i.e. it is assumed that the power $P_{WG}(t)$ depends on the wind speed $V(t)$ at the current time t and is described by the WG operating characteristic $P_{WG}(V)$;
- the excess power of the WG $P_{RP}(t_i)$ is completely recycled;
- energy losses during its storing in a SB and inversion are negligible;
- the switched-on DG generates the installed power, i.e. $P_{DG}(t) = \tilde{P}_{DG} = \text{const}$.

The WDPS is a closed-loop control system consisting of the following subsystems:

- power sensors, namely: power demanded by the PC $P_{PC}^{*}(t)$, generated by WG $P_{WG}(t)$ and by DG $P_{DG}(t)$, and current SB charge $Q_{SB}(t)$;
- controller that provides commands for switching the DG on/off $u_{DG}(t)$, as well as commands for redirecting power flows between the subsystems;
- WG and DG as power generating devices, and a SB as an energy storage device, jointly ensuring fulfillment the requirement $P_{PC}(t) = P_{PC}^{*}(t)$.

Due to the limited capacity of the SB and wind as a random process, the WDPS is a nonlinear stochastic dynamic system. The WDPS performance functional indicators can be estimated with an acceptable accuracy only by a simulation (Monte Carlo) method [14, 15]. The subsystems of the WDPS functional model are described by the following models.

A. Diesel Generator Model

The DG is characterized by its installed power $\tilde{P}_{DG}$, the unit fuel consumption r (L/kW h) and ability of the DG automatic reswitching. To ensure uninterrupted supply of power to PC, it is reasonable to choose the DG installed power $\tilde{P}_{DG}$ to be equal to the maximum "peak" power requested by the PC loads. Under the assumption $P_{PC}^{*}(t) = const$ the equality $P_{DG} = P_{PC}^{*}$ is provided.

B. Wind Model

Two approaches can be employed for simulating wind speed as a random process: the retrospective approach, envisaging use of wind speed data recorded during long-term observations at a ground-based weather station located near the WG deployment [16, 17] and the approach proposed in [15].

The second approach is used in this paper. The wind is considered as a vector stationary random process, consisting of two mutually uncorrelated components $V_k(t),\ k = 1, 2$. Each component is described by mean value m_k, variance $D_k = \sigma_k^2$ and covariance function $R_k(\tau) = \sigma_k^2 \exp(-\alpha_k |\tau|)$ for centered random process $\Delta V_k(t) = V_k(t) - m_k$. Time variations $\Delta V_k(t)$ are described by the first-order shaping filter. The $V(t)$ simulation is described (1) and consists of the following stages: simulation of white noises $\eta_k(t)$, simulation deviations $\Delta V_k(t)$, calculation components $V_k(t)$, calculation wind speed sample $V(t)$:

$$\begin{aligned} &\frac{d\Delta V_k}{dt} = -\alpha_k \Delta V_k + \sqrt{2\alpha_k}\sigma_k \eta_k(t),\ k = 1, 2, \\ &V_k(t) = m_k + \Delta V_k(t), \\ &V(t) = \sqrt{V_1^2(t) + V_2^2(t)}, \end{aligned} \tag{1}$$

where $\alpha_k = T_k^{-1}$; T_k is correlation time of the process $V_k(t)$; $\eta_k(t)$ is white noise with intensity $N_k = 1$.

The parameters of the wind speed model (1) are: m_k, σ_k, T_k. These parameters can be calculated by statistical processing of long-term observations of magnitude and direction of the wind at weather stations for various places in the country [15].

C. Wind Turbine Generator Model

Operating characteristic of the WG is described by the following model [14]:

$$P_{WG}(V) = \begin{cases} 0, \text{ if } 0 \le V < V_{MN},\ V \ge V_{ST}, \\ \tilde{P}_{WG} \cdot \left(\dfrac{V}{V_{RF}}\right)^3, \text{ if } V_{MN} \le V < V_{RF}, \\ \tilde{P}_{WG}, \text{ if } V_{RF} \le V < V_{ST}, \end{cases} \tag{2}$$

where V_{RF} is reference wind speed, at which installed power $\tilde{P}_{WG}$ of the WG was determined; V_{MN} is the "cut-in" (minimal) wind speed, at which wind turbine starts to rotate; V_{ST} is the "cut-off" (storm) wind speed, at which WG must be switched off.

