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PENETRATION AND INTEGRATION OF WIND POWER PLANTS INTO LITHUANIAN POWER SYSTEM

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New Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources enables member states of European Union not only to initiate changes in legislation, but also to set the mandatory requirements for renewable energy sources. Therefore the number and capacity of renewable power sources, especially wind power plants, in Lithuania tend to increase very fast. Beside the main advantages of wind power plants, related to environmental and climate changes requirements, some drawbacks, concerning additional balancing and reserve, could be stated. A lot of questions arise, which are related to operation individualities of wind power plants during steady and fault conditions, influence of wind power plants on the operation of transmission network relay protection and automation.

Introduction

Construction program of 200 MW of wind power plants in the western part of Lithuania is going to be realized until 2010. The total capacity of operating wind power plants in Lithuania at the beginning of 2008 reached 52 MW. Till the end of the year additional capacity of 100 MW was projected and projecting conditions for 250 MW of wind power capacity were issued. Aiming to reach the mandatory requirements of European Union [1] construction rate of wind power plants in Lithuania will increase. Fast penetration of wind power plants could be limited because of limited capacity of 110 kV power lines and Lithuanian power system stability problems. Further development plans of wind power plants are related to construction of wind power parks of up to 1000 MW in the Baltic Sea together with development of transmission network and additional generation and transmission reserve capacity. Development rate of wind power plants is influenced by facility of preparation of detailed plans, environ-

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mental evaluation and wind power plants manufacturing and construction duration. Because of these reasons the process of wind power plants' construction takes more time than in the other West European countries. Besides, due to the high demand and limited manufacturing possibilities it is possible that achievement of renewable energy utilization indicators until 2020 could be complicated for Lithuania.

From the point of view of electric power system stability, the total installed capacity of wind power plants should be such what power system frequency control providing frequency controllers could cope with fluctuations of wind power generation. The effect of wind power generation for electric power system and society is twofold. First, usage of wind power decreases the consumption of imported fossil fuel for electricity generation, provides some assumptions about security of supply, reduces emissions of reduction of greenhouse gases. The negative side is that balancing power of the Lithuanian power system should be provided by thermal power plants. Part of the generators will have to operate in the forced and unproductive modes. Other problems of wind power plants are related to operation of wind power plants during normal and fault conditions, influence of wind power plants on the operation of relay protection and automation of transmission network, operation of wind power plants during the short-circuit conditions in the network, start of synchronous and induction generators of wind power parks after voltage restoration in 110 kV network.

Maximum power deviation of electric power system

Maximum deviation of electric power system, which could be controlled by primary frequency control system, depends on the droop of speed regulators participating in the primary frequency control units, total nominal capacity of power units and the factor of dependence of power load on frequency (load damping). Assuming that power deviations are created only by wind power plants, their capacity P_{WP} can be calculated by equation [2]:

$$P_{WP} = \frac{P_G \cdot \Delta f_{\max}}{S \cdot f_N} + P_L D \frac{\Delta f_{\max}}{f_N}; \tag{1}$$

where

P_G	– rated capacity of generators participating in primary frequency control;
P_L	– electric power system load;
$\Delta f_{max} = 0.2$ Hz	– maximum permissible frequency deviation from the rated value;
$f_N = 50$ Hz	– rated frequency;
$S = 0.05$	– droop of speed regulators of the generators;
$D = 1.6$	– load damping factor.

Permissible penetration level of wind power plants can be determined in relation to the generating capacity of participating in the primary frequency control units or system load. Then the equation in relation to the generating capacity of participating in the primary frequency control units could be the following:

$$P_{WP} = P_G \frac{\Delta f_{\max}}{f_N} \left(\frac{1}{S} + \frac{P_L}{P_G} D \right), \tag{2}$$

and in relation to system load:

$$P_{WP} = P_L \frac{\Delta f_{\max}}{f_N} \left(\frac{P_G}{P_L \cdot S} + D \right). \tag{3}$$

Permissible power deviation of electric power system can be determined only knowing generating capacity of participating in the primary frequency control units and system load. For forecasting of deviation it is necessary to evaluate perspectives of generating capacity of participating in the primary frequency control units and forecast the growth of electric power system load.

