Voltage Control Aspects of Wind Generation in Meshed Distribution Grid

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***Abstract*— In the perspective of coming years the operation of accumulated wind generation in some areas of distribution network in Polish Power Grid will highly influence a voltage pattern. The analysis of necessary reactive power sources to keep voltage in permissible ranges and of an impact on grid losses was carried out. The cases of different wind farm reactive power operation modes were studied as well as usage of additional reactive power sources to maintain voltage in permissible ranges. Studies were carried out for various wind generation levels expected in the next few years.**

Keywords-component; wind farm, grid voltage control, reactive power compensation, distribution grid, Spanish model of wind farm controlling

I. Introduction

Wind power development came from the stage of performing expertises and issuing permissions for grid connection in which wind generation despite some connections of wind farms mainly remained on paper to the stage of realization and quick growth of total connected wind farms power. Total wind farms power, which received permissions exceeded in April 2010 15 000 MW. It can be expected that quite a big part of the issued permission will be realized in the coming years. The paper describes the results of the analysis of voltage aspects of wind generation on an area of high wind power development.

A. *Wind Power in Poland – basic facts and forecasts*

Total power of wind farms installed in Polish Power Grid (KSE) exceeded 720 MW (April 2010). According to EU directive 2009/28/WE, at least 15% of final energy consumption in Poland must come from renewable energy sources by 2020. According to *Energy policy of Poland until 2030* [1] to fulfill EU requirements, the share of energy coming from renewables in final electric energy consumption should be at the level of 12,2% in 2015 and 19,3% in 2020. The significant part of green energy will come from wind generation and this document predicts that it will be necessary connection of 3400 MW until 2015 and 6100 MW until 2020 to achieve assumed requirements. The document estimates potential of wind energy by 2020 to be around 16 000 MW.

B. *Studied area*

EHV grid in the analyzed area is shown in the figure 1. There is one coal power plant connected to the EHV grid (STA1) and one wind farm transformer station (WF1) connected to 220 kV grid. Connections with the rest of the power system can be seen in the figure – the lines coming out

