Comparative Analysis of Power Losses in Overhead Power Lines for High Voltage, for Different Parameters of the Aluminum Wires

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Abstract – **With regard to the widening use of renewable energy sources, it becomes necessary to increase the transmission capacity of the existing lines, exporting the produced electric energy to the power distribution system. This paper discusses an exemplary closed electric network for high voltage (110 kV). In view of the need to increase the transmission capacity two options are considered: increasing the cross-section of wires and replacement of traditional steel-aluminum wires with super heat resistant ones. A comparative analysis is made of power losses in both cases.**

Keywords – **Renewable energy sources, Transmission capacity, high voltage overhead powerlines.**

I. Introduction

The rapid development of electricity production from renewable sources and the requirements of the European Union in this area led to the need for a change in the strategies of the power system of Bulgaria. A typical example is the construction of wind farms in Northeastern Bulgaria. This region has a well-established power grid, whose capacity cannot meet the increasingly growing number of wind farms. The rapid construction of new lines or replacing the old lines with new ones of larger capacity could solve the problem, but the procedures on land expropriation and negotiations with local authorities would take a long time. A possible solution would be to increase the cross-section of the wires of the available high-voltage power lines (entailing a new mechanical sizing and replacement of poles, insulators and supporting fixtures) or to replace only the wires with so-called superheat resistant wires of the same cross-section (no need for replacement of poles here). The purpose of this paper is to assess the advisability of either option: fitting the power lines with superheat resistant wires or increasing the cross-sections.

II. Arrangement of the Task

Fig. 1 shows the structural design of a looped power network for high voltage. It connects to the power grid through nodes 1 and 13. It is designed to supply 10 local sub-stations (nodes 2, 3, 6 ÷ 13). Two large wind farms are connected to it, their installed capacity being 156MW and 35MW in nodes 4 and 5. A multitude of small wind farms (with total installed capacity of approximately 200MW) are connected to the distribution network of medium voltage; on the diagram, they are presented as equivalent sources while accounting for the circumstance that part of the power produced by them is utilized by consumers and thus it is not transmitted to the discussed network. All wind farms are presented as equivalent generators using PQ model, i.e. with assigned active and reactive power.

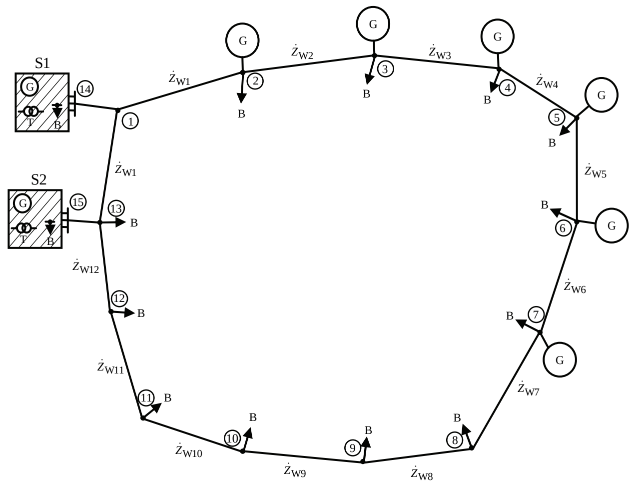

Fig. 1. Structural design of the discussed power network

All power lines are overhead and are presented by Π-shape equivalent circuits, taking into account their longitudinal and transverse parameters (Table I) without the active conductivities to the earth, and taking into account the crown effect and leakages. The active resistance of the wires is calculated at maximum permissible temperature, which is 70°C for conventional steel-aluminum wires, whereas for superheat resistant ones it is 210°C. Their total length is 267 km.

All three kinds of wires are combined alloys of aluminum and steel. The designations AC/ACO show the ratio of aluminum/steel: - AC (normal) - s_A/s_C = 5:1÷6:1;-ACO (reduced) - s_A/s_C = 8:1. The third type (ZTACIR) is s superheat resistant wire of aluminum alloy with zirconium, reinforced with iron-nickel alloy (invar) [1,2,3,4]. The wire is so designed that it would not sag down at temperatures of the order of 200°C. The maximum operative temperature is determined based on reduction of the physical and mechanical properties by 10% during the whole period of operation. Because the amount of zirconium in the alloy is small, the characteristics of the wires based on these alloys do not differ much from AC with the exception of their increased specific resistance.

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Table II shows the values of maximum permissible currents of the different wires [4.6]. A simulation has been made of a mode of maximum consumption in the presence of wind allowing maximum generation of all wind farms. The aim is to achieve as high generation as possible, while not exceeding the permissible currents for the cross-sections under consideration here and keeping the voltage at the nodes of the network within 98 ÷ 123 kV [5]. Three options are discussed, and the entire network is built with one of the wires indicated in Table. I. Calculations are made with Prof. Federico Milano's [7] program PSAT (Power System Analysis Toolbox).