D. Controller

The DG as a part of the WDPS is used to provide the power demanded by PC in periods of time when the power $P_{WG}(t)$ produced by the WG is insufficient and the SB is drained to the allowable depth of discharge, i.e. $Q_{SB}(t) \le Q_{SB,min}$. To reduce the number of DG switching-on n_{DG}, it is reasonable to keep up the operating DG in the state "switched-on" until a certain level of SB recharge $Q_{SB,LR}$ is reached. The output of the controller, implementing such a heuristic algorithm, is a binary function $u_{DG}(t) = 0 \cup 1$, where $u_{DG}(t) = 0$ means that the DG has to be or continues to be in the state "off" and $u_{DG}(t) = 1$ when the DG is or has to be in the state "on".

If the controller is a digital device generating the DG control commands $u_{DG}(t)$ within time intervals $\Delta t = t_{i+1} - t_i$, the command $u_{DG}(t_{i+1})$ is generated depending upon the combination of values $\Delta P(t_i)$, $Q_{SB}(t_i)$ and $u_{DG}(t_i)$ at the time t_i. A command $u_{DG}(t_{i+1}) = 1$, i.e. the DG is or remains to be switched-on, is generated under two situations:

$$\begin{aligned} &\Delta P(t_i) \le 0 \cap Q_{SB}(t_i) \le Q_{SB,min} \cap u_{DG}(t_i) = 0, \\ &\Delta P(t_i) \le 0 \cap Q_{SB}(t_i) < Q_{SB,LR} \cap u_{DG}(t_i) = 1, \end{aligned} \tag{3}$$

where $\Delta P(t_i) = (P_{WG}(t_i) + P_{DG}(t_i)) - P_{PC}^{*}$, $Q_{SB,LR} = K_{LR} Q_{SB}$,

$Q_{SB,\,min}{=}K_{SB,\,min}Q_{SB}$, $K_{SB,\,min}$ and K_{LR} are given coefficients that characterize the SB allowable depth of discharge and the SB recharge level, respectively.

A command $u_{DG}(t_{i+1})=0$ is generated or retained to be in the switched-off state in the following four situations:

$$\begin{aligned}
&\Delta P(t_i)>0\cap Q_{SB,\,min}\le Q_{SB}(t_i)\le Q_{SB,LR}\cap u_{DG}(t_i)=0,\\
&\Delta P(t_i)>0\cap Q_{SB}(t_i)\ge Q_{SB,LR}\cap u_{DG}(t_i)=0,\\
&\Delta P(t_i)\le 0\cap Q_{SB}(t_i)>Q_{SB,\,min}\cap u_{DG}(t_i)=0,\\
&\Delta P(t_i)<0\cap Q_{SB}(t_i)\ge Q_{SB,LR}\cap u_{DG}(t_i)=0.
\end{aligned} \tag{4}$$

E. Storage Battery Model

The charge $Q_{SB}(t)$ of a SB as a dynamic system is described by the differential equation:

$$\frac{dQ_{SB}}{dt}=\begin{cases}\Delta P_{SB}(t),\ \text{if } Q_{SB,\,min}<Q_{SB}(t)<Q_{SB,LR},\\ 0,\ \text{if } Q_{SB}(t)\le Q_{SB,\,min}\cup\ Q_{SB}(t)\ge Q_{SB,LR},\end{cases} \tag{5}$$

where ΔP_{SB} is the power loaded to or drained from the SB.

F. Complete Simulation Model

Mathematically, under the assumptions mentioned above, the functioning of the WDPS described by the equations (1)-(5) is a stationary and ergodic vector random process. The functional, environmental and operational performance indicators are estimated by statistical processing the system state variables obtained by simulating the system operation over a “long” time period T_{SM} with a simulation step Δt .

