Technical and economical analysis of the wind turbines interconnection with the windfarm substation

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*Abstract:*The article examines the solution of interconnection of wind turbines to park's substation. The technical solution for the substation interconnection with the wind turbines offers a choice between two voltage levels of 20 kV or 33kV. Depending on the choice of one of these levels, the technical solution of reactive power compensation is also influenced. This Article treats also economical costs deriving from use of each of these voltage levels.

*Keywords:*active energy, reactive energy, energycompensation, wind farm.

1. INTRODUCTION

Continuous growth in the number of wind farms respectively of the wind power installed in the recent years has forced the transport and system operators (OTS) to increase the grid connection rules in order to limit the wind farms effects on the grid quality and stability. These new rules require that electric power stations of any kind to support the grid during their operation. So from this point of view key aspects are the steady state and dynamic capacity of reactive power, continuous voltage control and behavior on grid breakdowns. For the purpose of this Article is analyzed the influence of the medium-voltage level used to interconnect the wind turbines on the technical solution for compensating the reactive power [1].

2. Technical and economic analysis of the wind turbines interconnection

2.1 Technical analysis of the wind turbines interconnection from energy losses point of view

Losses of electrical power in a three-phase network are determined by the relationship:

$$\Delta W = 3R\int_0^T i_T^2\,dt$$

These Joule losses are determined by the square of current i_T, which is variable with load and ohmic resistance on a grid phase.

For the reduction of energy losses at interconnection of wind turbines have been analyzed the usage of 20KV voltage level versus 33KV voltage level.

When nominal voltage in the grid U_n increases with the value u, variation of losses ΔP_n in the grid is given by the relation [2]:

$$\Delta P_n = \frac{S_k}{U_n^2}\,[1 - \frac{1}{\left(1+\frac{u}{100}\right)^2}]$$

As case study, it was modeled the Buzau wind farm120MW consisting of 40 wind turbines, connected to the injection substation by 24KV cables in accordance with sections and lengths from table [4].

Table 1. List of cables for 20KV

Types of cables	Length (m)	ΔP [KW]
Total 1X95MM2-AL-20KV	13425	141.07
Total 1X150MM2-AL-20KV	6235	120.91
Total 1X185MM2-AL-20KV	4070	114.95
Total 1X240MM2-AL-20KV	2210	58.9
Total 1X300MM2-AL-20KV	2490	66.22
Total 1X400MM2-AL-20KV	2930	89.45
Total 1X500MM2-AL-20KV	2415	55.03
Total 1X630MM2-AL-20KV	23255	642.26
Total 1X630MM2-CU-20KV	3670	88.76
Overall total cables MV	**60700**	**1377.55**

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Table 2. List of cables for 33KV		
Types of cables	Length (m)	ΔP [KW]
Total 1X95MM2-AL-30KV	23730	246.85
Total 1X150MM2-AL-30KV	4700	104.09
Total 1X240MM2-AL-30KV	5345	114.77
Total 1X400MM2-AL-30KV	23255	474.76
Total 1X500MM2-AL-30KV	3670	84.33
Overall total cables MV	**60700**	**1024.8**

For a period of 20 years, with an average operation time at maximum power of 40%, using the EDSA software (Electrical design and System Analysis), outcome is a ΔP=1377,55 KW and a loss of electrical power ΔW=96538 MWh. The value of lost electricity is estimated at 3.8 million euros.
According to the same scenario, using the turbines interconnection cables of 33KV according to the above table, results in a ΔP=1024,8 KW and a loss of electrical power ΔW=71817MWh representing 2.8 million euros.

2.2 Technical analysis of the wind turbines interconnection from reactive power compensation point of view

2.2.1 Conditionsrequiredin Romania

Wind turbines have some limitations in terms of achieving compliance with the Grid Code in terms of reactive power compensation.

In Romania the wind power parks must meet the conditions imposed by the Transmission System Operator through the Grid Connection Permit and through the technical norm "Technical requirements for connection to the public grid for wind power plants" ANRE code: 51.1.017.0 .00.03/04/09. Requirements for dispatchable wind power plants (DWPP) are:

- At voltages in the connection point located in the allowable voltage band, reactive power generated / absorbed by a DWPP must be continuously adjusted corresponding a power factor located at least at 0.95 inductive and 0.95 capacitive range.

- DWPP should be able to automatically control voltage - reactive power in PCC in any of the ways:

(a) voltage control;

(b) reactive power control changed with SEN

(c) power factor adjustment.

-Terms of detail on voltage and reactive power adjustment are determined by the Grid Operator in the Grid Connection Permit.

-The response speed of the voltage control system must be at least 95% of reactive power available per second.