TABLE I
PARAMETERS OF THE POWER LINES

Conductor type	r_o	x_o	C_o
	Ω/km	Ω/km	F/km
AC-185	0.1920	0.4043	$9.00931 \cdot 10^{-9}$
ACO-400	0.0888	0.3816	$9.57003 \cdot 10^{-9}$
ZTACIR-185	0.2783	0.4043	$9.00931 \cdot 10^{-9}$

TABLE II
MAXIMUM PERMISSIBLE CURRENTS AND OPERATIVE TEMPERATURE

Conductor type	$I_{доп}$	$\theta_{раб}$
	A	°C
AC-185	500	70
ACO-400	815	70
ZTACIR-185	906	210

III. RESULTS FROM CALCULATIONS

Calculations have been made at three stages:

1. Modeling of the design with wires AC-185, connecting consumers and adding power generated by the wind farms, so that none of the above limitations of current and voltage are violated;
2. Modeling of the design with wires ACO-400 with the same loads and generation and gradual increase of the power of wind farms until close maximum permissible currents are achieved through the power lines and non-permission of any increase or decrease of voltage outside the assigned limits.
3. Modeling of the design with wires ZTACIR-185 and the established mode achieved in item 2. Adjusting the generating powers until getting a permissible mode of maximum generation.

Part of the results from the calculations for the three stages are shown in Tables III ÷ V

TABLE III
RESULTS FOR VOLTAGES AND POWERS AT THE NODES AT STAGE 1 (AC-185)

Bus	U	phase	P_{gen}	Q_{gen}	P_{load}	Q_{load}
	kV	rad	MW	MVar	MW	MVar
Bus01	109.69	0.004	0.00	0.00	0.00	0.00
Bus02	116.15	0.124	10.00	-2.00	0.00	0.00
Bus03	121.27	0.194	34.18	6.00	0.00	0.00
Bus04	122.09	0.207	85.00	17.00	0.00	0.00
Bus05	118.57	0.171	16.00	3.20	0.00	0.00
Bus06	114.34	0.123	20.00	3.00	0.00	0.00
Bus07	110.92	0.079	0.40	-2.73	0.00	0.00
Bus08	108.57	0.042	0.00	0.00	9.20	4.50
Bus09	106.46	0.002	0.00	0.00	6.10	3.00
Bus10	105.72	-0.014	0.00	0.00	8.00	4.00
Bus11	105.18	-0.030	0.00	0.00	52.00	25.00
Bus12	105.59	-0.034	0.00	0.00	100.00	48.00
Bus13	106.48	-0.029	0.00	0.00	32.00	15.00
Bus14	110.00	0.000	-21.21	14.32	0.00	0.00
Bus15	110.00	0.000	79.43	91.69	0.00	0.00
Summary			223.8	130.48	207.3	99.5

The power generated by the wind farms at the first stage is limited by the size of the cross-section, i.e. by the permissible current in the wires. The wind farms exporting directly to the discussed network operate at cos φ=0.98 and produce 165.58 MW active power. The active power exported to the system is 21.21 MW.

TABLE IV
RESULTS FOR VOLTAGES AND POWERS AT THE NODES AT STAGE 2 (ACO-400)

Bus	U	phase	P_{gen}	Q_{gen}	P_{load}	Q_{load}
	kV	rad	MW	MVar	MW	MVar
Bus01	109.23	0.012	0.00	0.00	0.00	0.00
Bus02	112.21	0.188	10.00	-2.00	0.00	0.00
Bus03	116.20	0.302	34.18	6	0.00	0.00
Bus04	117.39	0.334	105.00	21.52	0.00	0.00
Bus05	115.24	0.303	35.00	7.2	0.00	0.00
Bus06	112.09	0.248	70.00	8.6	0.00	0.00
Bus07	108.98	0.176	0.40	-2.73	0.00	0.00
Bus08	107.11	0.119	0.00	0.00	9.20	4.50
Bus09	105.67	0.053	0.00	0.00	6.10	3.00
Bus10	105.27	0.026	0.00	0.00	8.00	4.00
Bus11	105.08	-0.001	0.00	0.00	52.00	25.00
Bus12	105.50	-0.012	0.00	0.00	100.00	48.00
Bus13	106.39	-0.011	0.00	0.00	32.00	15.00
Bus14	110.00	0.000	-60.46	36.66	0.00	0.00
Bus15	110.00	0.000	30.77	93.16	0.00	0.00
Summary			224.89	168.40	207.30	99.50

With the increase of the transmission capacity in the second model, the generation is increased to the upper limit of the transmission grid, whereby cosφ remains close to unity. 60.46 MW are delivered to the system, and the total active power, generated by wind power is 254.8 MW.