V. Economic Model of the WDPS

The predicted total cost C_{WDPS} of the WDPS consists of two components:

$$C_{WDPS}=C_{WDPS,PR}+C_{WDPS,AD},$$

where $C_{WDPS,PR}$ is a purchase cost of all system components, including DF, i.e. $C_{WDPS,PR}=C_{DPS,PR}+C_{WPS,PR}$; $C_{WDPS,AD}$ is an additional cost consisting of delivery, deployment, maintenance, insurance, and other overheads during the lifetime T , i.e. $C_{WDPS,AD}=C_{WPS,AD}+C_{DPS,AD}$.

The purchasing cost of the DPS consists of purchasing cost of the DG and the DF:

$$C_{DPS,PR}=C_{DG}+C_{DF},$$

where $C_{DG}=c_{DG}\tilde{P}_{DG}$; $C_{DF}=c_{DF}R_{DF}$; $R_{DF}=rE_{DF}$ is cumulative amount of DF over the lifetime T ; $E_{DF}=\tilde{P}_{DG}T_{DG}$; T_{DG} is the DG cumulative operating time over the lifetime T .

The purchasing cost of the WPS consists of purchasing cost of the WG, the SB and the CI:

$$C_{WPS,PR}=C_{WG}+C_{SB}+C_{CI},$$

where $C_{WG}=c_{WG}\tilde{P}_{WG}$; $C_{SB}=n_{SB}c_{SB}Q_{SB}$; $C_{CI}=c_{CI}\tilde{P}_{CI}$; $n_{SB}=ceil\left(T\cdot T_{SB}^{-1}\right)$ is number of SB sets which have to be replaced during the lifetime T ; T_{SB} is the lifetime of the SB set; c_{WG}, c_{DG}, c_{CI} are unit costs of purchasing a unit of power of WG, DG, CI; c_{SB}, c_{DF} are unit costs of 1 (kW h) of power for the SB and 1 (L) of DF, respectively.

In the simplified WDPS cost model, the additional cost can be assumed as proportional to the purchasing cost of the system, i.e.

$$C_{WDPS,AD}=K_{AD}(C_{WPS,PR}+C_{DPS,PR}).$$

Under the additional assumption that the coefficient K_{AD} for all components of the system can be considered the same, except the DF, for which the delivery cost of 1 (L) of fuel is $C_{DD}{=}K_{AD}{\cdot}T^{-1}$, then $C_{DF,DD}{=}(1{+}C_{DD})C_{DF}$. The total cost of the WDPS is calculated as follows:

$$C_{WDPS}=(1+K_{AD})(C_{WPS,PR}+C_{DG})+C_{DF,DD} \tag{6}$$

The predicted relative unit cost of power that is provided by the WDPS to the PC can be represented by the indicator $\bar{c}_{WDPS}=C_{WDPS}\cdot C_{DPS}^{-1}$.

A. State Financial Incentives

The WDPS would be more attractive to the PC if the unit cost of power provided by the system is commensurate with the power cost provided by the DPS only. The state financial incentives for the project could contribute to the achievement of this goal. For environmental reasons, government may encourage partial replacement of the power generated by the DG with the WG power. One of the options for such stimulation can be state incentives, for example, incentives for purchasing the WPS components: WG, SB and CI. These incentives can be set by the coefficient K_{SP} . With this coefficient, the cost of the WPS purchasing $C_{WPS,PR}$ should be taken into account in calculating the total cost (6) and is calculated using the relation:

$$C_{WPS,SP}=(1-K_{SP})C_{WPS,PR}.$$

B. Excess Energy Recycling

The reduction of the WDPS total cost (6) due to the recycling the excess power can be estimated as $C_{RP}=c_{RP}E_{RP}$, where E_{RP} is cumulative recycled energy over the lifetime T , c_{RP} is unit cost of 1 (kW h) of saved power. The resulting discounted cost model of the WDPS that takes into account the state incentives and energy recycling has a form:

$$C_{WDPS}{=}C_{WPS,SP}{+}C_{WPS,AD}{+}(1{+}K_{AD})C_{DPS,PR}{+}C_{DF,DD}{-}C_{RP}.$$

VI. Numerical Example

The WDPS functional simulation model and empirical economic model presented above as well as computer programs implementing these models can be used to solve the problems of the WDPS analysis and formation. An example of solving these two problems when WDPS is planned to be deployed in the settlement of Dikson, is considered in this section. The input data used in the example is presented in Appendix A. Prices are given in thousands of rubles (t.r.) and are methodological in nature.

