IMPACT OF WIND POWER PLANT OPERATION ON MV DISTRIBUTION GRIDS

Miloslava TESAROVA, Roman VYKUKA
University of West Bohemia – Czech Republic
tesarova@kee.zcu.cz, vykuka@kee.zcu.cz

Martin KASPIREK
E.ON Distribution – Czech Republic
martin.kaspirek@eon.cz

ABSTRACT

The paper summarizes the results of short-term voltage quality measurements in medium voltage distribution grids with connected wind power plants. The measurements were made in grids on supply territory of the utility E.ON Czech Republic in the 2013-2016 period. Voltage quality parameters were evaluated according to the standard EN 50160. Power flows of individual wind power plants were also evaluated and mutually compared to find the pattern of their performance in various year seasons. Finally, an impact of wind power plant operation on voltage quality parameters, mainly on voltage variations and flicker, was analysed.

INTRODUCTION

The supply territory of the E.ON utility in the Czech Republic has approximately 1.5 million customers and more than 1000 MW installed output of distributed energy sources (DES). The number of DES connected to the E.ON distribution grids has increased significantly, more than ten times from 2008. Large-scale photovoltaic, biogas and wind power plants belong to the most expanding DES that are usually connected to the medium voltage (MV) distribution grids. Unfortunately, it has brought new operational problems with voltage quality and back power flows.

Impact of DES on voltage quality (VQ) in LV grids has been analyzed [1]. The power source operation can cause the voltage increase up to 2% of nominal voltage in MV grids and 3% of nominal voltage in LV grids according to the Czech Distribution Code. In the worst case, parallely working MV and LV sources can cause overvoltage in the LV grid if the both grids are underloaded [1]. Voltage changes caused by source operation depend on the power factor of its power flows in the delivery point [2][3].

The paper presents the survey of voltage quality in delivery points of the MV wind power plants. It aims at the impact of their operation on voltage quality parameters (voltage variations and flicker). Moreover, power flows in delivery points of wind power plants were evaluated and mutually compared to find the pattern of their performance during a year.

Power backflows between distribution and transmission systems as well as between MV and HV distribution networks become a serious problem. Backflows of active power are sporadic between transmission and distribution systems. Unfortunately, backflows of reactive power are common; they occur mainly at early morning hours at weekends and on bank holidays, they are higher and longer in summer season [4]. Between HV a MV networks, backflows of active power occur in summer, if sources with large output are installed in downstream MV grid. Flows of reactive power are similar in summer and winter seasons, back flows are sporadic, but more frequent in case of cable MV grids [4].

INPUT DATA FOR VQ SURVEY

In comparison to photovoltaics, wind power plants are installed less often, only in several localities with good wind conditions. The installed capacity of wind power plants in the Czech Republic is 281 MW that is 1.3 % of total installed capacity. Capacity of wind power plants installed on the E.ON CR supply territory is only 21.95 MW in 9 wind farms/power plants (Table 1). Wind farms are connected to the MV grids and installed output of their generators varies from hundreds kW to a few MW. There were available measurement data from the 2013-2016 period. Power quality analyzers (class A) were installed in delivery points for a week or two weeks. Table 1 shows main parameters of wind power plants: total installed capacity of a wind power plant or farm and short circuit power S_k in the delivery point.

Table 1 *Wind power plants involved in the VQ survey*

Wind power park	Installed output (kW)	S_k (MVA)	Monitoring period	Plant utili-zation
Tulesice	2000	46	22.1. - 29.1. 2014	3.2 %
Bantice	2000	103	28.3. - 5.4. 2013	31.6 %
Brodek	2 x 600	52	3.6. - 12.6. 2014	1.5 %
Brezany	5 x 850	86	3.7. - 11.7. 2013	12.5 %
Pavlov 1	2 x 2000	47	11.7. -19.7. 2013 21.7. - 2.8. 2016 2.8. - 10.8. 2016	15.9 % 19.1 % 15.9 %
Pavlov 2	2 x 850	60	11.7. - 19.7. 2013 2.8. - 10.8. 2016	7.1 % 8.7 %
Protivanov	2 x 1500	41	11. - 19.11. 2013	24.8 %
Drahany	2000	33	19.11.- 3.12. 2013	47.0 %
Rozstani	1800	54	3. - 11.12. 2013	48.8 %

Based on power delivered the percentage utilization of wind-park capacity was calculated in given monitoring periods. Considerable differences are caused by seasons when the measurement was carried out. Relatively low utilization of wind parks is typical for summer months. The highest utilization can be expected in November and December. Two power plants (Tulesice and Brodek) were partially out of order so that it influenced their utilization. Utilization of wind farms was about 18 % in 2013, i.e. about 1600 kWh per kW of installed capacity.

