Assessment of Wind Power Impact on Power System Transmission Losses

Sanna Uski, and Inna Kim

Abstract—**Large-scale wind power may change and vary the load flows in a power system. Thus, it also has an impact on the transmission losses. The traditionally used simulation cases may not be representative for analyzing the overall impact on losses. This paper suggests a screening method for determining the simulation cases to be used for the analysis of wind power impact on transmission system losses. The approach is based on the estimated load data series and wind power production data series for wind power scenarios. The power system losses in the end are estimated by power system load flow simulations. The suggested method is demonstrated and illustrated by the wind power integration study for Kazakhstan. The results of the case study indicate a decrease in power transmission losses in the case of wind power integration to the power system of Kazakhstan according to the studied wind power scenario.**

***Index Terms*—load flow, power system losses, transmission losses, wind power.**

I. INTRODUCTION

Usually the best wind resources and thus wind power plant locations tend to be far from electricity consumption and the big load centers, as well as far from the other power plants.

In transmission systems with large power transmission over long transmission distances, the power transmission losses can be high. The power transmission losses range from a couple to several of per cents of the electricity consumption. Therefore, the power transmission losses are a significant power transmission system feature to be considered. As wind power is generally built in novel power production locations, it may change the transmission system power flows—and the transmission losses—quite significantly.

There are published only few studies in which the wind power impact on transmission losses has been considered. The European Wind Integration Study (EWIS) [1], [2] discussed only briefly the wind power influence on transmission system losses in some areas under the extreme study circumstances. In addition, Farahmand et al. have studied in [3] the power system transmission losses of future offshore wind power plants and offshore grids. Those study results were related to flow-based market model simulations and thus determined for the whole study year. The model used in the study by Farahmand et al. comprised of the European power system. Other research on the wind power impact on transmission losses is generally related and limited to the analysis of offshore interconnection options, e.g. in [4] and [6].

The guidelines for assessing the wind power impact on power system losses—especially in the AC grids—are not explicitly defined yet, and there are only few methods presented. Liu and Martin use in [7] the load flow simulation for each hour of the year for determining the system losses caused by wind power.

It may not always be possible nor worth the effort to simulate each hour of the year, and the typical winter peak simulation case may not give a good indication of wind power influence on transmission losses alone.

This paper describes a method for determining the simulation cases for studying wind power influence on power system losses, e.g., in wind power integration studies. The method, based on the analysis of wind power and load data series, is applicable generally in a power system or subsystem level. The method is demonstrated by the wind power integration study for the power system of Kazakhstan [8].

II. WIND POWER IMPACT ON THE POWER SYSTEM LOSSES

A. Wind power generation units in a power system

Wind power production is different by nature from the conventional power production in power systems. In addition to being variable production the wind power production units differ from the conventional power generators also in terms of the technical and electrical aspects. Due to the power electronic converters, the modern wind turbines, e.g., have rather broad and flexible capability of reactive power and voltage control.

Generally, the power production units are preferred operating close to the unity power factor as reactive power transmission also causes transmission losses. Non-unity power factor operation may also be used in normal operation.

In the assessment of the wind power impact on the power system losses, according to [9], omitting wind turbine reactive power control mode does not cause a huge error.

B. Power system transmission losses – analysis methodology

The power transmission losses are proportional to the current transmitted. As the load varies throughout the year—in the seasonal, weekday and diurnal time scale—the generation dispatch also varies.

The wind power impact on the power system transmission losses should be determined by a benchmark case and a study case. The study case contains wind power as part of the power system production portfolio. The benchmark case is without wind power production in the power system production

---

S. Uski is with VTT Technical Research Centre of Finland, (e-mail: sanna.uski@vtt.fi).

I. Kim is with Center of Energy Development in JSC “Kazakh Research Institute of Power Engineering named after Sh. Ch. Chokin”.

portfolio and the power production is covered completely by other forms of power generation. The wind power impact on the power transmission losses is assessed by calculating the difference in losses between these two cases.