A. System Analysis Problem

The sample PC in Dikson has a maximum power requirement of 1 (kW h) that will require $E_{PC}=87660$ (kW h) of total power generated over the system’s lifetime 10 years. To produce this amount of power using only a

DPS, the PC will need 21915 (L) of a DF, i.e. 183 (L) per month.

In the settlement of Dikson a mean value of the wind speed is 6.4 (m/s). A wind speed sample $V(t)$ during a month, simulated using the presented technique, is shown in Fig. 2.

Fig. 3 shows a histogram of the wind speed probability distribution plotted from the simulated sample $V(t)$ over $T_{SM} = 2.5$ years.

The average power generated by a WG with $\tilde{P}_{WG} = 3$ (kW) and operating characteristic (2) under Dikson's weather conditions is 1.04 (kW). The histogram of the power generated by the WG is shown in Fig. 4. Wind power $P_{WG}(t)>0$ is generating 83% of total time. If the capacity of a SB is unlimited, this power is sufficient for uninterrupted power supply to the PC with use a WPS only.

The dependence of the power substitution coefficient $K_{PS}(\tilde{P}_{WG}, Q_{SB})$, estimated for three values of the WG installed power $\tilde{P}_{WG}$, is shown in Fig. 5. This figure also plots DG mean monthly fuel consumption $R_{DFm}(\tilde{P}_{WG}, Q_{SB})$. The WDPS with $\tilde{P}_{WG} = 3$ (kW) and Q_{SB} = 5 (kW ħ) will spent 9957 (L) of DF during the system's lifetime 10 years, i.e. on average 83 (L) monthly. It is 44% of the fuel required when the DPS only is used. As can be seen from the plots (see Fig. 5) even at $\tilde{P}_{WG} = 3$ (kW), the coefficient K_{PS} exceeds 50% under Dikson's conditions. By increasing $\tilde{P}_{WG}$ and Q_{SB}, this coefficient can be increased to 84%. However, as it is shown below, in this case, the unit cost of power increases significantly.

The plots in Fig. 6 show that, firstly, the average monthly frequency of the DG switching-on n_{DG}, as well as the average monthly duration of the DG's switch-on sessions τ_{DG}, significantly depends upon the SB capacity Q_{SB} and the coefficient K_{LR}. At the WDPS formation, it is necessary to determine tradeoff values of the n_{DG}, τ_{DG}, Q_{SB}, K_{LR} parameters. Secondly, from operational considerations, it is preferable to use an automatically switched on/off DG. Calculations show that the DG switching characteristics are weakly dependent on the WG installed power $\tilde{P}_{WG}$. Also, it should be noted that the n_{DG} and τ_{DG} can be estimated using the WDPS simulation model only.

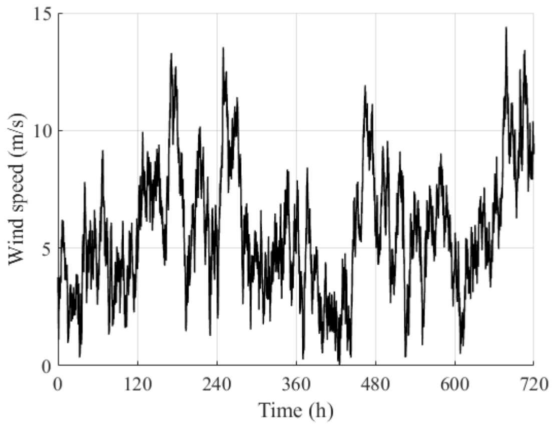

Figure 2. Simulated wind speed sample within a month.

