Cable Selection and Shunt Compensation for Offshore Windparks

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***Abstract*- The transmission of the electric power to shore and concepts for the electrical system of offshore wind farms are evaluated with respect to selection of a cable. Necessity of use of a shunt by an AC cable connection to shore is addressed, Consequences of the use of a higher insulation of cables, use of three single core cables in triangular and linear configuration is compared in the paper.**

1. Introduction

The application of wind energy throughout the world is growing fast. Wind farms located offshore are planned because of higher average wind speeds at sea and space limitations on-shore. Offshore wind farms will be different from their on-shore counterparts for several reasons. The turbines will on average have a larger diameters and rated powers, the farm will be difficult to access during periods with high winds, erection and maintenance will be more expensive, the turbine noise will probably not be an important issue, and a submarine electrical connection to shore will be required [1].

The DOWEC study [2] investigates the technical options for an offshore wind farm of 100-500 MW, with turbines rated at 5 MW and a distance to shore of 17-50 km [3]. The electrical system concerns the electrical power components between the generator shaft and the grid connection and it concerns the way these components are interconnected and operated. Its function is to convert mechanical power to electric power, to collect electric power from individual turbines, to transmit it to the shore and to convert to an appropriate voltage and frequency. The system consists amongst other of generators, cables, transformers and power electronic converters. Systems are mainly characterised by the type of voltage used within the farm and for the shore connection (AC or DC) and the frequency of the electrical signals (fixed or variable).

An inventory of configurations to collect the electric power from individual wind turbines and to transmit this power to an on-shore high-voltage power system node has been made in [4]. The inventory concerns both constant and variable speed wind turbines and transmission by AC and DC.
In this paper the submarine cable selection for the configurations with AC connection is investigated. First an inventory of electrical transmission system with a case study is presented. Next a cable limitations and selection of a cable for an AC connection is revealed. Use of the three single core cables under the seabed instead of one cable is considered. The necessity of the shunt often presented in the literature for the AC connection is investigated. All calculations made in this paper were performed by EEFARM program [3]. It is a power flow program containing detailed models of all components present in an offshore wind park.

2.Inventory of Electrical Transmission Systems

The way to interconnect the generators (often variable speed) with the high-voltage 50Hz power system is not trivial. Depending on the ratio between the individual turbine power (offshore typical 5 MW) and the wind farm power it will be necessary to collect the power at one or more collection levels with each voltage level different.

Table I

Power	Minimum required cable voltage @ 1000A			
	3 phase	DC	Resistive voltage drop	
MW	kV	kV	V/km	%km (with AC)
4	2	2	50	2.2%
20	12	10	50	0.4%
100	58	50	50	0.1%

The number of collection levels is a trade-off between investment costs and losses. The minimum voltage level is limited by the current carrying capability ('ampacity') of cables, being roughly 1000 to 1500 A. Choosing a low voltage will cause high losses and brings the necessity of parallel cables. On the other hand the application of high-voltage equipment is expensive because of the extra costs for space and insulation.
Two types of wind farms are distinguished: wind farms with constant speed turbines and wind farms with variable speed turbines. Wind farms with variable speed turbines require some adaptation of the variable turbine frequency to the constant grid frequency. The inventory of electrical transmission systems is given in the paper [4]. It will be not repeated here. Next, a case study is presented.

Case study

The offshore wind park with the power of 100 MW, with the use of 5 MW windturbines, 5 turbines per cluster and 4 clusters will be considered. The selected generator voltage is 4,15kV and the park is coupled to a 150 kV public net. The selection of voltage levels has an influence on the selection of the components such as transformator, cable, converter and in this way also on the losses. The selected voltage levels and power of all the components as a result of a flow model (losses included) are visible in the Fig.4-Fig.5

A. Constant Speed and Type of Clustering

Several methods to collect the power can be distinguished. In Fig. 4, two constant speed configurations are shown, one with string clustering (C1) and one with star clustering (C2). To the bus bar on the right hand platform in Fig. 4.b will be referred to as the 'park nodal point' and the bus bar on the left platform as the 'cluster nodal point'. The power and voltage ratings of the medium voltage (further MV) cables are comparable in both cluster options. The power rating of the low voltage (further LV) cables in the star cluster is substantially lower than the power rating of the MV cable. String configuration uses the same type of LV cable for interconnections of all the turbines and this cable must be designed for the power of whole cluster. Therefore, the power rating of the LV cable in string cluster is much higher than the power rating of the LV cable in star cluster.

The necessity of transformers near the turbines depends on the voltage rating of the cable and the voltage rating of the generators. With the star clustering, a turbine transformer can possibly be left out (as indicated in Fig. 4.b) if the generator voltage is sufficiently high (in our case study it is 4,15kV). With the string clustering, the transformer can only be left out if the generator voltage is at least several tenths of kV because of the limited current rating of cables. These generators are presently not available, so for the moment a transformer will be needed (as indicated in Fig4.a). This means that the number of transformers with the star clustering can possibly be lower then with the string clustering. On the other hand, the number of platforms with the star clustering is higher then with the string clustering as each cluster needs its own nodal platform for switchgear and a transformer. As the figure shows the type of clustering does not directly affect the architecture of the rest of the park, however the type of clustering is important for the voltage rating of converters in the cluster.

B. Individual Variable Speed

Two options for individual variable speed are shown in Fig. 5. The systems IV1 and IV2 of Fig.5 consist of traditional variable speed turbines with back-to-back low voltage converters. In system IV2 (Fig.5) medium voltage converters will be required when the converters are directly connected to the cable.