Potentially only a few cases are possible to be studied instead of the 8760 hourly cases for the whole year, that would give more accurate results. These few simulation cases ought to be the most representative and indicative ones and suitably selected for the purpose.

The snapshot load flow cases to be studied in the wind power integration study for Kazakhstan for example, was limited to the total of three cases.

The peak load case is a very common simulation case for the power system simulations in general. The peak load hour case, however, is a special case occurring only once per year, as pointed out also in [7]. It is probably also the most stressed power system normal operation situation. In addition, e.g., in the Nordic countries there seems to be correlation between the peak load hour and low wind power production—both due to very low temperatures—as pointed out in [9].

The method described in this paper helps out in the selection of the most typical cases and highest wind power impact cases for the power transmission loss analysis.

C. Setting up the load flow simulation cases

The power system load flow simulation model must be set up for each case to be simulated. The most accurate approach would be to use snapshot cases provided by generation and load dispatch models for each hour of the year combined with hourly wind power data series for each wind power plant to be included in the study for the future scenario.

Unless using the generation and load dispatch models' output for setting up the few power system load flow cases to be studies, at simplest the existing, e.g., peak load case can be scaled down suitably.

III. METHOD FOR SELECTING LOAD FLOW SIMULATION CASES

In determining the cases for the analysis of wind power production impact on transmission losses, the following should be considered:

1. frequent situation occurrence (within a year) and
2. higher wind power production rather than lower production, signifying more wind power impact.

A. Occurrence frequencies of incidents

Due to point 1. above, the load data $P_l \in (P_{l,peak}, P_{l,min})$ and wind power data (of individual wind power plant, wind power cluster, or the whole power system combined wind power data) $P_{wp} \in (P_{wp,nom}, 0)$ are analyzed, and bivariate frequency distribution matrix ***F*** of system load and wind power production is formed. The intervals $(P_{l,peak}, P_{l,min})$ between the peak and minimum load and $(P_{wp,nom}, 0)$ between the nominal wind power capacity and zero production are divided into subintervals as follows

$$(P_{l,peak}, P_{l,min}) \to (a, b), \tag{1}$$

$$(P_{wp,nom}, 0) \to (c, d), \tag{2}$$

$$\begin{cases} a = P_{l,peak} - (i-1)\frac{P_{l,peak}-P_{l,min}}{m} \\ b = P_{l,peak} - i\frac{P_{l,peak}-P_{l,min}}{m} \end{cases}, i = 1,2,\dots,m \tag{3}$$

$$\begin{cases} c = P_{wp,nom} - (j-1)\frac{P_{wp,nom}}{n} \\ d = P_{wp,nom} - j\frac{P_{wp,nom}}{n} \end{cases}, j = 1,2,\dots,n. \tag{4}$$

The bivariate frequency distribution matrix ***F*** consists of the elements f_{ij} expressing the occurrence frequency of the incidents when the P_l and P_{wp} data series are categorized by

$$P_{l,t} \in (a, b) \land P_{wp,t} \in (c, d),\ t = 1,2,\dots,8760. \tag{5}$$

The wind power production can be categorized e.g. by 10 %-unit intervals of the nominal wind power capacity, and the power system load categorized e.g. by 10 %-unit intervals between peak load and minimum load.

A good set of categories (for 10 x 10 table and determined by the Kazakhstan data analysis) that makes the most frequent situations stand out is, e.g. > 300 h; 300…200 h; 200…100 h; < 100 h. Using color scaling for visualization in the frequency occurrence matrix table, the table illustrates the power system characteristics with the studied wind power scenario at a single glance.

B. Energy influence

Considering only the frequencies of the occurrence, i.e., the number of hours per year, a certain high wind power production level and a certain low wind power production level could occur equally often over the year. However, the higher wind power production changes the power generation dispatch more in the system, and thus potentially has more influence on power transmission in the power system than the equally frequently occurring lower wind power production case. Larger influence on power transmission—being either increasing or decreasing the transmission compared to the benchmark case—has corresponding influence on the transmission losses. Thus, due to point 2. above, the energy production of wind power is considered instead of considering only the actual count of occurrence hours based on frequency distribution of data classification by (1)–(5) above.