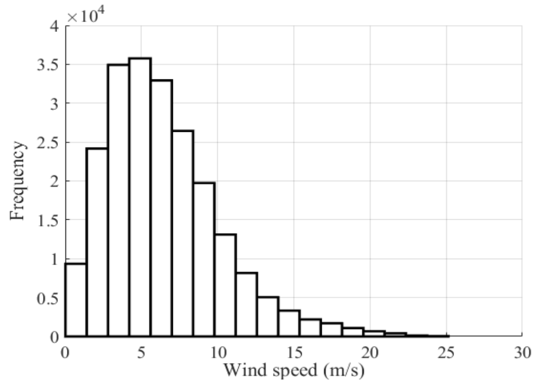

Figure 3. Wind speed histogram.

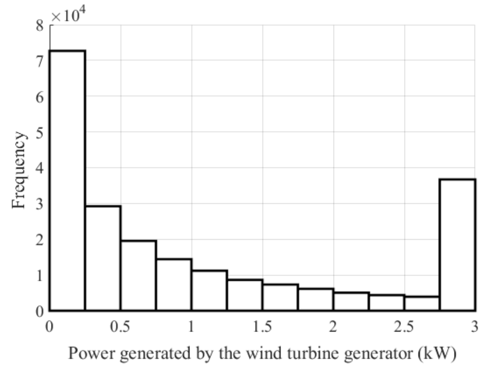

Figure 4. Histogram of power generated by the WG at $\tilde{P}_{WG}$ = 3 (kW).

Reducing the coefficient K_{LR} describing a recharging level of the SB results in reducing the amount of a DF used. For example, at $\tilde{P}_{WG}$ = 3 (kW) and Q_{SB} = 15 (kW ħ), reducing K_{LR} from 0.95 to 0.65 can save about 1000 (L) of DF during the system's lifetime 10 years. However, such savings are accompanied by increasing n_{DG}.

Based on the analysis, it was revealed that the energy recycling coefficient K_{RP} can be increased significantly by increasing $\tilde{P}_{WG}$. For example, if $K_{LR} = 0.9$ and Q_{SB} = 15 (kW ħ), increasing $\tilde{P}_{WG}$ from 3 (kW) to 9 (kW) results in doubling excess energy recycling K_{RP} from 30% to 60%. That additionally indicates the inexpediency of using a WPS with installed power $\tilde{P}_{WG}$ under which the average power generated by a WG exceeds the predicted total power of active PC loads.

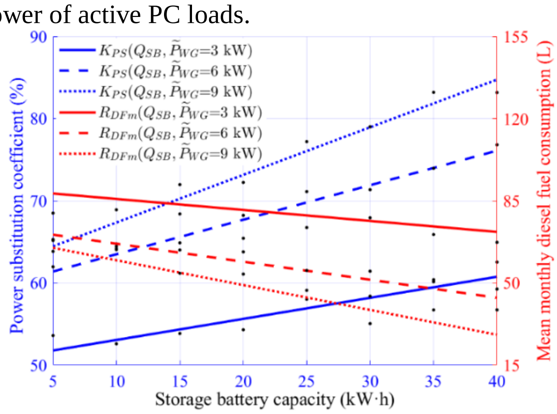

Figure 5. Dependence of the power substitution coefficient $K_{PS}(\tilde{P}_{WG}, Q_{SB})$ and mean monthly fuel consumption of the DG $R_{DFm}(\tilde{P}_{WG}, Q_{SB})$ at $K_{LR} = 0.9$.