TABLE V
RESULTS FOR VOLTAGES AND POWERS AT THE NODES AT STAGE 3 (ZTACIR-185)

Bus	U	phase	P_{gen}	Q_{gen}	P_{load}	Q_{load}
	kV	rad	MW	MVar	MW	MVar
Bus01	108.27	0.011	0.00	0.00	0.00	0.00
Bus02	113.17	0.256	10.00	-2.00	0.00	0.00
Bus03	119.77	0.412	37.18	-7.00	0.00	0.00
Bus04	122.18	0.455	117.00	-15.00	0.00	0.00
Bus05	119.82	0.418	35.00	-5.00	0.00	0.00
Bus06	116.23	0.354	91.00	8.59	0.00	0.00
Bus07	110.45	0.264	5.40	-2.73	0.00	0.00
Bus08	106.69	0.187	0.00	0.00	9.20	4.50
Bus09	103.68	0.095	0.00	0.00	6.10	3.00
Bus10	102.82	0.055	0.00	0.00	8.00	4.00
Bus11	102.34	0.015	0.00	0.00	52.00	25.00
Bus12	103.05	-0.006	0.00	0.00	100.00	48.00
Bus13	104.63	-0.012	0.00	0.00	32.00	15.00
Bus14	110.00	0.000	-54.43	81.36	0.00	0.00
Bus15	110.00	0.000	32.21	138.49	0.00	0.00
Summary			273.36	196.70	207.30	99.50

The third model is characterized by theoretically greater transmission capacity of the power lines in comparison with the second model at the same cross-section as the one in the first model, but with three times higher active resistances of wires, compared to the ones in ACO-400. The impact of this is clear from the calculated established mode. To generate the same or greater power as in the second model and keep voltages within permissible limits, the generators in the wind farms must operate in a mode of suppressed excitation, i.e. consume reactive power from the discussed network. However, this has a negative effect for it leads to depletion of the capacity of the power lines and limitation of the effective transmission. The produced active power is 295.58 MW.

Losses of active power increase more than three times with respect to a unit of transmitted active power.

In order to check the opportunities for maximum generation in the three models, we explore a minimal mode, designed in a simple way by means of decreasing the consumers' powers by 40% relative to the previous one. The calculations are repeated and again care is taken that the power lines are not overload and at the same time that the voltages at the nodes do not exceed the permissible ones.

TABLE VI
RESULTS FOR VOLTAGES AND POWERS AT THE NODES AT STAGE 4 (MIN. LOAD, AC-185)

Bus	U	phase	P_{gen}	Q_{gen}	P_{load}	Q_{load}
	kV	rad	MW	MVar	MW	MVar
Bus01	109.47	0.012	0.00	0.00	0.00	0.00
Bus02	114.42	0.170	17.20	2.14	0.00	0.00
Bus03	117.74	0.261	35.98	-6.97	0.00	0.00
Bus04	118.70	0.278	80.00	-1.00	0.00	0.00
Bus05	116.81	0.241	20.00	1.00	0.00	0.00
Bus06	114.25	0.189	23.00	2.40	0.00	0.00
Bus07	111.95	0.142	4.00	-0.30	0.00	0.00
Bus08	110.31	0.103	0.00	0.00	3.68	1.80
Bus09	108.76	0.058	0.00	0.00	2.44	1.20
Bus10	108.20	0.038	0.00	0.00	3.20	1.60
Bus11	107.75	0.019	0.00	0.00	20.80	10.00
Bus12	107.77	0.009	0.00	0.00	40.00	19.30
Bus13	108.15	0.006	0.00	0.00	12.80	6.00
Bus14	110.00	0.000	-61.68	25.17	0.00	0.00
Bus15	110.00	0.000	-17.55	47.83	0.00	0.00
Summary			100.95	70.27	82.92	39.90

The wind farms exporting directly into the discussed network operate at cos φ=0.98 and produce 180.18 MW active power. The active power exported to the system is 79.29 MW. For this purpose, 73 MVAr of reactive power must enter the system. To maintain the voltage, the wind farms in nodes 3 and 4 must consume reactive power.