Similarly to frequency distribution tables, these energy influence tables are categorized. A good set of categories that makes the most "wind energy influential" situations stand out is e.g. > 80 %; 80…60 %; 60…40 %; < 40 % of maximum value in the table, $max(E_{wp,i,j})$.

The occurrence frequency distribution tables and nominal wind power capacity are used in calculating the energy influence. The energy influence for each category is

$$E_{wp,ij} = f_{ij}(c+d)/2, \begin{cases} i = 1,2,\dots,m \\ j = 1,2,\dots,n \end{cases} \tag{6}$$

with terms *c* and *d* determined in (4).

IV. STUDY CASE: POWER SYSTEM OF KAZAKHSTAN

The analyzed wind power scenario consists of 2000 MW wind power production capacity for 2030. This wind power production capacity corresponds to about 4 % wind power penetration level in annual electrical energy production. The 2000 MW wind power scenario capacity is distributed in several locations in Kazakhstan. The study scenario wind power plant locations and capacities are shown in Fig. 1.

Fig. 1. Wind power scenario power plant locations and capacities of the Kazakhstan wind integration study. Wind power plant clusters circled.

The Western part of the country is loosely interconnected to the rest of the power system of Kazakhstan. In addition, the wind power scenario wind power plants in the Western part of the country logically form one wind power plant cluster of 600 MW (see Fig. 1). In the area of Northern and Southern zones, there is a stronger grid as well as the majority of consumption and power production. There also is generally large power transmission from North to South. Thus the wind power plants in the North and in the South form two wind power clusters of 500 MW and 900 MW respectively.

Hourly wind power production data series were prepared for each individual wind power plant in the scenario for the wind integration study of Kazakhstan, described in [8].

Hourly load data series for the analysis was formed for Kazakhstan based on the monthly load profile, summer low load and winter peak load daily profiles, as well as the predicted value for peak load for year 2030, described in [8].

In the load flow simulation there is assumed a unity power factor for wind power generation and reactive power limits are set to zero.

V. METHOD DEMONSTRATION BY KAZAKHSTAN CASE STUDY

In the study of Kazakhstan, the winter peak, summer low load and intermediate load case were pre-determined to be used in the wind integration study.

The occurrence frequency distribution of wind power production and load levels of the three wind power clusters as well as the whole country are shown in table II. The corresponding energy influence of the wind power occurrence frequency are shown in table III.

The energy influence matrices point out the most significant situations and determine the load flow simulation cases for the power system loss analysis. The results show that the peak load case—or even the highest load level of the ten levels between minimum and peak load—generally is not among the most frequently occurring ones or significant in terms of energy influence.

The most straightforward choice of the wind power production level is for the North wind power cluster, for which the highest wind power production category actually is the most influential irrespective of the load level as seen in table III. The largest wind power influence is a bit more emphasized in higher load levels than the lower ones.

For the largest wind power cluster, South, the most influential situations are in the power production range of 40–70 % production of the nominal power in the high load level categories 7 and 8.

In the West wind power cluster the most influential situations are on quite low load, combined with low wind power production. However, the medium load area with mid-production also shows some significance.

As synthesis of the above analysis and conclusions of the result tables II–III, the selected load flow cases to be simulated with wind power production levels are presented in table I.

TABLE I
STUDY CASES: DIFFERENT SYSTEM LOAD LEVELS AND CORRESPONDING WIND POWER PRODUCTION CASES.