-In normal operation of the grid, DWPP must not cause in the connection point rapid changes of voltage greater than ± 5% of nominal voltage.

2.2.2 Compensation methods

Reactive power compensation equipment

There are a couple of principles to achieve reactive power compensation. The simplest solution is without any doubts a combination of switched passive elements, i.e. switched capacitors and inductors. Figure 1 shows qualitatively the reactive current versus connected voltage of such a solution. The reactive current depends linearly on the grid voltage and as a consequence the reactive power changes with the square of the grid voltage. Depending on the amount of switched component branches, the reactive current can only be altered in more or less large steps. Due to the limited switching time of capacitors, the dynamic performance of this solution is reduced. Furthermore, switching transients have to be accepted with this solution as well as regular maintenance of the breakers.

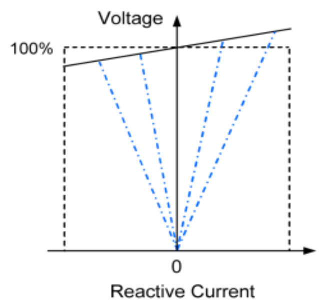


Fig. 1. Reactive current vs voltage for comutatedpasive components

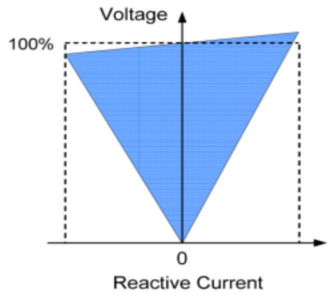


Fig. 2.Reactive current vs voltage forSVC

Figure 2 shows the reactive current

versus connected voltage of a well known and widely used reactive power compensator: the SVC (Static Var Compensator). The SVC combines thyristor switched capacitors (TSC) with thyristor controlled reactors (TCR). Doing so, a smooth variation of reactive power over the complete installed power range is possible.

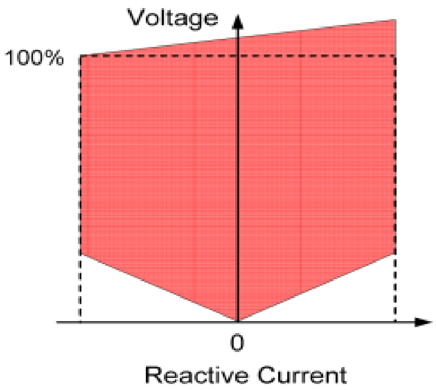


Fig. 3. Reactive current vs voltage forSTACOM

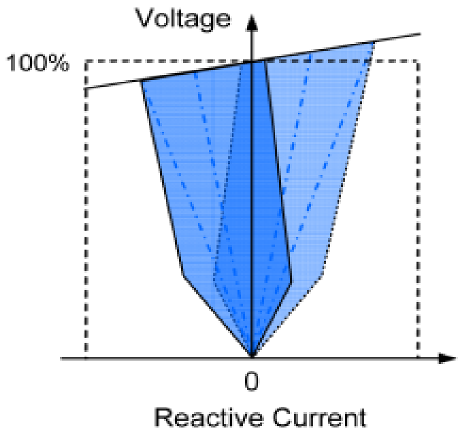


Fig. 4. Reactive current vs voltage for a mixt solution STATCOM/pasivecomutated components

Figure 3 shows the reactive current versus connected voltage of a STATCOM. The performance is similar to a SVC, i.e. it performs smooth variation of reactive current across its operating range with high dynamics. According to [4], “it has advantages when compared to the Static Var Compensator (SVC), e.g., current injection independent of the system voltage, faster control and less of a space requirement.” The STATCOM is described more in detail further on. Finally, Figure 4 shows a combination of switched passive components with a small-sized STATCOM. This solution still includes disadvantages of switched passive components, e.g. switching transients and the need for regular maintenance of the breakers.

From the user's point of view, a solution to reactive power compensation without mechanical switching components is therefore preferred.

Solution is further detailed with STATCOM (static synchronous compensator), which is more suitable for wind farms to achieve and meet the parameters required by Grid Code.

The solution with static switches

A STATCOM is in principle a voltage source converter (VSC) connected via an inductance to a grid. The concept has been known for many years and is described in detail e.g. in CIGRE publication no. 144, see [4]. Figure 5 shows an example of a STATCOM connected to a grid; Figure 6 shows the simplified single line diagram. The inductance can represent a reactor or a transformer. Reactive power can be altered by modifying the voltage amplitude of the VSC.