Capacity of primary frequency control units and electric power system load

Thermal, hydro and new nuclear power units can participate in primary frequency control. For determination of the capacity of primary frequency control units in Lithuania, it is assumed that in 2007 the 1st and the 2nd 150 MW units together with the 5th and the 6th 300 MW units of Lithuanian power plant are operating. Four 200 MW units of Kruonis hydro power storage plant, two 25 MW units of Kaunas hydro power plant, two 180 MW units of Vilnius cogeneration plant, 63 MW and 100 MW units of Kaunas cogeneration plant and 30 MW in small other power plants are under operation. It is forecasted that until 2010 capacity of primary frequency control units in Lithuanian power plant will increase till 1500 MW. Two additional units of 25 MW each will be reconstructed in Kaunas hydro power plant and will reach 100 MW. Capacity of small cogeneration power plants will increase up to 135 MW, and the remaining capacity of other power plants will not change. In 2015 the situation will be very similar to 2010, but it is forecasted that new 400 MW combined cycle power unit in Lithuanian power plant will be operating and capacity of small cogeneration power plants will increase up to 220 MW. It is planned that in 2020 two 400 MW combined cycle power unit in Lithuanian power plant will be operating and capacity of small cogeneration power plants will increase up to 270 MW. It is expected that in 2020 the first 1600 MW unit of the new nuclear power plant will start its operation, which will be capable to participate in primary frequency control. Maximum and real primary frequency control capacity is shown in Table 1.

Table 1. **Capacity of primary frequency control units**

Year	Frequency control capacity, MW	
	Maximum	Real
2007	2303	440
2010	3058	2383
2015	3543	1368
2020	5593	3418

Lithuanian electricity demand forecast for slow, average and fast economic growth scenario is based on econometric model [3]:

$$E_{ij}(t) = E_{ij}(t-1)[V_i(t)/V_i(t-1)]^{\alpha(ijl)} \times [P_{ij}(t)/P_{ij}(t-1)]^{\beta(ijl)} \times C_{ijl}, \qquad (4)$$

where E_{ij} – demand of energy form j in the sector i; V_i – economic activity of the sector i; P_{ij} – price of energy form j in sector i; $\alpha(ijl)$ – income elasticity in sector i for fuel j and end use l; $\beta(ijl)$ – price elasticity in sector i for fuel j and end use l; C_{ijl} – factor of additional energy saving in sector i for fuel j and end use l.

Maximum load of Lithuanian power system (Fig. 1) was calculated according to forecasted electric power generation for different scenarios and possible maximum load durations, which could reach 5900 hours in 2010 and would increase gradually up to 6000 hours in 2020.

The analysis shows that the most probable is the average maximum load growth scenario.

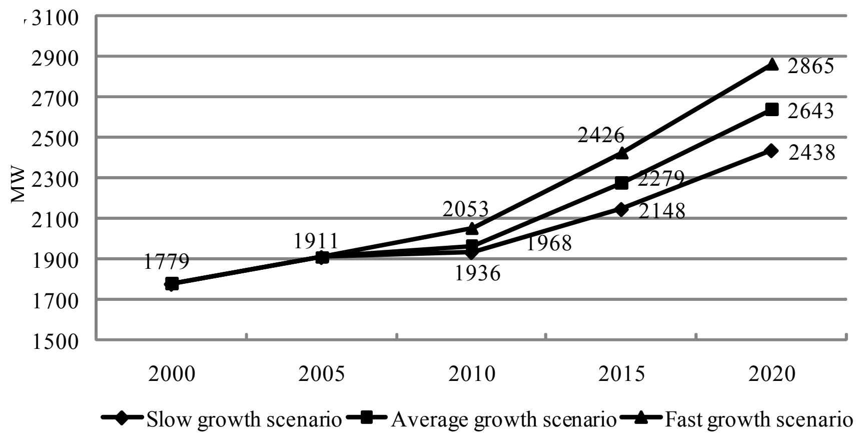

Fig. 1. Maximum load of Lithuanian power system.

Determination of wind power plants capacities

Calculations of penetration of permissible capacities of wind power plants are performed in relation to the generating capacity of participating in the primary frequency control units (Eq. 2) or system load (Eq. 3), taking into account forecast of load growth scenarios. Calculation results are shown in Table 2 and Fig. 2–4.