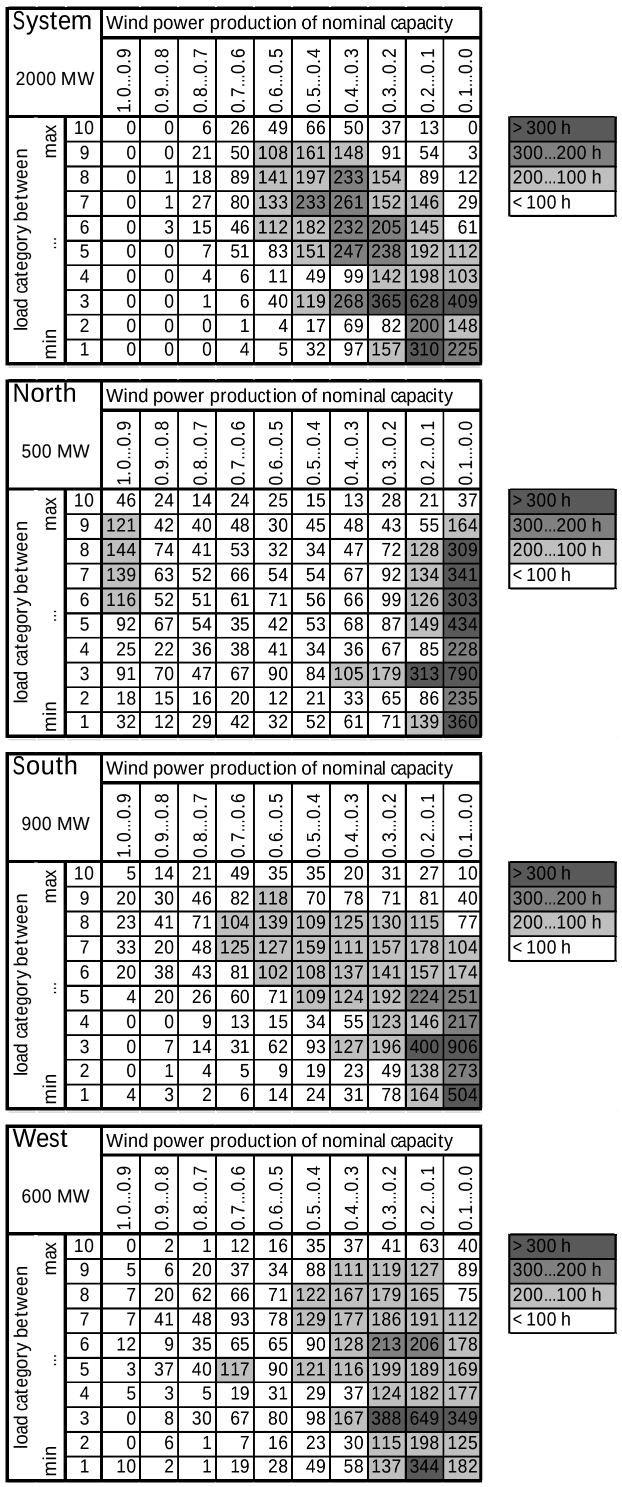
Winter peak case (23 620 MW)	Without wind power
	2000 MW wind power
	WEST 50 % production
	NORTH 95 % production
	SOUTH 65 % production
Medium load case (20 000 MW)	Without wind power
	WEST 50 % production
	NORTH 95 % production
	SOUTH 55 % production
Summer low day load case (15500 MW)	Without wind power
	WEST 30 % production
	NORTH 95 % production
	SOUTH 25 % production

Each cluster was analyzed separately in all three specified load cases, while wind power production in the other two clusters was set to zero. The simulations were run with the transmission system model implemented in RASTR simulation software. The model consists of the lines with 220 kV and higher in the power system of Kazakhstan, as well as Yekaterinburg area in Russia. Other power production in the power system was scaled evenly to correspond to the load.

The transmission losses were studied in two areas. The Western part of the power system is distant and loosely connected to the rest of the already vast system, so it is reasonable to consider separately the results of this area. The main focus is on the North-South transmission that is large, thus having significant impact on the power system losses. Therefore this big area of Northern and Southern zones is observed as one. In addition the total system losses were observed.

The simulation results for transmission losses are shown in Fig. 2. The whole system power transmission losses were highest in the winter peak load case without wind power, being 4.4 % of the total system load. The intermediate load case shows the most important and indicative results, as it represents the most frequently occurring situation and is evaluated to

TABLE II. BIVARIATE OCCURRENCE FREQUENCY DISTRIBUTION TABLES [h] OF LOAD AND WIND POWER PRODUCTION HOURLY DATA SERIES OF THE WHOLE SYSTEM AND DIFFERENT WIND POWER CLUSTERS.