TABLE VII
RESULTS FOR VOLTAGES AND POWERS AT THE NODES AT STAGE 5 (MIN. LOAD, ACO-400)

Bus	U	phase	P_{gen}	Q_{gen}	P_{load}	Q_{load}
	kV	rad	MW	MVar	MW	MVar
Bus01	109.53	0.020	0.00	0.00	0.00	0.00
Bus02	114.37	0.215	17.20	2.10	0.00	0.00
Bus03	119.25	0.331	35.98	6.90	0.00	0.00
Bus04	120.82	0.364	105.00	21.52	0.00	0.00
Bus05	119.16	0.338	35.00	7.20	0.00	0.00
Bus06	116.48	0.290	75.00	12.90	0.00	0.00
Bus07	113.40	0.223	6.00	0.09	0.00	0.00
Bus08	111.35	0.168	0.00	0.00	3.68	1.80
Bus09	109.50	0.104	0.00	0.00	2.44	1.20
Bus10	108.87	0.075	0.00	0.00	3.20	1.60
Bus11	108.37	0.047	0.00	0.00	20.80	10.00
Bus12	108.28	0.031	0.00	0.00	40.00	19.20
Bus13	108.49	0.024	0.00	0.00	12.80	6.00
Bus14	110.00	0.000	-104.93	23.07	0.00	0.00
Bus15	110.00	0.000	-67.47	39.83	0.00	0.00
Summary			101.77	113.61	82.92	39.80

When the network design is made with ACO-400, the possible generated power of the wind farms naturally increases to 274.18 MW. There is no need to alter the operative mode to maintain the voltages at the nodes. 172.41 MW are exported to the system, and 62.9 MVAr are imported.

TABLE VIII
RESULTS FOR VOLTAGES AND POWERS AT THE NODES AT STAGE 6 (MIN. LOAD, ZTACIR-185)

Bus	U	phase	P_{gen}	Q_{gen}	P_{load}	Q_{load}
	kV	rad	MW	MVar	MW	MVar
Bus01	108.22	0.018	0.00	0.00	0.00	0.00
Bus02	113.02	0.289	17.20	2.10	0.00	0.00
Bus03	118.83	0.458	35.98	6.90	0.00	0.00
Bus04	120.04	0.515	117.00	-30.00	0.00	0.00
Bus05	117.58	0.482	35.00	-10.00	0.00	0.00
Bus06	114.24	0.419	90.00	-16.00	0.00	0.00
Bus07	110.05	0.322	6.40	-0.18	0.00	0.00
Bus08	107.43	0.241	0.00	0.00	3.68	1.80
Bus09	105.51	0.144	0.00	0.00	2.44	1.20
Bus10	105.04	0.102	0.00	0.00	3.20	1.60
Bus11	104.85	0.060	0.00	0.00	20.80	10.00
Bus12	105.19	0.034	0.00	0.00	40.00	19.20
Bus13	105.87	0.021	0.00	0.00	12.80	6.00
Bus14	110.00	0.000	-89.86	84.33	0.00	0.00
Bus15	110.00	0.000	-56.78	107.02	0.00	0.00
Summary			154.94	144.18	82.92	39.80

The opportunities to produce electric power from wind have increased to 301.18 MW, but to maintain the voltage, wind farms need to consume about 56 MVAr reactive power, whereby the entering one increases to 191.35 MVAr. The active power exported to the system is 146.64 MW.

It should be noted that the presented results do not cover all possible modes and situations. It is not taken into consideration that during normal mode of operation, the power transmission grid should meet at least the „n-1“ [5] criterion of safety. Also, the temperature of the wires will not always be equal to the permissible one, which implies that the active resistances will also vary within certain limits. The most realistic idea about whether it is advisable to use superheat resistant wires, from the point of view of the grid operation, would be obtained by calculating the losses of energy based on real load schedules, with accounting for a possible heating of the wires.

Table IX shows a comparison between the losses of active and reactive power and what part they are of the total power generated by wind farms.

IV. CONCLUSION

Based on the results presented in this paper, the following conclusions can be made:

1. A replacement of wires would lead to increased opportunities for production of electric power from renewable sources, i.e. owners of wind farms could benefit from this;
2. A utilization of superheat resistant wires could significantly increase the losses of power and energy, which would increase the grid owners' expenses;
3. To retain the voltages at the nodes within permissible limits, wind farms might need to use modes of consumption of reactive power.

TABLE IX
RESULTS FOR TOTAL LOSSES OF POWER IN THE THREE MODELS

Conductor type	ΔP_{sum}	ΔQ_{sum}	ΣP_{gen}	ΣQ_{gen}	$\frac{\Delta P_{sum}}{\Sigma P_{gen}} \cdot 100$
	MW	MVar	MW	MVar	%
Maximal load					
AC-185	16.50	30.98	165.58	24.47	9.96
ACO-400	17.59	68.90	254.80	38.59	6.90
ZTACIR-185	66.06	97.20	295.58	-23.14	22.35
Minimal load					
AC-185	18.02	30.37	180.18	-2.73	10.00
ACO-400	18.85	73.80	295.58	50.71	6.38
ZTACIR-185	72.02	104.37	301.18	-47.18	23.91

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