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Wind Power Balancing using Flywheel Energy Storage System

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***Abstract*—The paper presents analysis of feasibility of wind parks' connection to the transmission network considering the grid capacity. The methodic for determination of maximum permissible power of wind parks is presented. Wind parks' connection in Lithuanian power system is analysed. Normal, maintenance and emergency conditions of Baltic power system operating autonomously, synchronously and asynchronously with IPS/UPS and the power system of Continental Europe are considered. Possibilities of the western part of Lithuanian power system's transmission network of 110 and 330 kV to transmit power generated by wind parks are evaluated. Partitioning of the transmission grid into zones with evaluated maximum permissible power of wind parks and their groups as well as connection locations are presented.**

***Index Terms*—Power generation planning, transmission lines, wind power generation, wind farms.**

I. INTRODUCTION

The economy of any country, its development pace, rational allocation of investment and the balance of payments are highly dependent on power systems. Electrical energy is one of the most important sources of energy, without which it is difficult to imagine contemporary life, work and education therefore electricity must be supplied without interruption and meet quality requirements.

The intermittent nature of wind power diminishes power supply quality [1], which therefore needs to be compensated [2]. One of the most reliable approaches of compensation is combined flywheels energy storage system (FESS) [3], installed close to the wind power generating units and hydraulic or pumped storage power plant, controlled by the automatic generation control (AGC) system.

The goal of this paper is to investigate the application of combined FESS and hydraulic power plant system in order to balance wind power output. Hydraulic power plant was modeled by classical model [6].

Fig. 1 shows a simplified scheme of wind, FESS and hydraulic power plant system investigated in this paper. The investigation was carried out and FESS power and energy required to balance the wind park output were determined by using different inertia of flywheels.

II. FLYWHEEL ENERGY STORAGE SYSTEM

The proposed flywheel energy storage system is composed of two principal building blocks: the energy storage module (ESM) and the energy conversion module (ECM). Energy storage flywheel system is one of the most valuable energy-saving technologies as it is simple and characterized by high energy density compared to other energy storage systems [4].

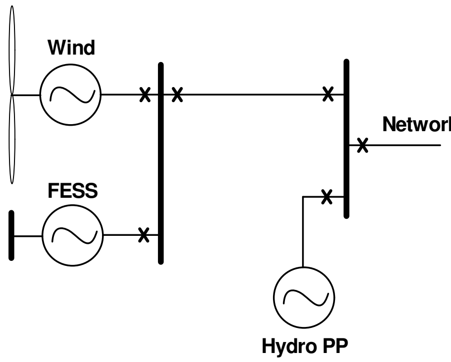

Fig. 1. Simplified Wind, FESS and Hydro PP scheme.

The energy storage module is a kinetic-energy-based storage device that contains a flywheel rotor assembly and a motor/generator. This assembly is designed to operate at high speeds (more than 10000 RPM) to achieve highest energy storage density, usually measured in Wh/kg. Moreover, it has a superconducting magnetic bearing (SMB) at the bottom of the flywheel rotor and a permanent magnet (PMB) at the top of it as shown in Fig. 2 [3]. The superconducting magnetic bearing (SMB) suppresses the vibrations of the rotor and the permanent magnet bearing (PMB) passively controls the rotor position.

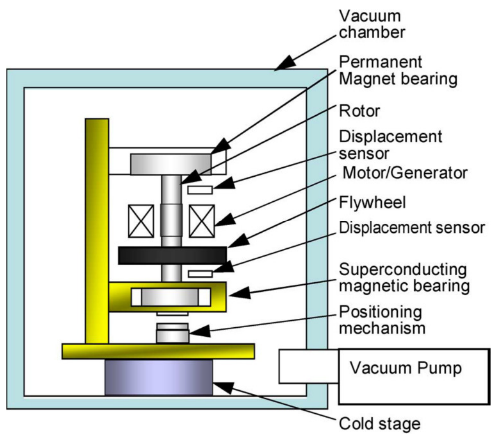

Fig. 2. Energy storage module.

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The flywheel rotor assembly rotates in a low-pressure environment to reduce drag loss. The main interface between the ESM and ECM is the three-phase motor-generator connector.

The ECM includes a standard bi-directional inverter and variable-speed motor drive. It contains IGBT power electronics. The ECM operates each individual flywheel in charge, discharge, or float modes. The ECM also manages all flywheel sensors and hosts the remote monitoring system available to the central control. This remote monitoring system allows the central controller to check system status and to assure readiness when called upon to change modes of operation.