Analysis of calculation results shows that capacity of wind power plants in the period from 2010 till 2020 could reach from 8.24% to 8.59% of maximum generating capacity of participating in the primary frequency control units depending on the system load growth scenarios (Fig. 2). If only real generating capacity of participating in the primary frequency control units would be available, capacity of wind power plants should not exceed 8.35–8.77% of this capacity. Relative minimal and maximal values of wind power plants, determined according to frequency control capacity, are very similar,

Table 2. **Relative and absolute capacity of wind power plants**

Year	Slow growth scenario				Average growth scenario				Fast growth scenario				P_{WP}, MW	
	P_{WP}/P_{PFC}, %		P_{WP}/P_{ESL}, %		P_{WP}/P_{PFC}, %		P_{WP}/P_{ESL}, %		P_{WP}/P_{PFC}, %		P_{WP}/P_{ESL}, %			
	max	real	max	real	max	real	max	real	max	real	max	real	max	real
2007	8.55	8.90	10.0	7.30	8.55	8.9	10.0	7.3	8.55	8.9	10.0	7.3	202	28
2010	8.47	8.60	11.6	9.15	8.53	8.68	10.4	8.22	**8.59**	8.75	**9.38**	7.45	263	205
2015	8.31	8.53	17.2	10.2	8.39	8.69	13.6	8.11	8.44	**8.77**	12.2	**7.31**	442	255
2020	**8.24**	**8.35**	**21.5**	**15.2**	8.36	8.52	14.8	10.5	8.38	8.54	14.2	10.1	618	432
Average	8.34	8.49	13.9	9.59	8.43	8.63	12.9	8.94	8.47	8.69	11.9	8.29		

Remark: P_{WP} – capacity of wind power plants; P_{PFC} – capacity of primary frequency control units; P_{ESL} – electric power system load.

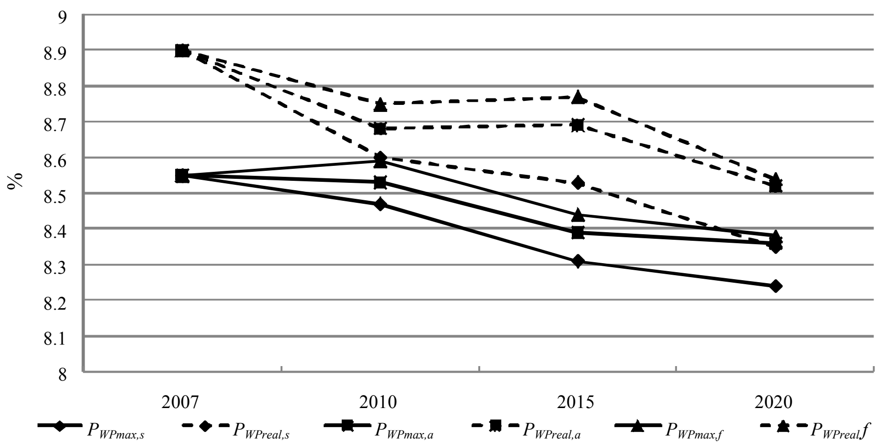

Fig. 2. Relative capacity of wind power plants in relation to the generating capacity of participating in the primary frequency control units.

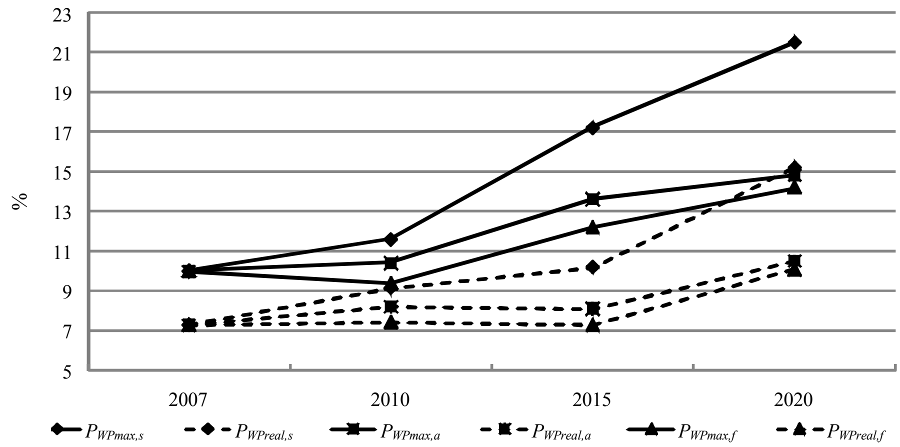

Fig. 3. Relative capacity of wind power plants in relation to the system load.