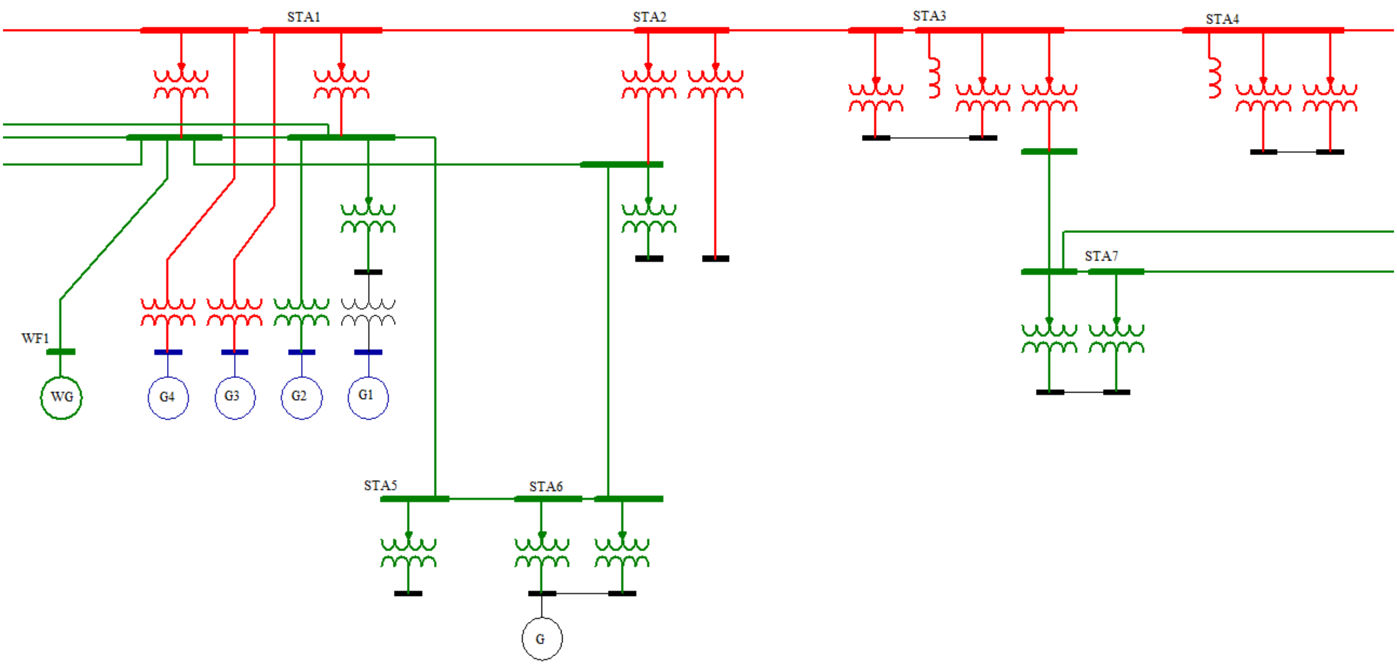

Figure 1. EHV grid in the analyzed area.

from stations to the border of the figure. The analyzed area matches a real area with a perspective of high wind power development in KSE. On the high wind power development area ca 30% of wind farms with permissions for grid connection are located.

The analyzed area is a part of a big power system. It consists of:

- 8 EHV stations:
  - 4 stations with 400 kV switching yards and
  - 6 stations with 220 kV switching yards,
  - 1 wind farm transformer station (220 kV).
- 120 HV stations and wind farm transformer stations.
- One coal power station (STA1) with:
  - 4 units generating 420 MW in summer light load (SLL),
  - 4 units generating 700 MW in summer peak load (SPL).
- 3 power plants generating total power of 99 MW.
- 32 wind farms:
  - 31 wind farms connected to HV grid,
  - 1 wind farm connected to EHV grid (WF1).

Basic data of the studied area were collected in table I.

TABLE I. THE AREA BASIC DATA

	Number of sources	Number of generators	Grid	Power	
				SLL	*SPL*
Coal power plant	1	4	EHV	320 MW	590 MW
		1	HV	100 MW	110 MW
Other lesser heat power plants	3	3	HV	99 MW	99 MW
Renewable generation[1]	16			7 MW	7 MW
Power load				432 MW	751 MW
Shunts			EHV	-120 MVAr -50 MVAr	

In the analyzed area there are two shunt reactors in summer light load:

- –50 MVAr at the 400 kV bus in STA3 station[2]
- –120 MVAr at the 400 kV bus in STA4 station

Shunt configuration in EHV network is based on the contingencies analysis of a model with connected wind farms generating 25% of nominal power. The shunts configuration assures in single contingency keeping voltages in EHV grid in the permissible range without any changes in that configuration.

C. *Analyzed levels of wind generation*

Three levels of wind generation were analyzed (table II):

- without wind generation
- 354 MW of wind generation in the area – a level of nominal present wind generation
- 1415 MW of wind generation in the area – a level of wind generation probable in a few years

TABLE II. WIND GENERATION

	Number of sources	Total power	Total power
		[MW]	*[MW]*
Wind generation		354	1415
Wind farms in EHV grid	1	70	280
Wind farms in HV grid	31	284	1135

D. *Analysis Assumptions*

- Generators and transformers keep 117÷118 kV on HV side.
- The outages of each branch and each double circuit line in EHV network were analyzed as well as crucial lines in HV network, especially lines coming out from EHV/HV stations.
- If it is not stated otherwise the analysis concerns the summer light load model. The most of voltage problems were noticed while studying summer light load models. Studying other demand models: summer peak load, and winter light load and winter peak load did not show any new voltage problems connected with wind generation.
- Generators or transformers in the area were configured in order to minimize losses and reactive power.
- Parameters especially observed in carried analysis:
  - voltages,
  - reactive power flows,
  - reactive power reserve on generators,
  - positions of taps in EHV/HV transformers.

II. VOLTAGE CONTROL REGULATIONS

There are several approaches to voltage and reactive power controlling in power system in presence of wind generation depending on wind farms operation mode:

A. *Constant cosφ operation mode*

Wind farm operating with constant cosφ does not regulate grid voltage. Usually wind turbine generators operate with cosφ = 1 to minimize production losses. This mode was common in the beginning of wind energy development. In that operation mode the growth of wind generation increases grid voltage problems.