The flywheel energy storage system applies the kinetic energy E_{FW} of a ω_{FW} angular speed rotating mass with J_{FW} inertia. The maximum kinetic energy corresponds to the maximum angular speed:

$$E_{FW} = \frac{1}{2} J_{FW} \cdot \omega_{FW}^2, \tag{1}$$

$$E_{FW\max} = \frac{1}{2} J_{FW\max} \cdot \omega_{FW\max}^2. \tag{2}$$

To utilize the kth part of the E_{FWmax} energy, the following expression can be written

$$k = \frac{E_{FW\max} - E_{FW\min}}{E_{FW\max}}. \tag{3}$$

The kinetic energy can be controlled by the M_{FW} torque of the electrical drive of the flywheel

$$P_{FW} = -\frac{dE_{FW\max}}{dt} = -M_{FW} \cdot \omega_{FW}. \tag{4}$$

It is assumed that electrical machine (EM) is in motor mode at charging ($P_{FW} < 0$) and in generator mode at discharging ($P_{FW} > 0$).

The usual operating range of the FESS electrical drive is presented in Fig. 3 on the $\omega_{FW} - m_{FW}$ plane. In the $\omega_{FWmin} \leq \omega_{FW} \leq \omega_{FWmax}$ normal operating range the maximum power demand is $-P_{FWmax}$ at charging and $+P_{FWmax}$ at discharging. The maximum driving torque of the drive is and the maximum braking torque is $-M_{FWmax}$.

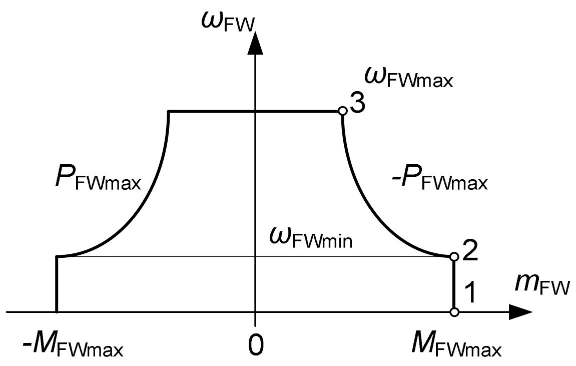

Fig. 3. FESS operating range.

The nominal motor mode operating point of the drive should be set to point 2, where: $M_{FWn}=M_{FWmax}$, $\omega_{FWn}=\omega_{FWmin}$ *and* $P_{FWn}=-M_{FWn}\,\omega_{FWn}=-P_{FWmax}$.

The task of the flywheel drive is to balance the pulsation of the wind turbine power (P_G) caused by the turbulence. According to Fig. 4, the necessary flywheel power is $P_{FW} = P_{Gav} - P_G$. The P_{FW} must remain in the $\pm P_{FWmax}$ interval, while the energy fluctuation calculated by the integral of the power   must remain in the $\pm\Delta E_{FWmax}$ interval. Satisfying these two conditions, the flywheel operates in the $\omega_{FWmin} < \omega_{FW} < \omega_{FWmax}$ angular speed range and is capable of balancing the pulsation of the P_G wind turbine power.

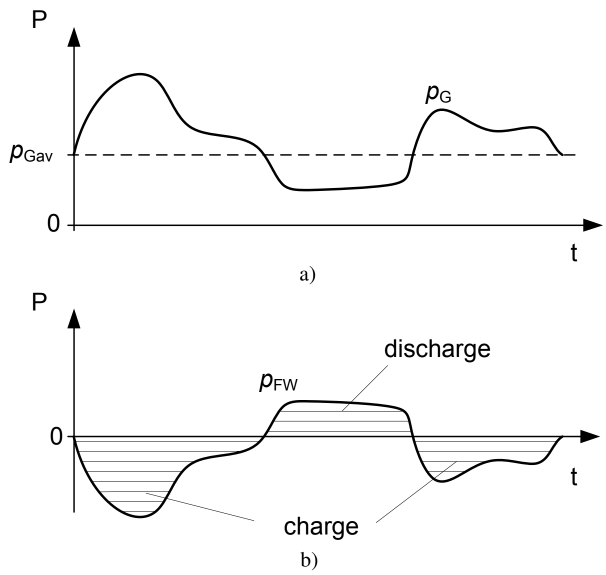

Fig. 4. Wind turbine with FESS operating mode.