System		Wind power production of nominal capacity									
2000 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	0	0	6	26	49	66	50	37	13	0
	9	0	0	21	50	108	161	148	91	54	3
	8	0	1	18	89	141	197	233	154	89	12
	7	0	1	27	80	133	233	261	152	146	29
	6	0	3	15	46	112	182	232	205	145	61
…	5	0	0	7	51	83	151	247	238	192	112
	4	0	0	4	6	11	49	99	142	198	103
	3	0	0	1	6	40	119	268	365	628	409
	2	0	0	0	1	4	17	69	82	200	148
min	1	0	0	0	4	5	32	97	157	310	225

- > 300 h
- 300…200 h
- 200…100 h
- < 100 h

North		Wind power production of nominal capacity									
500 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	46	24	14	24	25	15	13	28	21	37
	9	121	42	40	48	30	45	48	43	55	164
	8	144	74	41	53	32	34	47	72	128	309
	7	139	63	52	66	54	54	67	92	134	341
	6	116	52	51	61	71	56	66	99	126	303
…	5	92	67	54	35	42	53	68	87	149	434
	4	25	22	36	38	41	34	36	67	85	228
	3	91	70	47	67	90	84	105	179	313	790
	2	18	15	16	20	12	21	33	65	86	235
min	1	32	12	29	42	32	52	61	71	139	360

- > 300 h
- 300…200 h
- 200…100 h
- < 100 h

South		Wind power production of nominal capacity									
900 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	5	14	21	49	35	35	20	31	27	10
	9	20	30	46	82	118	70	78	71	81	40
	8	23	41	71	104	139	109	125	130	115	77
	7	33	20	48	125	127	159	111	157	178	104
	6	20	38	43	81	102	108	137	141	157	174
…	5	4	20	26	60	71	109	124	192	224	251
	4	0	0	9	13	15	34	55	123	146	217
	3	0	7	14	31	62	93	127	196	400	906
	2	0	1	4	5	9	19	23	49	138	273
min	1	4	3	2	6	14	24	31	78	164	504