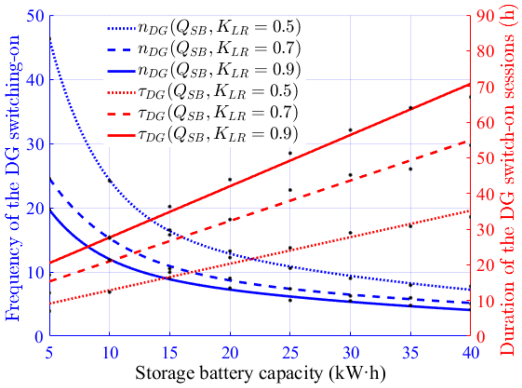

Figure 6. Dependence of the average monthly frequency of DG switching-on $n_{DG}(Q_{SB}, K_{LR})$ and the average duration of the DG switch-on sessions $\tau_{DG}(Q_{SB}, K_{LR})$ at $\tilde{P}_{WG} = 3$ (kW).

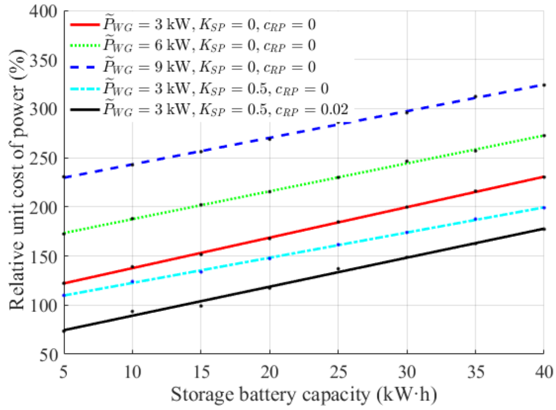

Figure 8. Relative unit costs of power $\bar{c}_{WDPS}(\tilde{P}_{WG}, Q_{SB}, K_{SP}, c_{RP})$ generated by the WDPS at $K_{LR} = 0$.

The contour curves $K_{RP}(Q_{SB}, K_{LR})$ at $\tilde{P}_{WG} = 3$ (kW) are shown in the Fig. 7. From this figure we can conclude that it is reasonable to select the pair Q_{SB}, K_{LR} in the quadrangle highlighted by the dotted lines when the WDPS is formed.

Dependence of the relative unit cost of power on the WG installed power and the SB capacity is demonstrated by the three upper lines in Fig. 8 for a nominal variant of the WDPS, i.e. without state incentives and without the excess energy recycling ($K_{SP} = 0$, $c_{RP} = 0$). As can be seen from the graphs, the relative unit cost of power increases linearly in proportion to $\tilde{P}_{WG}$ and Q_{SB}. For all combinations of $\tilde{P}_{WG}$ and Q_{SB}, the unit cost of power generated by the WDPS exceeds the power unit cost generated by the DPS only. The smallest excess is observed at the minimum considered values of $\tilde{P}_{WG} = 3$ (kW) and $Q_{SB} = 5$ (kW h).

The two lower lines of Fig. 8 characterize the indicator $\bar{c}_{WDPS}$ for $\tilde{P}_{WG} = 3$ (kW) with state incentives ($K_{SP} = 0.5$, $c_{RP} = 0$) and jointly with state incentives and saving cost by the recycling of excess energy ($K_{SP} = 0.5$, $c_{RP} = 0.02$). Plots in the Fig. 8 show that the cost of power provided by the WDPS can be kept at the level of power cost of the DPS only. However, this goal can be attained only with state subsidies and with using an auxiliary subsystem for excess energy recycling.

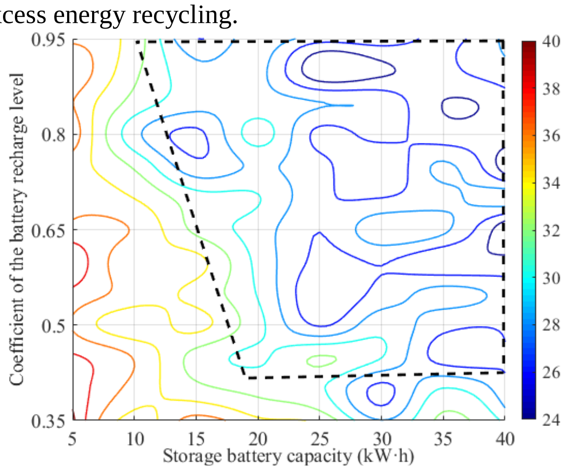

Figure 7. Dependence of the energy recycling coefficient $K_{RP}(K_{LR}, Q_{SB})$ at $\tilde{P}_{WG} = 3$ (kW).