The dynamic model of flywheel energy storage system developed in this paper is presented in Fig. 5. MATLAB Simulink software was used to evaluate dynamic behavior of FESS. Maximum efficiency is reached, when FESS system operates without interruption, therefore margins of active power and available accumulated capacity ($\pm P_{FWmax}$, $\pm P_{FWmin}$, $\pm E_{FWmax}$, $\pm E_{FWmin}$) were evaluated in this model. It is assumed that FESS utilization is set to 90 percent (k=0,9). The initial accumulated energy

$$E_{FW\,int.} = \frac{E_{FW\max} - E_{FW\min}}{2}. \tag{5}$$

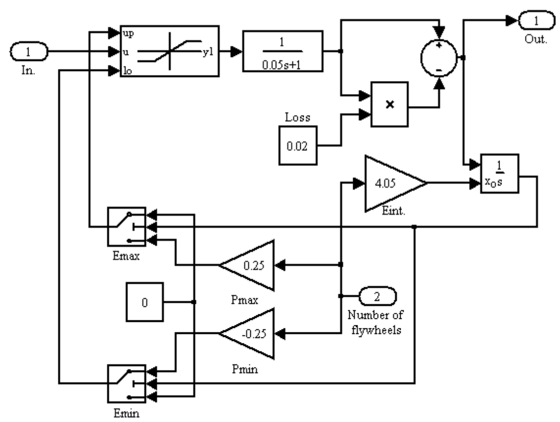

Fig. 5. FESS dynamic model.

"Beacon Power" fourth generation flywheel unit parameters [5] are described in Table I.

TABLE I. FLYWHEEL PARAMETERS.

Maximum output power	250 kW
Nominal power	100 kW
Output energy	25 kWh
Standby loss	<2 % of rated power
Speed	>10 000 RPM
Response time	Instantaneous
Flywheel weight	1360 kg
Flywheel diameter	0,9 m

III. THE DETERMINATION OF FESS POWER AND ENERGY

Actual wind park data were used in this investigation. Wind park installed power is 30 MW. The wind park power generation data is shown in Fig. 6. The difference between actual and forecasted power output was evaluated by root mean squared error and equaled to 7 percent.

It is assumed that hydro unit is controlled by automatic generation control system (AGC) and imitates the difference between real and forecasted power and tries to compensate it. The difference between real and forecasted power of the wind park and hydro unit power is shown in Fig. 7.

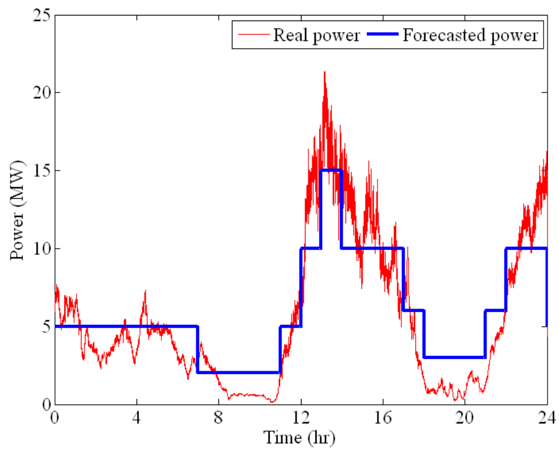

Fig. 6. Wind park actual and forecasted power.

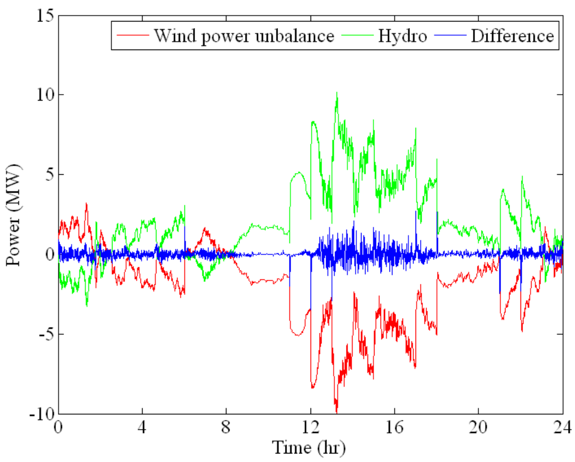

Fig. 7. Hydro unit power and the power unbalance

FESS system balances (ΔP=0) the difference between wind park unbalanced power and hydro unit power. The manufacturer of flywheels specifies that response time to unbalance is instantaneous therefore it is assumed that inertia of the FEES is equal to the inertia of the power converters (T_{FESS}=0,05 s). As mentioned above, the rated flywheel unit power is 100 kW and rated energy is 25 kWh. Fig. 7 clearly shows that one flywheel unit is not enough to balance the wind park. The results of the investigation show, that system of thirty flywheel units with rated power of 3 MW and energy of 0.75 MWh is needed. Operation results of FESS system of ten and thirty flywheel units are shown in Fig. 8 and Fig. 9.