VOLTAGE QUALITY EVALUATION

Voltage quality parameters are in compliance with the standard EN 50 160. Voltage variations and flicker are described in detail in the following sections. Details about other VQ parameters are described in [5].

Voltage variations

For each 10 min sample of line-to-line voltages, the maximum and minimum values of all three measured voltages were evaluated and then 99% percentiles and 100% percentiles (i.e. absolute maximum and minimum) were calculated. Under normal operating conditions during each one week period, at least 99 % of the 10 min mean r.m.s. values of the supply voltage shall be below the upper limits of Un+10 %; and at least 99 % of values shall be above the lower limits of Un–10 %; and all shall be within the range of Un ± 15 %.

Figure 1 shows voltage variations and maximum and minimum values of supply voltage in the delivery point for each individual wind farm. The figure also illustrates the impact of short-circuit power at delivery points on voltage variations.

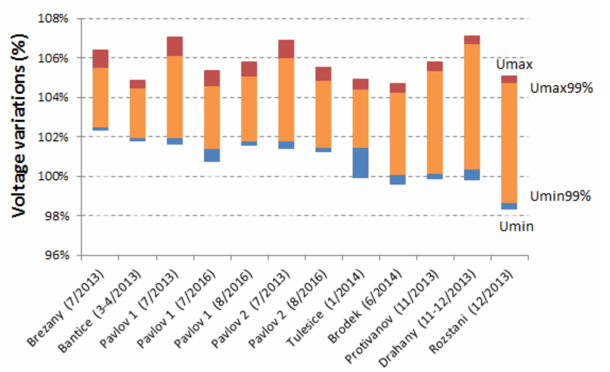

Figure 1 *Voltage variations (absolute maximum and minimum, 99% percentiles)*

For example, voltage at the delivery point with high short-circuit level (Bantice) differs from 101.8 to 104.9 % of nominal voltage, but voltage in the weakest delivery point (Drahany) is within the range 99.8-107.1 % of U_n.

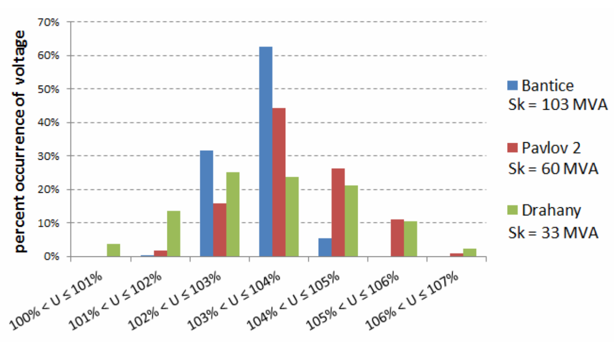

Figure 2 *Voltage occurrence at delivery point of wind farms with different short-circuit level*

Voltage occurrence at delivery points of wind farms with different short-circuit power is shown in Figure 2. Comparison of above-mentioned wind farms is completed by the wind farm Pavlov 2 with middle short-circuit power. The lower short-circuit power in delivery point is, the wider and lower envelope curve of voltage occurrence is. Similar voltage conditions are also in other weak delivery points at the end of the long MV feeders (e.g. Drahany, Protivanov and Rozstani) where supply voltage can drop below nominal voltage. Despite it, voltage in all delivery points is in compliance with the standard EN 50 160.

Flicker

Under normal operating conditions, during each period of one week the long-term flicker severity P_{lt} caused by voltage fluctuation should be less than or equal to 1 for 95 % of the time.

Comparison of the long term flicker severity P_{lt} is in Figure 3. Besides 95 % percentile of the long-term flicker severity which has to meet the requirement of the standard EN 50160, absolute measured value is also presented. As in case of voltage variations, higher values of flicker severity are measured in delivery points with lower short-circuit power, but its impact on difference between 95% and 100% percentiles is not quite obvious.

