Simulation of Dynamic Operating Modes of a Hybrid Wind Power Plant

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ABSTRACT

Nowadays, standalone power supply systems using wind power plants are becoming more and more widespread. However, use of such systems requires substantiation, as their efficiency in each specific case depends on many factors, both climatic and cost-related. The article addresses building such hybrid wind power plant in order to choose its parameters that would ensure maximum efficiency of the system in case of variable wind speeds.

Formulation of the problem:

Duration of autonomous operation of a wind power unit (WG) in conditions of dead calm or when WG-generated power is less than power consumption by the load is determined by capacity of buffer rechargeable batteries. Increasing capacity of the batteries leads to a considerable increase in capital costs, thus reducing cost-effectiveness of wind energy. Therefore, in order to ensure uninterrupted power supply to consumers, hybrid electric systems are used, including WGs, intermediate combined DC energy storage (batteries and supercapacitors), and generating sets that operate on hydrocarbon fuels, most common being Diesel-generating plants (DG).

Figure 1 shows proposed structure of such an autonomous electrical hybrid wind power unit, while this unit may also include other generating power plants using renewable energy sources (photoelectric, geothermal, bio- and hydropower) [1-4].

Fig. 1: General arrangement of an autonomous power generating unit with a hybrid WG.
Designations and abbreviations used in Figure 1:
WG - wind generator; Tr - transformer; DG - diesel generator; PMSM - permanent magnet synchronous motor; R - rectifier; SC - super-capacitor; C - contactor; DC/DC - DC converter; DC/AC - inverter.

Use of DES makes it possible to supply power to consumers in low wind speeds, but at the same time it reduces efficiency of the system expressed in cost of fuel per 1 kWh of power, especially in variable load and wind speed conditions [5, 6]. In such conditions, vital task is choosing optimal elements of the power generating unit, namely WGs and rechargeable batteries. This requires consideration of static and dynamic modes of WG operation for charging the batteries in order to determine the influence of WGs and batteries characteristics on system efficiency.

Methods:

In order to support these objectives, a computer simulation of a hybrid WG incorporated into uninterrupted power supply unit was made in MatLab SimPowerSystems environment. This computer model is shown in Figure 2. System operation was simulated for a WG with synchronous permanent magnet generator with 5 kW rated power at 12 m/s rated wind speed, with a wind wheel having a typical aerodynamic characteristic (nominal speed is $Z_{nom}=4$).

![Fig. 2: - A computer simulation model of a hybrid WG.](image)

Computer simulation of wind wheel (windmill) operation in the form of torque to RPM rate at a given wind speed was made in the Simulink environment according to formulas (1) - (3) [7-9]. Between wind power efficiency $C_p$ and relative windmill torque there is relationship defined by the expression:

$$C_p = \frac{\bar{M} \cdot Z}{\rho \pi R^3 V^2},$$

whereas $C_p$ is wind power efficiency; $\bar{M}$ is relative torque developed by the wind wheel; $Z$ is wind wheel speed.

In doing so, for the ease of calculations, the abstract aerodynamic characteristics of wind wheel torque was approximated by a sextic polynomial [8, 10]:

$$\bar{M} = a_6 Z^6 + a_5 Z^5 + a_4 Z^4 + a_3 Z^3 + a_2 Z^2 + a_1 Z + a_0.$$  

The coefficients in expression (2) that correspond to a typical aerodynamic characteristic of a three-bladed wind wheel are: $a_6=13.6 \cdot 10^{-6}$; $a_5=49.9 \cdot 10^{-5}$; $a_4=69.1 \cdot 10^{-4}$; $a_3=44.5 \cdot 10^{-3}$; $a_2=0.125$; $a_1=0.093$; $a_0=0.025$ [11].