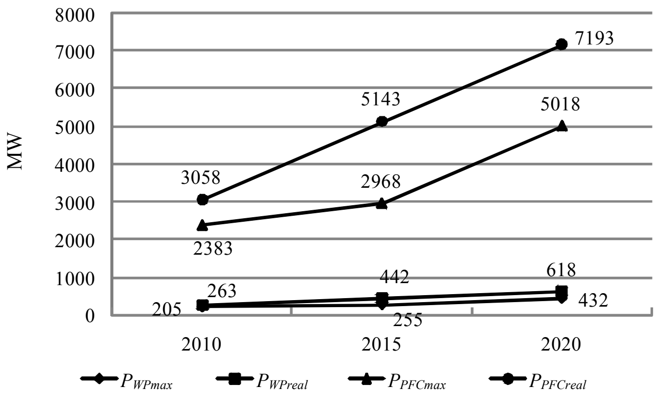

Fig. 4. Capacities of wind power plants and frequency control units.

and the difference is not exceeding 0.35% of maximum and 0.42% of real generating capacity of participating in the primary frequency control units.

Capacity of wind power plants, determined in relation to system load, is calculated with higher uncertainty, which varies from 9.4% to 21.5%, depending on the scenarios of system load growth (Fig. 3).

Having the scenarios for real primary frequency control capacity and different power system load, relative capacity of wind power plants is in the range from 7.3% to 15.2% of system load. Relative minimum and maximum values of wind power plants, determined according to system load, differ more than two times, and the difference is 12.1% and 7.9%, having maximum and real primary frequency control capacity.

Analysis shows that maximum wind power capacity in Lithuania in 2010 could be 263 MW, in 2015 – 442 MW and in 2020 – 618 MW, real capacity of wind power plants in 2010 could be 205 MW, in 2015 – 255 MW and in

2020 – 432 MW (Fig. 4). These calculations are valid for isolated operation of Lithuanian power system.

Operation of wind power plants in normal conditions

Analysis of wind power parks connected to Vėjas I and Benaičiai transformer substations (TS) in Lithuanian Baltic sea region shows that wind power generation is very volatile and is close to load variation (Fig. 5). It could be seen from the figures that with weak wind (period 01.–30.09.2008.) small power drops could be observed, and with strong wind (period 01.01.–31.08.2008) large power drops could be observed. Therefore fast growth of wind generation capacity could influence system operation regimes. Striving to maintain static and dynamic stability of the electric power system, it is necessary to limit fast growing penetration of wind power up to permissible variation level of capacities or to require to settle control over wind power parks.