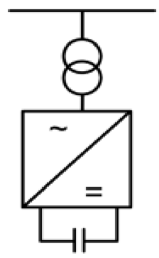


Fig. 5. STATCOM, a VSC connected to the grid

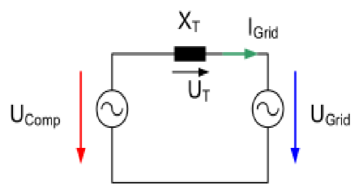


Fig. 6. Simplified single line diagram of a STATCOM

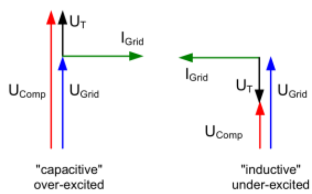


Fig.7.Vector diagram for capacitive and inductive STATCOM operation

The phasor diagram in Figure 7 helps to understand the principle of the STATCOM. For this purpose, a transformer with a turns-ratio of 1:1 or a reactor is assumed. In addition, constant grid voltage is assumed. Therefore, the grid voltage vector U_{Grid} remains at a constant value. If the value of the compensator voltage vector U_{comp} is higher than the grid voltage vector, the vector of the voltage drop across the inductance X_T is in the same direction as the compensator voltage vector. Therefore the compensator current I_{Grid} flows in positive direction as per the definition in Figure 6.

In this situation, the STATCOM acts like a capacitor. If the value of the compensator voltage vector U_{Comp} is lower than the grid voltage vector, the vector of the voltage drop across the inductance X_T is in the opposite direction compared to the compensator voltage vector. Therefore the compensator current I_{Grid} flows in negative direction as per the definition in Figure 6. In this situation, the STATCOM acts like an inductor. Since in all situations the current I_{Grid} is phase shifted by 90° compared the grid voltage U_{Grid}, the STATCOM power is purely reactive.

An analysis of the requirements given in the UK Grid Code shows that the required reactive power is approximately one third of the nominal active power of a wind park. Typical wind park nominal power range is between 30 MW and 100 MW for on-shore wind parks. As a consequence, required reactive power compensation is in the range of about 10 Mvar to 35 Mvar.

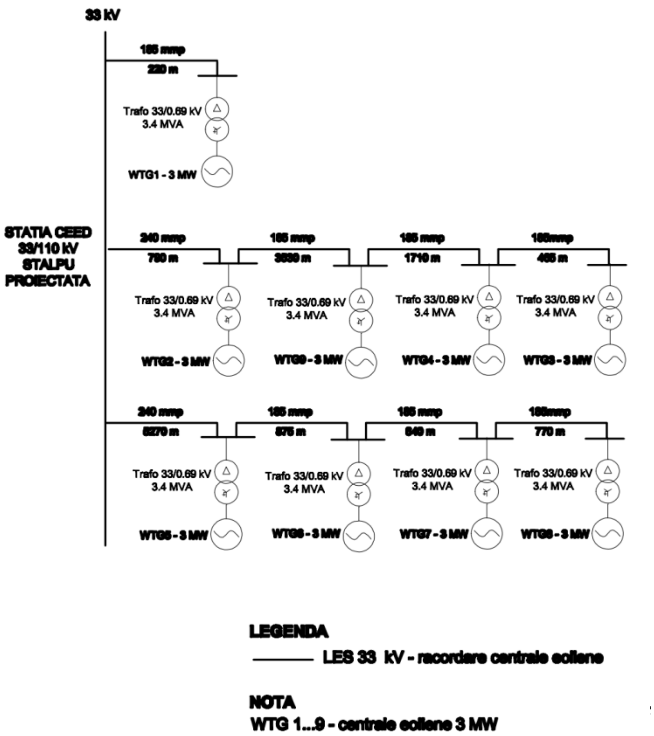
Loss of reactive energy in electrical cables has the expression:

$$\Delta Q = \frac{P^2}{U_n^2} X_L \quad [VAr]$$

The addition of reactive energy of the cables is:

$$Q_{cablu} = Y\, U_n^2 \quad [VAr]$$

The analyzed case study refers to connection of 9 wind turbine of Vestas 3MW type, according to the single wire electrical schematic of interconnection from figure 8 [5].



interconnection

Have been analyzed the component elements of the grid for the evacuation of power in SEN (National Energetical System) (24/33KV) as well as the various operating modes of the electricity generators, taking account of their parameters and the conditions imposed in technical connection permit.

The results for the two versions analyzed are listed in the tables 3 and 4.

We can notice that there are no significant differences between use of 24KV cables respectively 33KV, the necessary of maximum reactive power is for a charge of 100% of the wind turbines in inductive regime.

In conclusion, in order to allow the wind farm operation in a wide range with compliance with power factor imposed by technical connection permit, it is necessary and sufficient the mounting of a compensation system consisting of capacitors battery of 3MVAr and an inductance of 1 MVAr, connected to the Medium Votage bar of transformer station as shown in Figure 2.