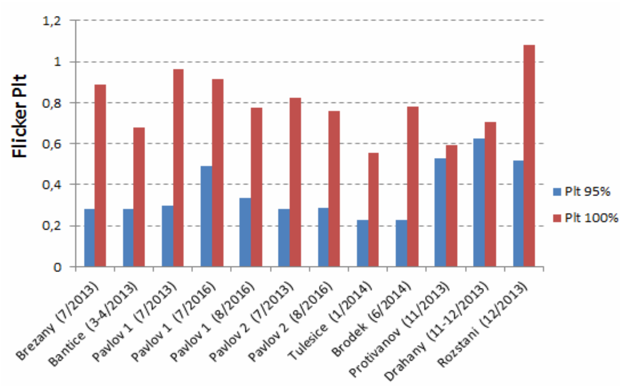

Figure 3 *Long-term flicker P_{lt} (95%, 100% percentiles)*

POWER FLOW EVALUATION

Further, power flows of individual wind farms were evaluated and mutually compared to find the pattern of their performance during a year.

Active power flow analysis

Detailed analysis was carried out for 5 selected wind farms with different utilization of their capacity, and short-circuit power in delivery points. Figure 4 shows the impact of year seasons on active power delivered by the wind farms. Wind farm Drahany (green curve) has operated at almost full capacity in November and December, and its exploitation belonged to the highest ones. On the contrary, the output of the wind farm Pavlov 2 (red curve) operated in July has not exceeded 10 % of its installed output most of the time.

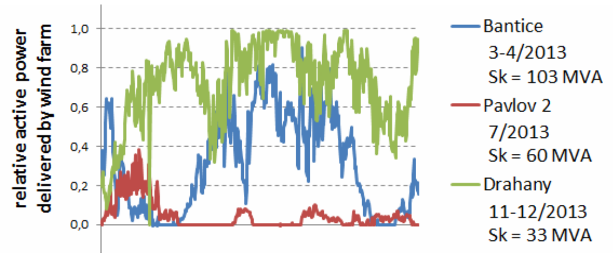

Figure 4 *Example of relative active power delivered by wind farms in various year seasons*

Frequency of occurrence of the relative active power delivered by wind farms and corresponding distribution functions are presented in Figure 5 and Figure 6.

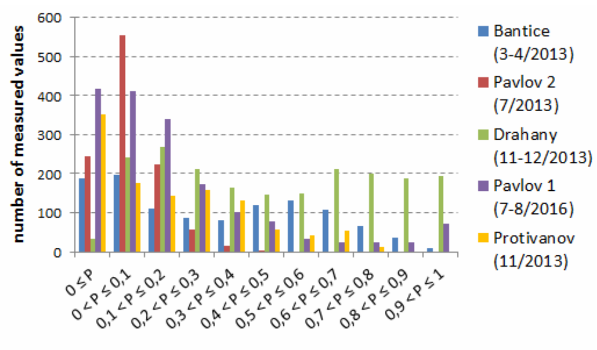

Figure 5 *Occurrence of relative active power delivered by wind farms in various year seasons*

Wind farm Drahany (green curve) produced power almost all time of measurement (its distribution function goes almost from zero), and was operated at less than half capacity during about half of operating time. Although measurement of wind farm Protivanov (yellow curve) carried out in the same season as Drahany, its output was zero during 1/3 of operating time. Wind farm Pavlov 2 (red curve) was out of order during 22 % of operating time, and operated at less than 10% of its capacity during about 3/4 of operating time, and power produced never exceeded 40% of its capacity.

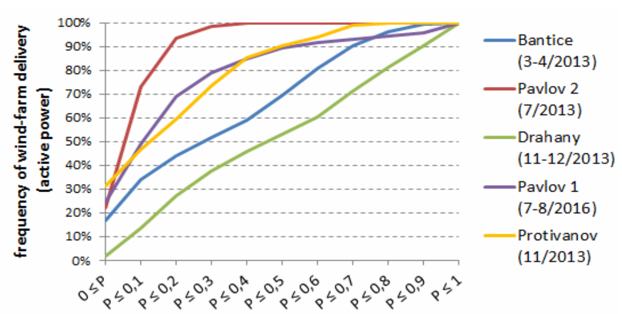

Figure 6 *Distribution functions of relative active power delivered by wind farms in various seasons*

Reactive power flow analysis

Voltage changes caused by operation of a wind power plant depend on the power factor of its power flow in the delivery point [3]. Relation between active and reactive power flows of a wind power plant is very strong (see Figure 7). Although active power is delivered into grid, reactive power can be consumed. Quantity and character of consumed reactive power depends on operation mode of a wind plant. Voltage changes caused by wind power plant operation in the under-excited state (reactive power is consumed) are smaller than in the over-excited state (reactive power is generated).