B. *Operation in determined range of cosφ*

This is currently the most common wind farm operation regulation. According to Polish TSO (PSE-Operator) Grid Code (IRiESP) wind farms connected to EHV or HV systems

[1] Renewable generation other than wind generation
[2] It is assumed in the paper negative value for shunt reactor and positive for shunt capacitor

should be capable of participating in grid voltage regulation in the range of cosφ = $0{,}975_{CAP}÷0{,}975_{IN}$[3]. Regulated voltage or reactive power can be set remotely from central management system.

C. A group of wind farms operating as a wind power plant

A group of farm can be managed by a central system (WFMS) and treated from the grid point of view as one generation source behaving like conventional power plant. It applies mainly to a group of farms located close to each other and especially big farms connected to the EHV grid or group of farms connected to the EHV grid by one separated transformer. Such wind farms participate in grid voltage regulation in the determined range of cosφ ($0{,}975_{CAP}÷0{,}975_{IND}$ in KSE). An example of such approach can be Wind Farm Cluster Management System applied in German Power System (first system was tested in the grid of E.ON Netz) [3]. Similar systems are applied in Spain and Portugal.

D. The Spanish model of wind farm reactive power controlling

The Spanish regulation of voltage control is based on bonuses and penalties depending on the reactive power system factor for the special regime generation [4][5]. Table III shows the value of power factor and the percentage incentive/penalization in the different daily demand periods. Depending on the local needs there are 7 zones each with the different schedule of demand periods. This way of reactive power control is in the economical character. Apart from that economical way of controlling, wind farms active and reactive power generation are controlled by Control Centers, which send time shift instructions to farms to avoid danger of abrupt changes in voltage profile in consequence of simultaneous change in reactive power in a big zone.

TABLE III. REACTIVE POWER BONUS IN THE SPANISH REGULATION

Type of Power Factor	Power Factor	Bonus [%]		
		Peak Load	Medium Load	Low Load
Inductive	pf < 0,95	-4	-4	8
	0,95 ≤ pf < 0,96	-3	0	6
	0,96 ≤ pf < 0,97	-2	0	4
	0,97 ≤ pf < 0,98	-1	0	2
	0,98 ≤ pf < 1	0	2	0
	1	0	4	0
Capacitive	0,98 ≤ pf < 1	0	2	0
	0,97 ≤ pf < 0,98	2	0	-1
	0,96 ≤ pf < 0,97	4	0	-2
	0,95 ≤ pf < 0,96	6	0	-3
	pf < 0,95	8	-4	-4

The Spanish power system peak demand is 45 GW and wind power capacity exceeded 16 GW. Such level of wind energy penetration of KSE is expected after 2020. The maximum instantaneous peak wind production was nearly 11 GW (~70%).

Spanish regulation variant analysis was carried out on the assumption that all wind farms operate in the optimal mode (with the highest available bonus). The value of the bonus is out of interest in this analysis. The Spanish variant was treated as a case of operating wind farms with constant cosφ equal for farms in the same zone.

III. WITHOUT WIND GENERATION

In *n-1* analysis no voltage out of the permissible range was noticed in summer light load model with no wind generation. There was not much reserve of reactive power (32 MVAr) on the power station generators[4].

In the summer peak load model analysis there were three contingencies causing voltage drop below the permission minimum in HV stations far away from transformers and energy sources. On EHV/HV transformers rather small flows of reactive power can be observed.

IV. 354 MW OF WIND GENERATION

A. Base Case – cosφ = 1

In summer light load model all generators in the power station operate with minimum or nearly minimum reactive power. Operating without reserve of reactive power of the only big power station in the area is not safe, what is proved by the problems noticed in contingency analysis. Some reactive power sources are necessary.

Wind generation of 354 MW at cosφ = 1 does not cause voltage problems in summer peak load model. The power station operates with safe reactive power reserve.

B. Shunt installation – cosφ = 1

Overvoltages that occurred in analyzed summer light load *n-1* contingencies can be eliminated by installing –50 MVAr shunt reactor to the 400 kV bus in the power station (STA1), or by installing two shunt reactors in 110 kV stations in the vicinity of wind farms, –10 MVAr near the station STA1 and –25 MVAr near the station STA3.