- > 300 h
- 300…200 h
- 200…100 h
- < 100 h

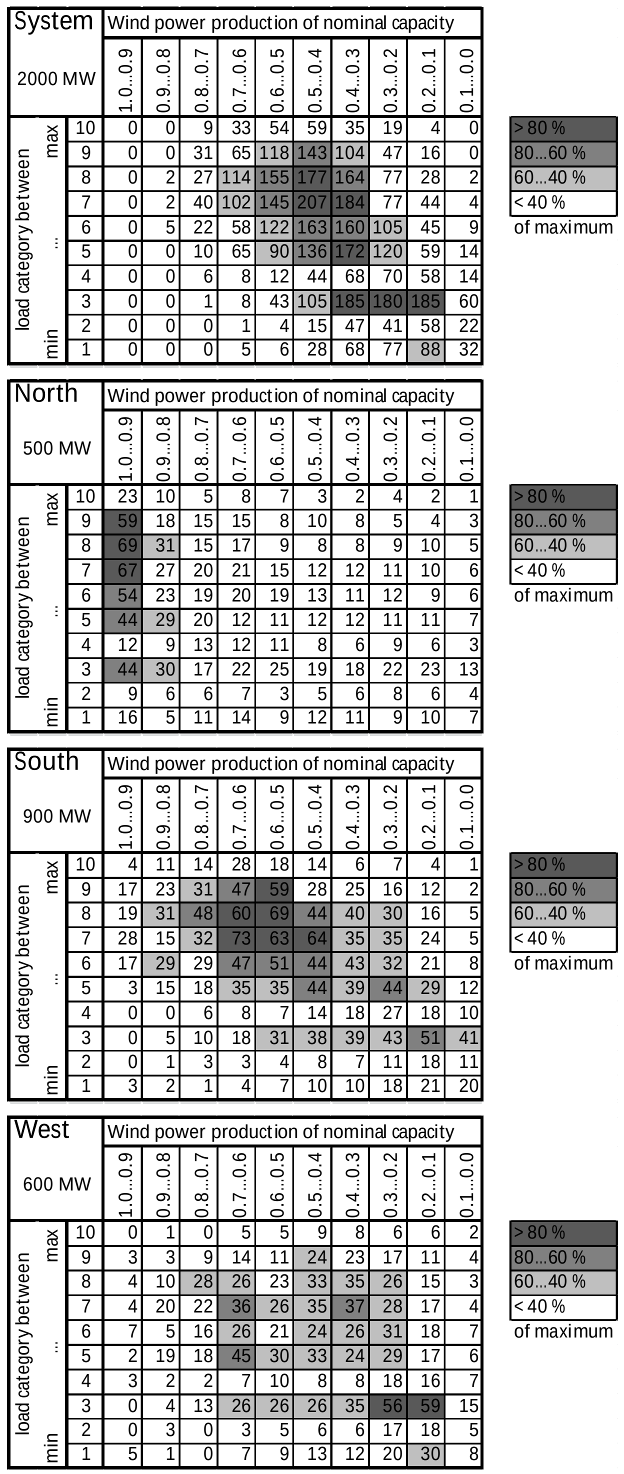
West		Wind power production of nominal capacity									
600 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	0	2	1	12	16	35	37	41	63	40
	9	5	6	20	37	34	88	111	119	127	89
	8	7	20	62	66	71	122	167	179	165	75
	7	7	41	48	93	78	129	177	186	191	112
	6	12	9	35	65	65	90	128	213	206	178
…	5	3	37	40	117	90	121	116	199	189	169
	4	5	3	5	19	31	29	37	124	182	177
	3	0	8	30	67	80	98	167	388	649	349
	2	0	6	1	7	16	23	30	115	198	125
min	1	10	2	1	19	28	49	58	137	344	182

- > 300 h
- 300…200 h
- 200…100 h
- < 100 h

be among the situations with wind power having the most potential influence as discussed above.

The results of the simulation runs indicate that wind power in any of the studied wind power scenario locations is likely to decrease the overall power transmission losses in the system.

TABLE III. ENERGY INFLUENCE [GWh] OF THE WHOLE SYSTEM WIND POWER SCENARIO AND WIND POWER CLUSTERS. COLOR SCALES ARE DERIVED FROM THE MAXIMUM ENERGY INFLUENCE VALUE WITHIN EACH SUB-TABLE.



System		Wind power production of nominal capacity									
2000 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	0	0	9	33	54	59	35	19	4	0
	9	0	0	31	65	118	143	104	47	16	0
	8	0	2	27	114	155	177	164	77	28	2
	7	0	2	40	102	145	207	184	77	44	4
	6	0	5	22	58	122	163	160	105	45	9
…	5	0	0	10	65	90	136	172	120	59	14
	4	0	0	6	8	12	44	68	70	58	14
	3	0	0	1	8	43	105	185	180	185	60
	2	0	0	0	1	4	15	47	41	58	22
min	1	0	0	0	5	6	28	68	77	88	32

- > 80 %
- 80…60 %
- 60…40 %
- < 40 %

of maximum

North		Wind power production of nominal capacity									
500 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	23	10	5	8	7	3	2	4	2	1
	9	59	18	15	15	8	10	8	5	4	3
	8	69	31	15	17	9	8	8	9	10	5
	7	67	27	20	21	15	12	12	11	10	6
	6	54	23	19	20	19	13	11	12	9	6
…	5	44	29	20	12	11	12	12	11	11	7
	4	12	9	13	12	11	8	6	9	6	3
	3	44	30	17	22	25	19	18	22	23	13
	2	9	6	6	7	3	5	6	8	6	4
min	1	16	5	11	14	9	12	11	9	10	7