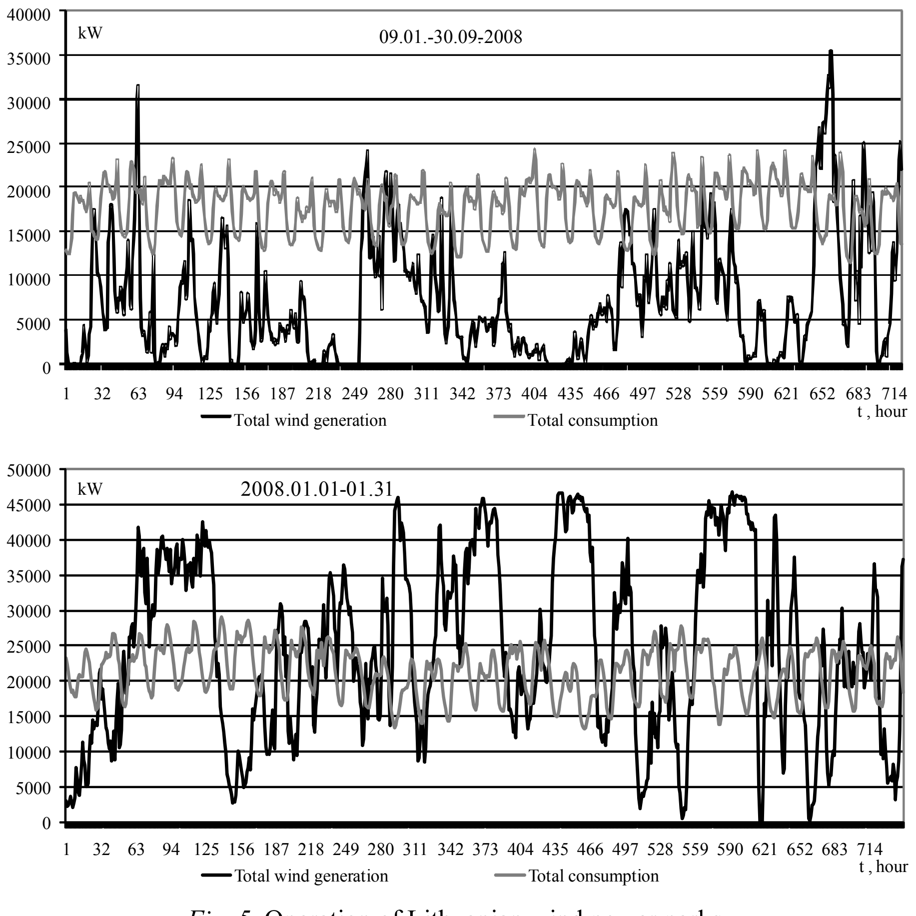

Fig. 5. Operation of Lithuanian wind power parks.

Utilization factors of installed capacities of wind power parks are not high (Fig. 6). For the “Vestas” type wind power plants with induction generators connected to Benaičiai TS utilization factor is 0.283, and for “Enercon” type wind power plants with power converters connected to Vėjas I TS this factor is 0.255.

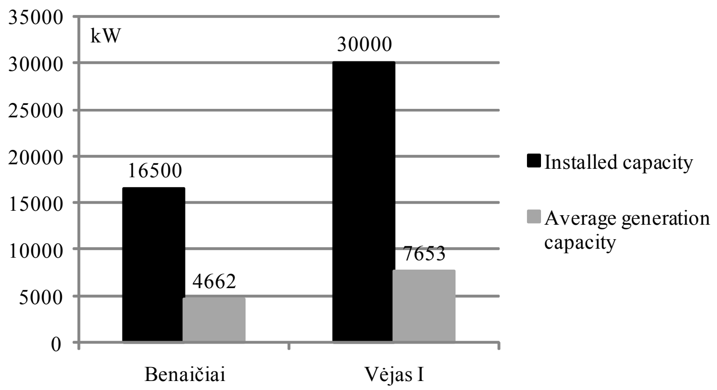

Fig. 6. Installed and average generation capacity of Lithuanian wind power parks in 2007.

Analysis of operation of wind power plants during short-circuit faults

Short-circuit faults are quite often in electric power network. Small generators should not be damaged due to the faults in the outer network, because electric power network should not be responsible for this. First of all the resistant equipment should be chosen for electric power generation [4].

For the calculation of the steady state short-circuit currents, methods described in various international and national standards, i. e. IEC 60909 and etc., are used. Actual electric power network is usually simplified to the equivalent network. Standard actual network elements include power lines, cables, transformers, synchronous generators and motors, induction motors and voltage sources.

Variety of small distributed electric power plants determines unequal influence on short-circuit currents in electric power network. Short-circuit currents of small synchronous and asynchronized generators are calculated according to classical theory. Depending on connection scheme and parameters of synchronous generators, short-circuit currents can exceed nominal current values 10 times, short-circuit currents of asynchronous generators can reach 5–7-fold nominal current values. In the case of power plants with converters (wind and solar power plants, fuel cells, etc.), after occurrence of a short-circuit in electric power network, converters are closed and start operation just after the short-circuit is ended. Short-circuit currents of generators should not exceed 1.5 nominal current values [4].

Analysis of short-circuit currents of wind power plants was performed on the basis of experimental investigation. One-phase short-circuit faults in 110–330 kV Lithuanian electricity transmission network were analyzed.

During these short-circuit faults data from connection stations of wind power plants Vėjas I and Benaičiai were registered. Wind power plants with synchronous generators and converters are connected to Vėjas I TS, and wind power plants with asynchonized generators are connected to Benaičiai TS.

On November 6, 2007 short-circuit at Priekulė TS occurred, during which data from Vėjas I TS and Benaičiai TS were recorded (Fig. 7 and 8).