C. Wind farms voltage regulation in the range of cosφ = $0{,}975_{CAP}÷0{,}975_{IND}$

Like in the previous case, using wind farm abilities of generating/consuming reactive power in the range of cosφ = $0{,}975_{CAP}÷0{,}975_{IND}$ allows power system operation in the permissible range of voltages. Wind farm connected to EHV system generates 16 MVAr of reactive power, all farms connected to HV network altogether generate 9 MVAr and consume –22 MVAr.

In this case Q_{IND} = –22 MVAr and Q_{CAP} = 25 MVAr was used in the base contingency what makes a need of reactive power about –6,2%÷7,1% of P_{WG} (total power of wind generation).

[3] If it is not stated otherwise cosφ concerns connection point of a wind farm to the grid

[4] if it is not stated otherwise the power station term concerns the coal power station (STA1)

D. Wind farms operation in determined cosφ = const – Spanish model

Spanish regulation variant analysis was carried out on the assumption that all wind farm operates with the same cosφ = $0{,}991_{IND}$ (tanφ = –0,133). Such value of cosφ at the point of connection of a wind farm to the grid matches approximately the cosφ = 1 on wind farm generators.

No voltage problems in *n-1* contingency were noticed in the summer light load. Total reactive power Q_{IND} = –47,2 MVAr was used, what makes a need of reactive power –13,3% of P_{WG}.

Wind farms operation in determined cosφ = const seems to be the convenient mode of wind farms operation in a grid with low and medium wind generation penetration level.

V. 1415 MW of Wind Generation

1415 MW is the feasible nominal quantity of power generation for the studied area in a few years, made as an assumption based on a forecast for the analogous area of the real power system. 1415 MW of wind generation is about 30% of total power of wind farms with permissions for grid connection which corresponds to the analyzed area. That amount of wind generation is 80% of wind power on that area forecasted for 2020 and 42% of total wind power for 2015 [1][2]. On account of assumed few years perspective of power system, most of new farms to be connected to EHV grid were not taken into consideration because of longer time of the realization of investment in the power system demanded in permissions for grid connection for those farms (building new EHV lines).

A. Base Case - cosφ = 1

In the summer light load model to keep voltage in the permissible range in *n-1* contingency it was necessary to set voltage 115.3÷116.5 kV on HV buses in three EHV/HV stations. Four ULTC's tap position are set to the last or the last but one position. All generators in the coal power station operate with minimum or nearly minimum reactive power.

Such conditions do not assure the safe operating conditions of power system. Some reactive power sources are necessary.

Similarly in the summer peak load model there was no possibilities to avoid overvoltages in HV systems keeping about 117,5 kV on EHV/HV transformers without any additional reactive power sources.

B. Shunt installation – cosφ = 1

The installation of –100 MVAr shunt reactor to the 400 kV bus in the power station (STA1) was examined. It improved the operation of EHV network, but it wasn't enough to eliminate overvoltages in *n-1* contingencies in 110 kV grid.

To eliminate overvoltages in HV network besides –100 MVAr (or at least –50 MVAr) shunt reactor at the 400 kV bus in STA1 station, installing shunt reactors in HV station was necessary. Two shunt reactors (–30 MVAr and –15 MVAr) were installed near STA3 station and two more (–15 MVAr and –10 MVAr) in vicinity of STA2. Regarding a need of installation quite big shunt reactor in HV grid, it is better for the safety of system power operation to install several shunt reactors near wind farms then one or two bigger ones. That leads to the idea of using rather an ability of generating/consuming reactive power by wind farms.

Total reactive power of used in the case was –170 MVAr (–12,0% of P_{WG}). Total reactive power of needed in summer peak load was about –60 MVAr.

C. Wind farms voltage regulation in the range of cosφ = $0{,}975_{CAP}$÷$0{,}975_{IND}$

In spite of wind farms ability of reactive power generating/consuming for safe system operation a shunt reactor to the 400 kV bus in the power station (STA1) was installed. The shunt reactor allowed to reduce the surplus of reactive power in the area. –50 MVAr shunt reactor didn't provide the safe reserve of reactive power on generators operating on EHV systems (only 35 MVAr). For analysis –100 MVAr shunt reactor was applied. The wind farm (WF1) connected to EHV system generates 6 MVAr of reactive power, all farms connected to HV network altogether generate 13 MVAr and consume –85 MVAr.