- > 80 %
- 80…60 %
- 60…40 %
- < 40 %

of maximum

South		Wind power production of nominal capacity									
900 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	4	11	14	28	18	14	6	7	4	1
	9	17	23	31	47	59	28	25	16	12	2
	8	19	31	48	60	69	44	40	30	16	5
	7	28	15	32	73	63	64	35	35	24	5
	6	17	29	29	47	51	44	43	32	21	8
…	5	3	15	18	35	35	44	39	44	29	12
	4	0	0	6	8	7	14	18	27	18	10
	3	0	5	10	18	31	38	39	43	51	41
	2	0	1	3	3	4	8	7	11	18	11
min	1	3	2	1	4	7	10	10	18	21	20

- > 80 %
- 80…60 %
- 60…40 %
- < 40 %

of maximum

West		Wind power production of nominal capacity									
600 MW		1.0…0.9	0.9…0.8	0.8…0.7	0.7…0.6	0.6…0.5	0.5…0.4	0.4…0.3	0.3…0.2	0.2…0.1	0.1…0.0
load category between max	10	0	1	0	5	5	9	8	6	6	2
	9	3	3	9	14	11	24	23	17	11	4
	8	4	10	28	26	23	33	35	26	15	3
	7	4	20	22	36	26	35	37	28	17	4
	6	7	5	16	26	21	24	26	31	18	7
…	5	2	19	18	45	30	33	24	29	17	6
	4	3	2	2	7	10	8	8	18	16	7
	3	0	4	13	26	26	26	35	56	59	15
	2	0	3	0	3	5	6	6	17	18	5
min	1	5	1	0	7	9	13	12	20	30	8

- > 80 %
- 80…60 %
- 60…40 %
- < 40 %

of maximum

The most significant influence on transmission losses are seen related to the wind power cluster in the South. In the typical representative intermediate load case, the transmission losses could be reduced from 2.4 % to 2.1 %, and even in the peak load case from 4.4 % to 3.5 %—which could be realistic

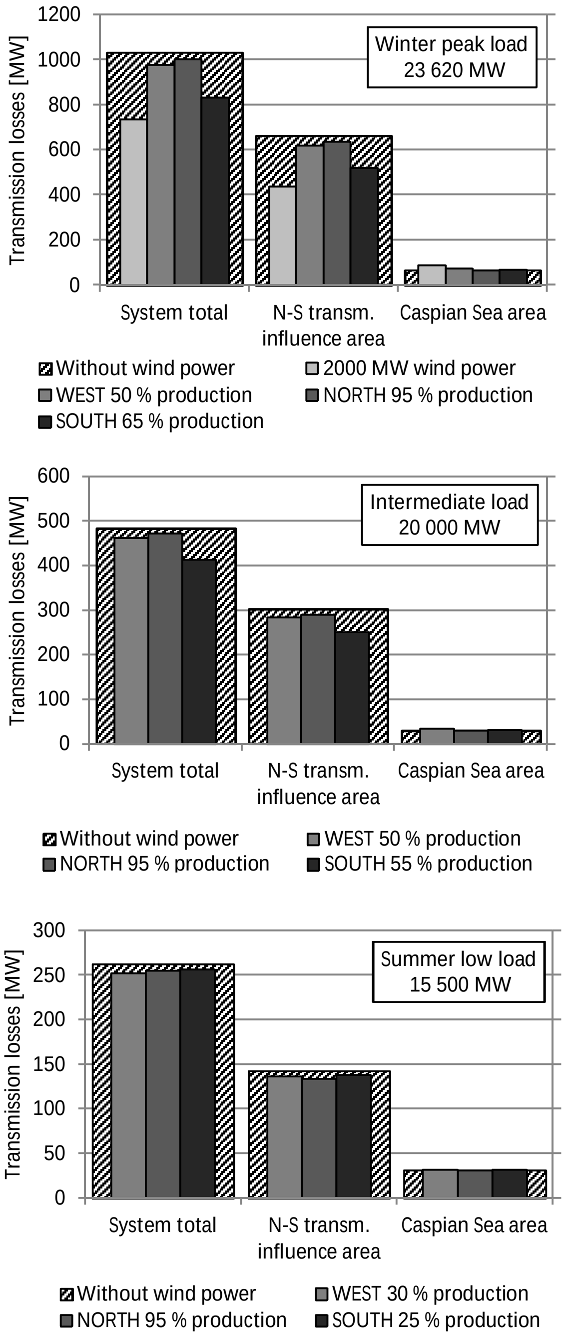


Fig. 2. Different wind power cluster (as well as the whole wind power scenario full capacity production) influences on transmission losses in system level and two specific transmission areas in different load levels; winter peak load, intermediate load and summer low load.

situation, considering that the South wind power cluster is producing 65 % of the nominal capacity in the study case.