Transition from the wind wheel relative aerodynamic torque to the torque developed by the wind turbine is made according to the formula:

$$M_s = \frac{1}{2} \bar{M} \pi R^3 \rho V^2,$$

whereas $M_s$ is the torque developed by the wind turbine, Nm; $R$ is the radius of the wind wheel, m; $\rho$ is air density, kg/m$^3$ (under normal conditions of 1.225 kg/m$^3$); $V$ - wind speed, m/s.
The remaining elements of the system, including a three-phase synchronous permanent magnet generator (parameters: stator phase resistance $R_s$ (ohm) - 0.22; armature inductance (H) - 0.00165; voltage constant (V peak LL/krpm) - 550; pole pairs $p$ - 20) and rechargeable batteries (lead-acid) with various voltage levels were simulated by means of SimPowerSystems.

**Main part:**

During the research, waveforms of changes in rotation speed and electromagnetic torque of the generator, generator output power, load power and battery charging current were taken in the conditions of changing wind speed for batteries with various rated voltage. Waveforms were taken at voltages between 24 V (0.154 r.u.) and 120 V (0.769 r.u) at 12 V increments.

From the obtained data about dependence on WG power on wind speed for various rated battery voltages, characteristics of WG were derived relative units (r.u.) as shown in Figure 3. Battery voltage is measured in r.u. and is defined by expression $U^* = \frac{U_{\text{nom.bat.}}}{U_{\text{gen.}}}$ (relation of nominal battery voltage $U_{\text{nom.bat.}}$ to the amplitude of linear open-circuit voltage of WG generator $U_{\text{gen.}}=156$ V at rated speed).

**Fig. 3:** Power characteristics of WG with regard to the variation of nominal voltage of batteries obtained from simulation (lines) and experiments (stars).

The diagram shows that if a higher nominal battery voltage ($U^*$) is selected, the maximum WG power to load ($P^*$) increases, too, at rated (calculated) wind speed for this wind turbine, which is a positive fact. However, when a higher rated battery voltage ($U^*$) is selected, the minimum operating speed of the WG increases, too, which has an adverse effect on efficiency of the wind power unit in areas with predominantly light winds. Thus, depending on wind conditions (taking into account average wind speed and wind speeds distribution by gradations (e.g., Weibull)), one can determine the most effective basic (rated) voltage level of the battery, which will ensure maximum power generation of WG for the selected period at WG location.

**Conclusion:**

Adequacy of the developed computer simulation model was tested on a standalone electrical unit with a hybrid Breeze 5000 (Бриз 5000) wind turbine (rated power of a three-phase synchronous permanent magnet generator is 5 kW, rated speed is 300 rpm, calculated (rated) wind speed is 12 m/s) located at experimental test site of the "Gorny (Горный)" National University of Mineral Resources. Wind speed at WG location was recorded with a "Vetromer-1 (Ветромет–1)" anemorumbometer.

Data about power supplied by the WG to load (for battery charging) were obtained using a Fluke 43B power quality analyzer.

During the experiment we obtained work points of WG power dependence on wind speed with various number of 12 V rated voltage batteries connected to rectifier's output. The batteries were connected in series,
their number varied between 2 and 8. Batteries used were 200 Ah lead-acid maintenance-free sealed gel batteries.

Experimental points (in the form of stars) of dependence of WG power on wind speed at various rated battery voltages are shown in Figure 3.

Using a Fluke 43B power quality analyzer, waveforms of currents and voltages were taken at rectifier input. Reproducibility of computer modeling with the data obtained during the experiment was not worse than 90%.

Conclusions:

- A computer simulation model of a hybrid WG with a PMSM has been developed in the MatLab Simulink system, which made it possible to investigate static and dynamic processes. The dynamic model of WG-Battery system presented in this article makes it possible to:
  - identify rated battery voltage influence on the output power of WG generator with direct connection via its rectifier;
  - identify changes in electromagnetic torque characteristics of the generator upon change of output voltage of the rectifier;
  - obtain wind wheel (generator) speed change characteristic at different wind speeds.

The obtained dependences can be used to determine the amount of power generated by a hybrid WG on selected nominal voltage of intermediate DC energy storage for various wind conditions (taking into account average wind speed and wind speed distribution by gradations (e.g., Weibull)).

REFERENCES