In this case Q_{IND} = –185 MVAr and Q_{CAP} = 19 MVAr was used in the base contingency what makes a need of reactive power about –13,1%÷1,3% of P_{WG}.

In summer peak load voltage outside the permissible range was noticed in two of analyzed *n-1* contingencies. In the first case it was low voltage (104.5 kV) in a HV station powered through a long route of lines after the loss of connection to EHV/HV transformer station. This case is without any connection with wind generation. The second case is high voltage of 121,2 kV in a wind farm station.

Q_{IND} = –160 MVAr and Q_{CAP} = 9 MVAr was used in the base contingency of summer peak what makes a need of reactive power about –11.2%÷0.6% of P_{WG}.

D. Wind farms operation in determined cosφ = const – Spanish model

Several variants of the Spanish model were analyzed in the summer light load model. In the first one an assumption was made that all the wind farms operate with the same cosφ = 0.991_{IND} (tanφ = –0.133). In two zones of wind farms concentration in 110 kV network (one near STA1 and STA2, the other near STA3) there were problems with keeping voltages in the permissible range and the reserve of reactive power on generators in the power station (STA1) was rather low. Installing –50 MVAr shunt reactor nor –100 MVAr, although improved reserve of reactive power on generators, did not eliminate all noticed overvoltages in *n-1* contingencies.

To eliminate overvoltages in these two zones shunt reactors were installed in HV stations: –10 MVAr near STA2 and –15 MVAr near STA3. The wind farm connected to EHV system generates –37 MVAr of reactive power, all farms connected to HV network altogether consume –151 MVAr. Total reactive power of used in the case was –214 MVAr (–15.1% of P_{WG}).

In other variants an increase of wind farm reactive consumption was tested instead of installing shunts:

- The area was divided into two zones, the first near stations STA1, STA2, STA3, STA5 and STA6. Wind farms in this zone operate with $\cos\varphi = 0{,}9805_{IND}$ ($\tan\varphi = -0{,}200$). The second zone near stations STA4, and STA7 and the wind farm connected to 220 kV system WF1. Wind farms in this zone operate with $\cos\varphi = 0{,}991_{IND}$ ($\tan\varphi = -0{,}133$).
  To eliminate overvoltages in *n-1* contingencies in that case installation of –10 MVAr shunt reactor in a HV station in vicinity of wind farm group near STA3 was necessary. Total reactive power of used in the case was –239 MVAr (-16,9% of P_{WG}).
- Resignation of that HV shunt reactor requires dividing the area into three zones. The first one near stations STA1, STA2, STA5 and STA6. Wind farms in this zone operate with $\cos\varphi = 0{,}9805_{IND}$ ($\tan\varphi = -0{,}200$). The second zone near the station STA3 with $\cos\varphi = 0{,}975_{IND}$ ($\tan\varphi = -0{,}223$). The third zone near the stations STA4, and STA7 and the wind farm connected to 220 kV system WF1 $\cos\varphi = 0{,}991_{IND}$ ($\tan\varphi = -0{,}133$).
  No voltage problems were noticed in *n-1* contingencies. Total reactive power of used in the case was –242 MVAr (-17,1% of P_{WG}).
  An increase of reactive power flow on 400/110 kV Transformers in station STA3 can be seen (40÷50 MVAr from EHV grid to HV grid).

In the summer peak the area was divided into three zones, the first near the stations STA1, STA2, STA5 and STA6 and the wind farm connected to 220 kV system WF1. Wind farms in this zone operate with $\cos\varphi = 1$ ($\tan\varphi = 0$). The second zone near the station STA3 with $\cos\varphi = 0{,}9805_{IND}$ ($\tan\varphi = -0{,}200$). The third zone near the stations STA4, and STA7 with $\cos\varphi = 0{,}991_{IND}$ ($\tan\varphi = -0{,}133$).
Only in one *n-1* contingency too low voltage was noticed (104,3 kV) in a HV station powered through a long route of lines after loss of connection to EHV/HV transformer station and it was without any connection with wind generation (like in case C – regulation in range of $\cos\varphi = 0{,}975_{CAP} \div 0{,}975_{IND}$). Total reactive power of used in the case was –172 MVAr (-12,2% of P_{WG}).