During short-circuit at Priekulė TS effective one-phase (A phase) current value at Vėjas I TS increased from 95.6 to 99.3 A or 1.04 times operating current and after 0.12 s decreased more than 2 times and after another 0.4 s

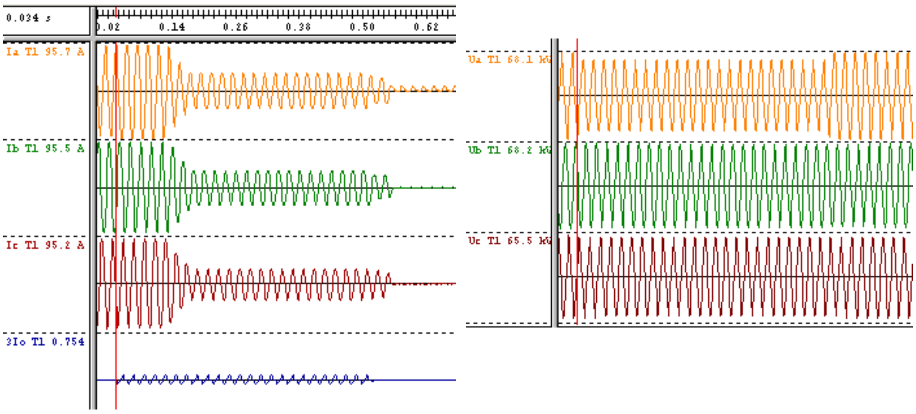

Fig. 7. Vėjas I TS currents and voltages during one phase short-circuit at Priekulė TS in 2007-11-06.

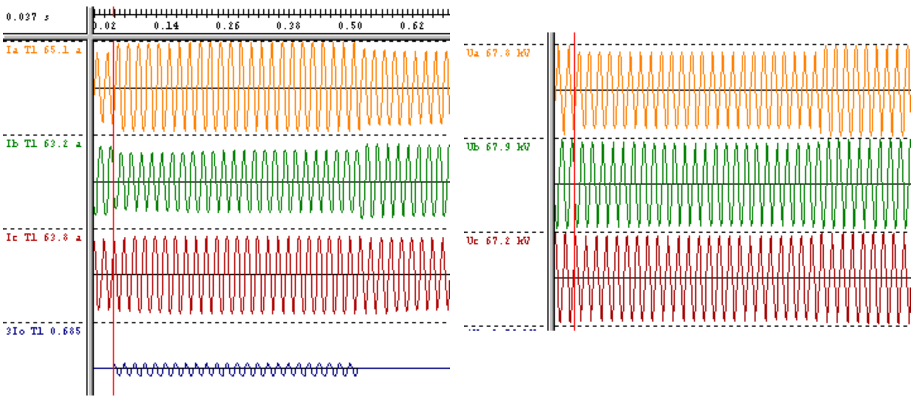

Fig. 8. Benaičiai TS currents and voltages during one phase short-circuit at Priekulė TS in 2007-11-06.

decreased to zero. It could be guessed that the biggest part of power plant converters were closed fast (after 0.12 s) and the other part operated 0.4 s more. Phase voltage (A phase) decreased from 68.3 to 55.8 kV or 0.82 times operating voltage and was restored after 0.5 s after disconnection of short-circuit. Due to relatively distant short-circuit, wind power plant with converters discharged fully after 0.1 s and after 14.5 min reached the initial capacity again, creating the average variation of 20 MW.

In the analyzed case at the Benaičiai TS effective value of one phase (A phase) current increased from 63.5 to 79.8 A or 1.25 times operating current. Operating mode is quite symmetrical. Phase voltage (A phase) decreased from 69.3 to 58.7 kV or 0.85 times operating voltage, and it was restored after 0.5 s after disconnection of short-circuit. Power plant maintained the generating capacity and did not introduced any power flow variations.

Not adequate response of one wind power plant into distant short-circuits shows that this park does not meet connection to the system requirements or control of power plant equipment and protection system do not ensure safe operation during fault conditions in the system. Trying to decrease the number of wind power plants disconnections and maximum power deviations, Lithuanian transmission system operator requires that wind power should not disconnect from power network, when at the high voltage connection point voltage suddenly decreases to zero, after 0.25 s jumps till 25 % and after 0.5 s gradually increases till 90 % of nominal value (Fig. 9). The same requirements are also set by European system operators.