B. System Formation Problem

To determine optimal values for the WDPS parameters at the system formation phase, it is necessary to solve an optimization problem with a vector criterion consisting of the following scalar criteria:

$$\bar{c}_{WDPS} \to \min, \; K_{PS} \to \max, \; K_{RP} \to \min, \; n_{DG} \to \min.$$

Different optimization methods can be used to solve this problem, such as linear convolution method, method of successive concessions and others. All these methods envisage transformation of a vector criterion into some "equivalent" scalar criterion. In the numerical example considered in this paper, a method was used in which the relative unit cost of power $\bar{c}_{WDPS}$ was considered as the single scalar criterion, and the other three criteria were transformed into constraints:

$$K_{PS} \ge \hat{K}_{PS} = 50\%, \; K_{RP} \le \hat{K}_{RP} = 30\%, \; n_{DG} \le \hat{n}_{DG} = 10.$$

The following optimal (reasonable) values of the WDPS parameters were determined:

$$\tilde{P}_{WG} = 3 \text{ (kW)}, \; Q_{SB} = 15 \text{ (kW h)}, \; K_{LR} = 0.9,$$
$$K_{SP} = 0.5, \; c_{RP} = 0.02.$$

With these parameters, the following values of the WDPS performance indicators were attained:

$$\bar{c}_{WDPS} \approx 100\%, \; K_{PS} = 55\%, \; K_{RP} = 29\%,$$
$$n_{DG} = 9, \; \tau_{DG} = 36 \text{ (h)}.$$

The maximum 12 days interval between the DG switching-on sessions was observed, the longest DG switch-on session lasted 120 (h).

VII. Conclusions

The results of the analysis carried out in this work show that when a hybrid WDPS for a stand-alone PC is being formed, it is necessary to consider not only the mean wind speed at the location of the system deployment, but also its random fluctuations in time. The parameters of wind speed variability significantly affect both selection the SB capacity and the fuel amount for the DG to provide the uninterrupted supply of a power to the PC during long periods of windless weather.

The technique WDPS formation from the components available on a market that takes into account functional, economic, operational and environmental indicators of its performance is presented. The technique is based on two models: a functional model of the WDPS as a nonlinear dynamic system with wind as a correlated in time random process and an economic model for predicting the costs of purchase, delivery, deployment, and operation of the system. The economic model also allows to consider possible state incentives as well as cost saving due to recycling the excess power generated by the WG during periods of strong and/or prolonged wind.

The numerical example illustrating usage of the described technique for deploying the WDPS in the settlement of Dikson, Russian Federation is presented. Calculation results show that the reasonable parameters of the system, primarily the installed power of the WG and the capacity of the SB, should be chosen as a tradeoff solution. This solution should consider not only the unit cost of power provided by the system to the PC, but also the coefficient of substitution of hydrocarbon fuel for DG by wind energy as an indicator of the environmental efficiency of the system, as well as the frequency of DG switching-on as the operational indicator. To maintain the total cost of the WDPS at the level of the DPS cost, the state incentives, as well as the use of an auxiliary subsystem for recycling the excess power generated by the WG should be provided.