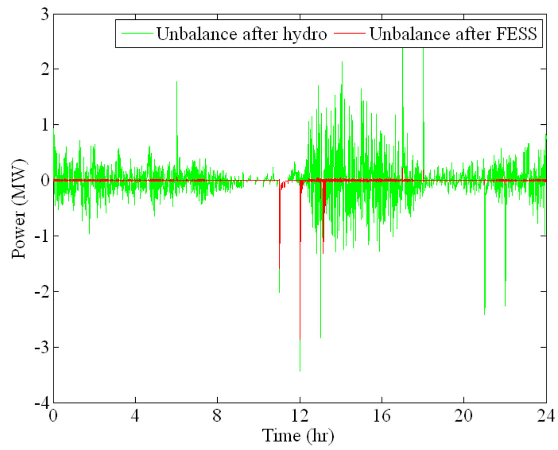

Fig. 8. Operation of 10 units FESS.

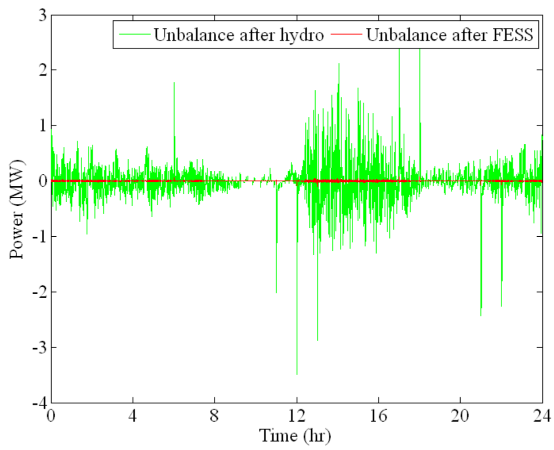

Fig. 9. Operation of 30 unit FESS.

IV. THE INVESTIGATION OF BASIC OPERATING REGIMES

Investigating the determination of FESS power and energy it was assumed that FESS inertia was equal to the inertia of power converters. The results show that in order to balance the wind park of 10 MW installed power, 1 MW of FESS power is required. It is worth mentioning that hydro unit operates controlled by AGC system in this case.

Instantaneous theoretic FEES system response (T_{FESS}=0,005 s) and system operation with large inertia (T_{FESS}=0,5 s) were investigated. Hydro unit operates controlled by AGC. The investigation results of 30 units FESS system operation are shown in Fig. 10 and Fig. 11.

Fig. 10 shows FESS operation with theoretic inertia time and clearly seen that balancing quality is excellent due to hydro and FESS units.

Fig. 11 shows FESS operation with large inertia time. It is shown that magnitude of unbalance after hydro and FESS operation gets ahead 0,5–1 MW and it means that FESS with large time constant is inadequate to achieve perfect balancing quality [6].

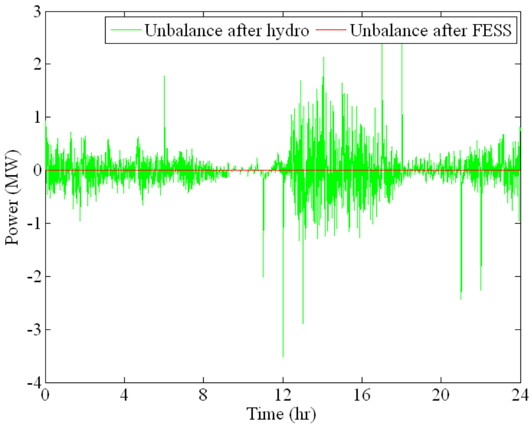

Fig. 10. Operation of 30 unit FESS with 0,005 s inertia.

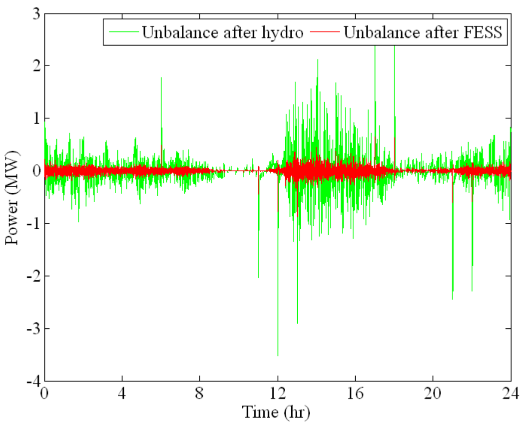

Fig. 11. Operation of 30 unit FESS with 0,5 s inertia.

V. CONCLUSIONS

1. Dynamic models of hydro PP and flywheels energy storage system were composed and designed to operate in coordinated regime to balance actual wind park.

2. The balancing wind park of 30 MW power needs 3 MW and 0,75 MWh of FESS power and energy and it amounts 10 percent of total rated power. The hydro PP operates controlled by AGC system in this case.

3. Investigation of FESS power and inertia showed that theoretic inertia of 0,005 s ensures excellent balancing quality, while the FESS inertia is equal to power converters time constant of 0,05 s.

4. FESS with large time constant (0,5 s) is inadequate to achieve excellent balancing quality.

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