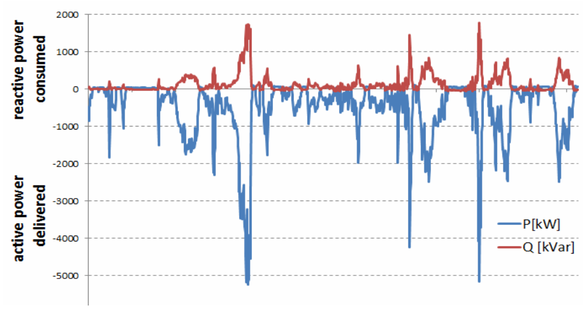

Figure 7 *Active power delivered and reactive power consumed of wind farm Pavlov 1 (7-8/2016)*

Reactive power flows in delivery points of wind power plants were evaluated and mutually compared. Frequency of occurrence of the reactive power consumed by wind farms and corresponding distribution functions are presented in Figure 8 and Figure 9.

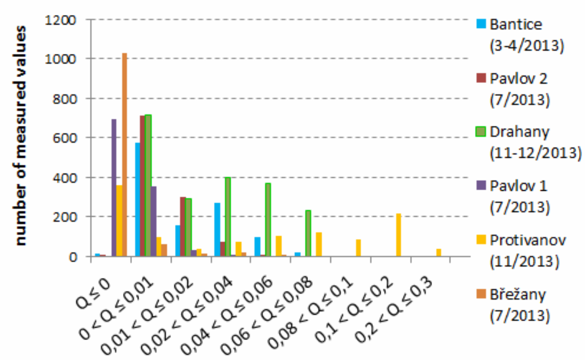

Figure 8 *Occurrence of relative reactive power consumed by wind farms*

Reactive power quantity is expressed as reactive power-to-installed output ratio. Minus sign indicates consumption of capacitive reactive power, i.e. inductive reactive power is delivered to the grid. The operation mode with the consumption of capacitive reactive power ($Q \leq 0$) occurs in time of very low or zero production (e.g. wind farm Pavlov 1 in July, wind farm Protivanov in November). It is also evident from Figures 8 and 9 that reactive power consumption does not exceed 10% of wind farm capacity, with the exception of Protivanov.

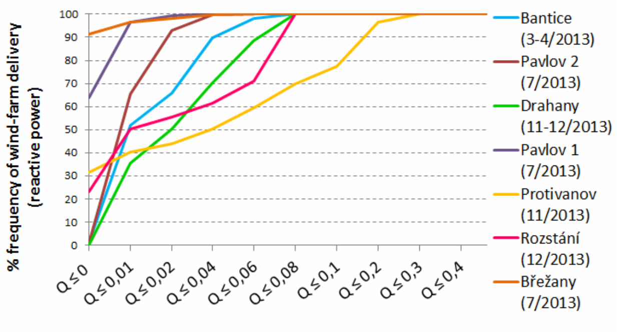

Figure 9 *Distribution functions of relative reactive power consumed by wind farms*

The wind farm Protivanov has the highest reactive power consumption, about 750 kVAr, at full capacity 3000 kW (see Figure 10), with power factor 0.97. Consumption of reactive power (inductive – green columns, capacitive – violet columns) is presented in Figure 10. Consumption of capacitive reaction power is usually lower than 1% of wind farm capacity. Extreme of active power flows closely coincides with maximum of reactive power flows.

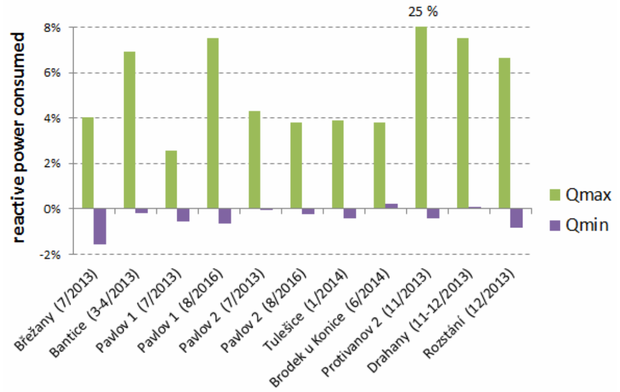

Figure 10 *Summary of reactive power consumed by wind farms (related to their capacity)*

In case of wind farms operated at almost full capacity, the power factor varied within 0.91-1 range (power factor lagging – inductive reactive power is consumed). In case of very low or zero production, the power factor is low or even leading (capacitive reactive power consumed). Impact of operation mode of a wind farm on its power factor is shown in Figure 11.