Comparing to voltage regulation in the range of $\cos\varphi = 0{,}975_{CAP} \div 0{,}975_{IND}$ described in previous paragraph, Spanish regulation causes certain increase of losses (table IV).

VI. Keeping Higher Voltage in 110 kV Grid

An impact of increasing voltage in 110 kV grid on power system operation in presence of high level wind generation was analyzed. In that case generators and transformers were keeping 119.5÷120.5 kV on HV side.

Some observations were made:

- Increase of voltage in HV grid caused a higher risk of overvoltage occurrences in *n-1* contingencies, especially in HV stations far from EHV/HV transformers or big power plants.
- The surplus of reactive power in the HV network appeared and in consequence of that some more shunt reactors had to be installed.
- Increase of branch losses can be observed (table IV).

The conclusion can be drawn that in the high level of wind energy penetration of power system keeping voltage near the high limit (ca. 120 kV) is less safe and causes more losses. Generators and EHV/HV transformers should keep ca. 117÷118 kV on HV side.

TABLE IV. Losses and Charging Summary. Summer Light Load Models

	Losses		Charging
	[MW]	*[MVAr]*	*[MVAr]*
$\cos\varphi = 0{,}975_{CAP} \div 0{,}975_{IND}$ 117÷118 kV	39.7	208.9	312.0
Spanish model without shunts cosφ = const 117÷118 kV	40.2	213.1	306.6
Spanish model with shunts cosφ = const 117÷118 kV	41.0	215.2	305.6
$\cos\varphi = 0{,}975_{CAP} \div 0{,}975_{IND}$ 119.5÷120.5 kV	41.0	219.5	307.4

VII. Conclusions

The wind generation of 1415 MW in the studied area corresponds to a situation that can be feasible in KSE in a few years. Safe operation of power system with such level of penetration of wind generation requires additional reactive power in the grid. The carried analysis shows that amount of inductive reactive power needed in the base case and most of *n-1* contingencies is at least about –11,2% of total power wind farms (P_{WG}). It is about a half of reactive power that should be accessible from wind farms according to IRiESP (and expressed in permissions for grid connection).

In the area of high growth of wind generation installing a shunt reactor in EHV network in spite of reactive power generating/consuming ability of wind farms connected to HV network may allow to reduce total reactive power demand.

Above a certain level of wind energy penetration of power system wind farms participation in grid voltage regulation is usually controlled by WFMS. WFMS main aims are keeping grid voltage in permissible range and often minimizing losses and reactive power utilization. It usually leads to the operation of wind farms with different power factor. In such approach a normal wind farm operation changes only after a command from central system (or after a change of wind).

Wind farms located in vicinity can operate with the same power factor which depends on a zone (wind farm localization) and demand schedule (season, time of the day). Wind farms can operate independently according to a schedule. Control procedure guidelines can be sent by WFMS when an update is needed. In such approach, wind farm should be divided into groups located in vicinity. Each group would have assigned one of several operation schedules. Such way of wind farm controlling is especially useful in areas with stable demand rhythms.

In contingencies with significant influence on voltage profile near a wind farm as well in case of rapid voltage change in the connection point to the maximum/minimum value, the wind farm operating with constant power factor should change operation mode into voltage regulation (voltage limiter mode).

When the procedure guidelines are not obligatory, the management is in the economical character system of incentive/penalization (Spanish regulations). Spanish regulation variant analysis was carried out on the assumption that all wind farms operate in the optimal mode (with the highest available bonus). Otherwise, if operation in not the optimal mode were permitted there would be a risk of overvoltage occurrences in *n-1* contingencies and some more reactive power sources would be required in zones of wind farms concentration in HV grid.

In order to minimize the risk of overvoltage occurrences and to minimize losses generators and EHV/HV transformers should keep ca. 117÷118 kV on HV side.

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