VI. CONCLUSIONS

Confirmed by the case study results and conclusions presented in this paper, it is clear that the peak load case is among the least representative and indicative cases to be used for assessing wind power production impact on power system losses. Instead, power system load and wind power data should be analyzed to determine the power flow loss analysis cases if only a limited number of cases can be simulated instead of running analysis for all the hours of the year.

This paper suggests the selection of indicative load flow cases to be done through analysis of occurrence frequency of load level combined with occurrence frequency of wind power production level, and more particularly energy influence of wind power production level. The frequency distribution and energy influence matrices/tables and their formulation were introduced in this paper. These color scaled tables show visually the most frequently occurring and wind power influential situations throughout the year. The presented tables are visually effective, as well as globally comparable.

For demonstration of the method, the simulation cases for Kazakhstan case study were selected and implemented, and power flow simulations were ran in order to identify power system losses. Comparing the simulation results with wind power to corresponding load flow simulations without wind power, it is evident that wind power in Kazakhstan located at least partly according to the study scenario, could decrease power transmission losses in some degree.

VII. REFERENCES

[1] "European Wind Integration Study (EWIS) – Towards a Successful Integration of Large Scale Wind Power into European Electricity Grids", Final report, March 2010.

[2] "European Wind Integration Study (EWIS) – Towards a Successful Integration of Large Scale Wind Power into European Electricity Grids", Final report – Appendix 3.1, Modelling of markets and flexibility needs, 2010.

[3] H. Farahmand, D. Huertas-Hernando, L. Warland, M. Korpås, and H.G. Svendsen, "Impact of system power losses on the value of an offshore grid for North Sea offshore wind", IEEE PES PowerTech, 2011 Trondheim. pp. 1–7.

[4] M. Aragüés-Peñalba, A. Egea-Àlvarez, O. Gomis-Bellmunt, and A. Sumper, "Optimum voltage control for loss minimization in HVDC multi-terminal transmission systems for large offshore wind farms", *Electric Power Systems Research*, Vol. 89, pp. 54–63, August 2012.

[5] R. Sharma, T.W. Rasmussen, K.H. Jensen, V. Akhmatov, "Modular VSC converter based HVDC power transmission from offshore wind power plant: Compared to the conventional HVAC system", in IEEE Electrical Power and Energy Conference, 2010. EPEC 2010.

[6] N. Barberis Negra, J. Todorovic, and T. Ackermann, "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms", *Electric Power Systems Research*, Vol. 76, Issue 11, pp. 916–927, July 2006.

[7] S. Liu, and D. E. Martin, "Evaluation of Power System Losses Caused by Wind Farm Interconnection based on Statistical Method", IEEE PES Transmission and Distribution Conference and Exposition (T&D), 2012.

[8] H. Holttinen, S. Uski-Joutsenvuo, J. Kiviluoma, "Power system assessment for wind energy development in Kazakhstan" Final report, January 2011.

[9] J.J. Zhao, X. Li, J.T. Hao, C.L. Zhang, and J.P. Lu, "Wind Farm Reactive Power Output Optimization for Loss Reduction and Voltage Profile Improvements", in IEEE 6th International conference on Power Electronics and Motion Control Conference, 2009. IPEMC '09. pp.1099–1103.

[10] H. Holttinen, S. Rissanen, G. Giebel, X. G. Larsén, A. L. Løvholm, E. Berge, "Variability and smoothing effect of wind power production compared to load variability in the Nordic countries" in 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 2012.