APPENDIX A INPUT DATA FOR A NUMERICAL EXAMPLE FORMATION OF WDPS IN THE SETTLEMENT OF DIKSON, RUSSIAN FEDERATION

Subsystem	Input data
WDPS	$T = 10$ (years);
PC	$P^*_{PC} = 1$ (kW);
DG	$\tilde{P}_{DG} = 1$ (kW); $r = 0.25$ (L/kW h) ;
WM	$m_1 = -1.03$ (m/s); $\sigma_1 = 6.26$ (m/s), $T_1 = 47.2$ (h), $m_2 = 0.57$ (m/s), $\sigma_2 = 3.67$ (m/s), $T_2 = 34.4$ (h);
WG	$\tilde{P}_{WG} = [3,9]$ (kW), $V_{MN} = 3$ (m/s), $V_{RF} = 10$ (m/s), $V_{ST} = 25$ (m/s);
Controller	$K_{SB,\,min} = 0.3$, $K_{LR} = [0.35,0.95]$;
SB	$T_{SB} = 5$ (years), $Q_{SB} = [5,40]$ (kW h);
Economic model	$c_{RP} = 0.02$ (t.r./kW h), $c_{DG} = 50$ (t.r./kW), $K_{AD} = 2$, $c_{DF} = 0.065$ (t.r./L), $c_{WG} = 100$ (t.r./kW), $K_{SP} = 0.5$, $c_{SB} = 10$ (t.r./kW h), $c_{CI} = 20$ (t.r./kW);
Simulation model	$T_{SM} = 2.5$ (years); $\Delta t = 0.1$ (h).

APPENDIX B NOMENCLATURE

Symbol	Description
P^*_{PC}	power requested by the power consumer (kW)
P_{PC}	power received by the power consumer (kW)
E_{PC}	total energy received by the consumer over the lifetime (kW h)
$\tilde{P}_{WG}$	installed power of the wind turbine generator (kW)
$\tilde{P}_{DG}$	installed power of the diesel generator (kW)
P_{WG}	power generated by the wind turbine generator, kW
P_{DG}	power generated by the diesel generator (kW)
P_{RP}	excess power generated by the wind turbine generator (kW)
Q_{SB}	energy storage battery capacity (kW h)
ΔP_{SB}	power loaded to or drained from the storage battery (kW)
u_{DG}	control command to switch on/off the diesel generator
$K_{SB,\,min}$	coefficient of the allowable depth storage battery discharge
K_{LR}	coefficient of the storage battery recharge level
R_{DF}	cumulative amount of diesel fuel (L)
R_{DFm}	mean monthly fuel consumption of the diesel generator (L)
r	unit fuel consumption (L/kW h)
n_{DG}	average frequency of the diesel generator switching-on
τ_{DG}	average duration of the diesel generator switch-on sessions (h)
T_{SB}	lifetime of the storage battery set (years)
T	lifetime of the wind-diesel power system (years)
K_{PS}	coefficient of power substitution
K_{SP}	coefficient of the state financial incentives
V	wind speed (m/s)
V_{RF}	reference wind speed (m/s)
V_{MN}	“cut-off” (storm) wind speed (m/s)
V_{ST}	“cut-in” (minimal) wind speed (m/s)
m_V	mean value of a wind speed (m/s)
σ_V	standard deviation of a wind speed (m/s)
Δt	simulation step (s)
T_{SM}	simulation time (s)
K_{AD}	coefficient of the additional costs
n_{SB}	number of storage battery sets
C_{CI}	cost of the controller-inverter (t.r.)
C_{SB}	cost of the storage battery (t.r.)
C_{DF}	cost of diesel fuel (t.r.)
C_{DD}	delivery cost of 1 (L) of diesel fuel (t.r.)
C_{DG}	cost of the diesel generator (t.r.)
C_{DPS}	cost of the diesel power system (t.r.)
C_{WG}	cost of the wind turbine generator (t.r.)
C_{WPS}	cost of the wind power system (t.r.)
C_{RP}	cost of the recycled excess power (t.r.)
$C_{WDPS,PR}$	purchase cost of the wind-diesel power system (t.r.)
$C_{WDPS,AD}$	additional cost of the wind-diesel power system (t.r.)
C_{WDPS}	cost of the wind-diesel power system (t.r.)
c_{RP}	unit cost of 1 (kW h) of saved power (t.r./kW h)
$\bar{c}_{WDPS}$	relative unit cost of 1 (kW h) of the wind-diesel power system

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

VB developed a concept of the paper and supervised the research. VB and MT wrote the paper, developed programs, analyzed the data and plots. Both authors had approved the final version.

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