On November 10, 2007 from 20 h 10 min. till 22 h 30 min. repetitive short-circuit faults in 330 kV power lines Kruonis HPSP – Sovetsk occurred (Fig. 10). During short-circuit faults wind power plants with converters were operating at nominal capacity, and wind power plants with asynchronized generators were operating at 10–16 MW generating power. Generating power of wind power plants connected to Vėjas I TS decreased by 20 MW or by 67%.

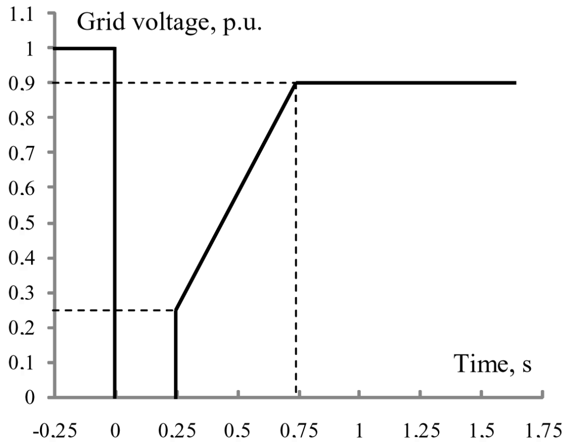

Fig. 9. Acceptable voltage variation profile of wind power plant.

Wind power plants with asynchronized generators connected to Benaičiai TS were reacting to short-circuits much less. After the first short-circuit generating power decreased from 9 to 4 MW, and after the second and fifth – generating power decreased by 3 MW. It could be seen that wind power plants with asynchronized generators are more stable in the sense of generating power.

Investigation analysis shows that wind power plants with converters (Vėjas I TS) tend to discharge not only in the case of near, but also to reduce generating capacity during distant faults. With increasing number of such wind power plants, problems in electric power system may occur related to system stability and permissible frequency variation range. Wind power plants with asynchronized generators influence system regimes much less.

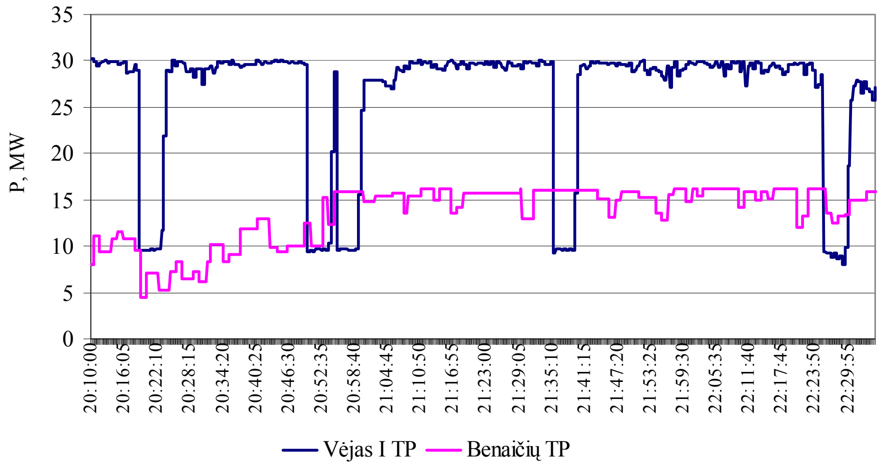

Fig. 10. Generating capacities of Vėjas I and Benaičiai TS during short-circuit faults in 330 kV power line Kruonis HPSP – Sovetsk in 10-11-2007.

Conclusions

1. The performed investigation shows that permissible capacity of interruptible power plants is determined more precisely in relation to the capacity or primary frequency control units and not in relation to electric power system load.
2. When reaching the substantial level of interruptible power plants in electric power system balance, it is necessary to include them into primary frequency control and supply of ancillary services or limit the total installed capacity of wind power plants.
3. It was determined that wind power capacity in Lithuania in the period 2010–2020 could reach from 8.24% to 8.59% of maximum generation

capacity of primary frequency control units. Maximum wind generation capacity in Lithuania in 2010 could reach 263 MW, in 2015 – 442 MW and in 2020 – 618 MW.

4. Wind power plants with asynchronized generators are more stable and keep their generating power during short-circuit faults, but can induce quite big short-circuit currents in electric power system.
5. Wind power plants with power converters tend to discharge not only in the case of near faults, but also to reduce generating capacity during distant faults and induce large power variations. With increasing number of such wind power plants, problems in electric power system may occur related to system stability and permissible frequency variation range.

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