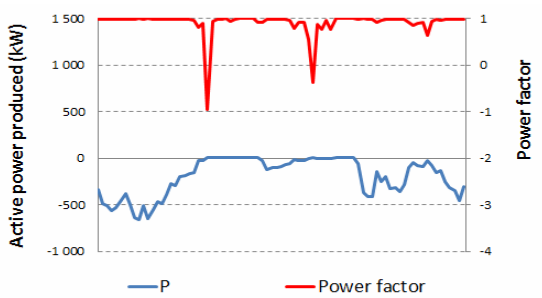

Figure 11 *Impact of operation mode on power factor*

IMPACT OF WIND FARM OPERATION ON VOLTAGE QUALITY IN DELIVERY POINTS

To evaluate the sensitivity of VQ parameters in the delivery point on wind farm operation, correlation coefficients of active power produced versus voltage variations and short-term and long-term flicker severity were determined. Correlation analysis proves dependence of a measured variable on other ones. Correlation coefficients are scale of the dependence. Strong dependence can be considered if correlation coefficient is 0.7 and higher. An example of strong dependence of active power delivered and reactive power consumed by wind farm generators is presented in Figure 7. The correlation coefficient amounts to 0.97.
Relation between active power delivered by a wind farm and voltage variations and flicker severity in the delivery point was evaluated. Results of correlation analysis are summarized in Table 2, wind farms are sorted by short-circuit power in delivery points.

Table 2 *Correlation coefficients of active power and voltage parameters for selected wind farms*

Wind power park	Install. output (kW)	S_k (MVA)	Utilization	Correlation coefficients active power versus		
				U	Pst	Plt
Bantice	2000	103	32 %	0.31	0.01	0.04
Brezany	1700	86	13 %	0,51	0,08	0,02
Pavlov 2	1700	60	9 %	0.53	0.28	0.30
Rozstani	1800	54	49 %	0.66	0.14	0.05
Pavlov 1	4000	47	16 %	0.56	0.33	0.33
Protivanov	3000	41	25 %	0.81	0.83	0.79
Drahany	2000	33	47 %	0.77	0.70	0.70

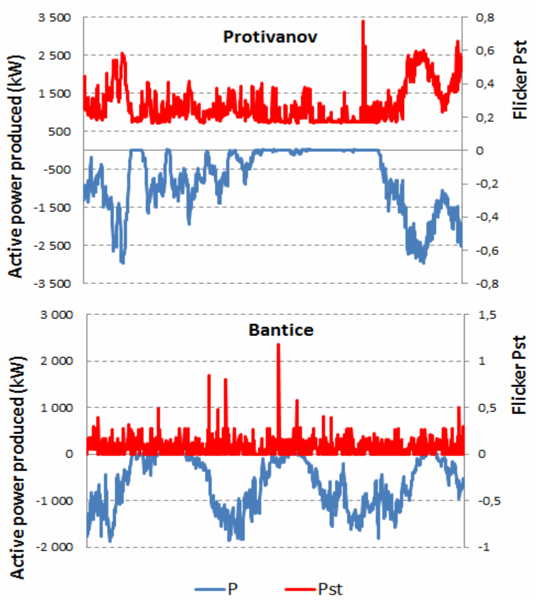

Figure 12 *Course of active power delivered and flicker Pst for two wind farms connected into delivery points with different short-circuit power*

Operation of all wind farms has impact on voltage changes in delivery points, but impact of individual wind farms is different. Voltage is influenced by wind farm operation in a large extent in delivery points at the end of long MV feeders (Drahany – 27 km, Protivanov – 21 km, Rozstani – 17 km and Pavlov – 18 km). Strong coupling between power production and flicker severity is also obvious for these wind farms. Relation between wind farm operation and short-term flicker level P_{st} measured in the delivery point illustrates Figure 12. In the case of wind farm Protivanov, correlation of power produced and flicker severity is strong (correlation coefficient amounts to 0.83), it is easyly visible if courses of both variables are compared each other, in the contrary to wind farm Bantice (correlation coefficient is only 0.01).