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Table 3 : Wind farm operation at 33KV

Turbine functioning mode		**Inductive (cosΦi)**				**Neutral**	**Capacitive (cosΦc)**	
		0,96	**0,97**	**0,98**	**0,99**	**1**	**0,99**	**0,98**
Values in PCC								
Zero load	P [MW]					0,587		
	Q [MVAr]					0,836		
	cosΦrez					0,57		
10%	P [MW]	2,438	2,438	2,438	2,438	2,438	2,438	2,438
	Q [MVAr]	0,153	0,264	0,392	0,556	0,94	1,32	1,485
	cosΦrez	0,998	0,994	0,987	0,975	0,93	0,87	0,854
50%	P [MW]	13,22	13,22	13,22	13,22	13,22	13,22	13,22
	Q [MVAr]	-4,005	-3,43	-2,76	-1,93	10,96	1,91	2,708
	cosΦrez	0,957	0,968	0,979	0,99	1	0,99	0,98
100%	P [MW]	26,67	26,68	26,68	26,68	26,68	26,67	26,67
	Q [MVAr]	-11,21	-9,99	-8,61	-6,88	-2,92	0,86	2,434
	cosΦrez	0,922	0,936	0,952	0,968	0,994	0,999	0,99

Legend:

Wind turbines operating range which produces no disturbance in PCC (cosΦrez = + /- 0.95.

Wind turbines operating range which requires compensation (in PCC is out of allowed range cosΦrez = + /- 0.95.

Table 4 : Wind farm operation at 24KV

Turbine functioning mode		**Inductive (cosΦi)**				**Neutral**	**Capacitive (cosΦc)**	
		0,96	**0,97**	**0,98**	**0,99**	**1**	**0,99**	**0,98**
Values in PCC								
Zero load	P [MW]					0,558		
	Q [MVAr]					0,466		
	cosΦrez					0,76		
10%	P [MW]	2,469	2,469	2,469	2,469	2,469	2,469	2,469
	Q [MVAr]	-0,215	-0,104	0,024	0,188	0,572	0,955	1,118
	cosΦrez	0,996	0,999	1	0,997	0,974	0,933	0,911
50%	P [MW]	13,28	13,28	13,28	13,28	13,28	13,28	13,28
	Q [MVAr]	-4,304	-3,729	-3,067	-2,23	-0,289	1,615	2,414
	cosΦrez	0,951	0,963	0,974	0,986	1	0,993	0,984
100%	P [MW]	26,84	26,83	26,83	26,83	26,82	26,82	26,82
	Q [MVAr]	-11,27	-10,07	-8,69	-6,97	-3,01	0,786	2,359
	cosΦrez	0,922	0,936	0,951	0,968	0,994	1	0,996

Legend:

Wind turbines operating range which produces no disturbance in PCC (cosΦrez = + /- 0.95.

Wind turbines operating range which requires compensation (in PCC is out of allowed range cosΦrez = + /- 0.95.

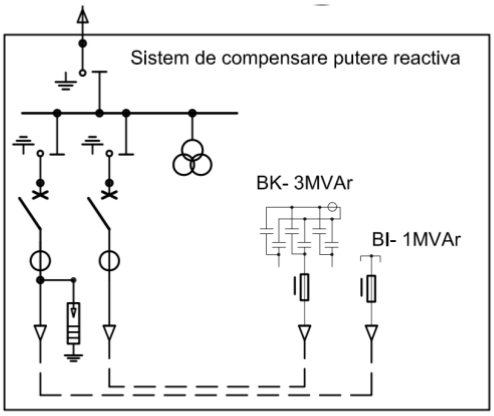

Fig. 9 Reactive power compensation system

2.3 Technical analysis of the wind turbines interconnection from MV cables cost point of view

Following the cost analysis for medium-voltage cables resulted that the cost of the medium-voltage cables is less in the case of 33KV solution compared to 24KV solution with about 672 611 lei or 152 866 Euro, if using in the both cases cables of type NA2XS2Y at the corresponding insulation level for each variant.

3. Conclusions

Technical and economic analysis of the wind turbines interconnection with the wind farm substation is strictly necessary in order to achieve a solution that fully complies with requirements specified in the technical connection permit, respectively quality of electricity at the point of common coupling.

The connection solution to the injection substation though 33KV cables and equipment's creates discomfort from the point of view of specialization of maintenance teams and ensuring the stock of spare parts.

This discomfort is covered by the advantages of reducing losses of electricity on cables and reduced costs of electric cables.

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