Figures 13 and 14 complete the results of correlation analysis (Table 2) by comparison voltage variations for extreme operation modes: maximum and minimum active power produced and maximum active power consumed.

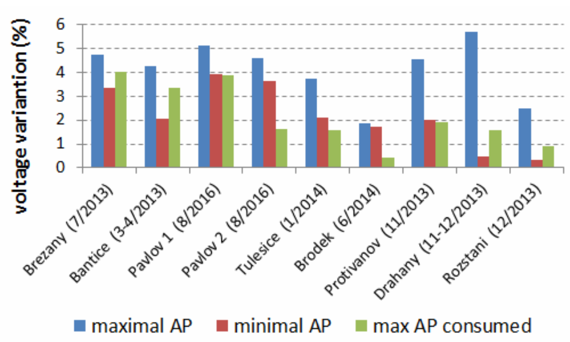

Figure 13 *Impact of wind-farm operation modes on voltage variations*

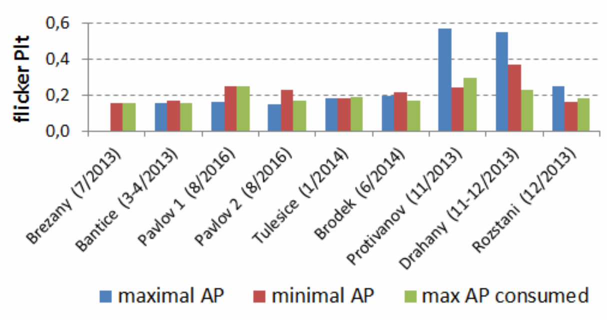

Figure 14 *Impact of wind-farm operation modes on long-term flicker P_{lt}*

CONCLUSIONS

Voltage quality parameters were evaluated in delivery points of the MV wind power plants and were in compliance with the standard EN 50 160.

To evaluate sensitivity of VQ parameters on wind farm operation, the relation between active power production and voltage variations and flicker severity in the delivery point was evaluated. As expected, operation of wind farms has impact on voltage changes as well as flicker severity, but impact of individual wind farms is different. Both VQ parameters are influenced by wind farm operation in a large extent in delivery points at the end of long MV feeders. In these points, the supply voltage varies within the range of nearly 7.5% U_n and can drop below the nominal voltage. Higher values of flicker severity were measured again in delivery points with low short-circuit power, but the correlation with power produced was not as strong as in the case of voltage variations, mainly for delivery point with short-circuit power above 50 MVA.

Power flows in delivery points of wind farms were evaluated and mutually compared to find the pattern of their performance during a year. As expected, power production varies greatly during a year. Extreme of active power flows closely coincides with maximum of reactive power flows. In generation mode, inductive reactive power is usually consumed because of less impact on voltage changes. Its consumption is usually below 10% of wind farm capacity. Consumption of capacitive reaction power is usually lower than 1% of wind farm capacity and is more frequent in the case of wind farms operated considerably below their installed capacity.

ACKNOWLEDGMENTS

This work was supported by the project SGS-2015-031.

REFERENCES

[1] D. Mezera, 2013, "Voltage quality in the low voltage distribution grids with the high penetration of distributed energy sources", *Proceedings of the 14th International Scientific Conference on Electric Power Engineering 2013*, Czech Republic

[2] F. Bernáth, P. Mastný, 2014, "Distributed generation and voltage control in distribution network - Reactive power control of power sources", *Proceedings of the 15th International Scientific Conference on Electric Power Engineering 2014,* Brno, Czech Republic

[3] R. Goic, D. Jakus, J. Krstulovic, J. Vasilj, 2011, "Voltage profile analysis ", *Proceedings of the 21st International Conference on Electricity Distribution (CIRED 2011)*, Frankfurt, Germany, paper 0989

[4] J. Jiricka, D. Mezera, M. Kaspirek, 2014, "Analysis of reactive power flows between transmission and distribution systems and distribution networks", *Proceedings of the 9th Conference on energetic disturbance in distribution and industrial networks (ERU 2014)*, Brno, Czech Republic (in Czech)

[5] M. Kaspirek, D. Mezera, P. Jaros, 2016, "Impact of wind power plants on the medium voltage distribution grid", *Proceedings of the 6th International Scientific Conference Renewable Energy Source*, Tatranské Matliare, Slovak Republic