In the systems IV3-IV5 Fig. 5, the back-to-back converter is split in separate AC/DC converters and a DC/AC converter. The voltage rating of the DC-system is in the MV range (10-50 kV). These MV DC systems, also referred to as DC-light systems, are being developed by ABB amongst other and are based on voltage source converters. DC-systems with multiple DC-inputs (multi-terminal DC light) are not available yet and will require an extensive development program. In IV4 (Fig. 5) the DC/AC converter is placed near the cluster node whilst in IV5 the DC/AC converter is placed down stream the collection point of all clusters, which results in the elimination of a cluster transformer. On the other hand, the power rating of the DC/AC converter and the DC-cable is much higher and so is the required voltage level. Because of the high voltage level, these converters will have relatively high costs per kVA.

Other configurations listed in paper [4] are Cluster – Coupled Variable Speed and Park – Coupled Variable Speed. These configurations use a DC connection to shore, therefore not studied here.

3. Limitations of cables

Concerning power transmission several aspects of cables are of importance. It is mainly transmission length, capacitive current and losses and thermal aspects. The thickness of the cable insulation increases with the voltage rating and should be sufficient to prevent a breakthrough, while the conductor cross-section increases with the current rating. Fig. 2 shows the losses as a function of current. The maximum current for a certain cross section is determined by the ability to remove heat from the conductor, which is highly obstructed by the presence of the insulation. Therefore, the ampacity is mainly determined by a thickness of the insulation, a conductivity of the conductor and thermal properties of the soil in which the cable is buried. For example in Fig. 2, the maximal amount of heat that can be removed is 18 W/m, which is reached at about 1200 A. Excessive heating will deteriorate the insulation and will lead to accelerated aging.

For low and medium power the three conductors of a three-phase connection are integrated in a single cable. Mostly the centres of the conductors form a triangle, however some manufacturers (e.g. Pirelli) use a flat cable to improve the thermal management. For high-power cables three separate cables are applied, where the cables are laid in the soil with spacing up to 1m to avoid thermal interaction. Depending on a soil type, voltage level and a type of insulation, the conductive core of the cable has a capacitance to the soil. The total capacitance of the cable is proportional to the total length of the cable. When an open cable is connected to an ac voltage source, a current will flow into the cable according to (1). Here U is the rms voltage, ω is the radial frequency of voltage, C' is the capacitance per meter and l is the length of the cable. With increasing length, the capacitive charging current will reach the value of the maximum allowable current of the cable; this length is called the *transmission length* and is roughly 100 –150 km, depending on a cable type. For a cable that is connected to a load (the grid) the current in the cable will be the (complex) sum of the load current and the capacitive current. For a short cable, the maximal load current is almost equal to the ampacity of the cable. For a longer cable, an increasing part of the current carrying capability is used for charging current and so less power can be transferred to the grid. If cable losses are neglected, we can write for the total current phasor at the sending end (2).

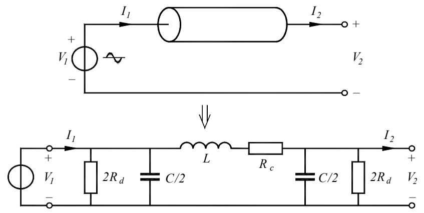

Fig. 1. Simple cable model

$$I_C = \frac{U}{\omega C' \ell} \quad (1)$$

$$I_C(j\omega) = \frac{U(j\omega)}{j\omega C' \ell} + I_{grid}(j\omega) \quad (2)$$

As an example Fig. 3 shows the current I_{grid} that can be transported to the grid as a function of the cable length for 150kV cable with a conductor cross-section of 1200 mm^2. Further it is assumed that the power factor of the grid is 1.

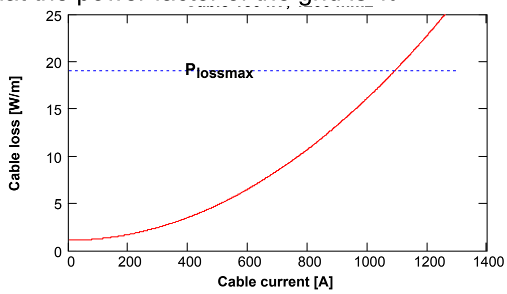

Fig. 2. Losses as a function of current

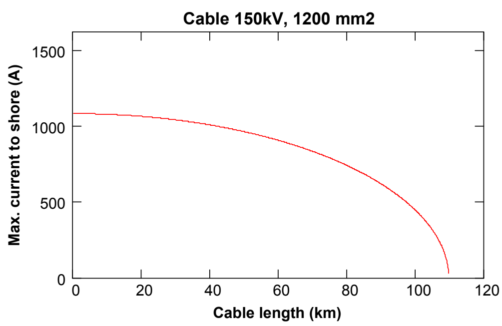

Fig. 3. Maximal transported current versus cable length

The transmission length can be extended by compensation of the capacitive current at both ends of the cable. With an optimal compensation, the transmission length can be roughly doubled. Note that the current inside the cable is depending on the co-ordinate along the cable as we have a distributed capacitance. Because the diameters of submarine cables are much smaller than the skin depth of the electromagnetic wave at 50 Hz, the simple cable model as shown in Fig. 1 can be applied. This model represents the capacitance, the resistive losses and the inductance of the cable. The resistance R_c represents the conduction losses and the resistance in parallel to the capacitors represent the dielectric losses, which occur even at no load. For XLPE (polyethylene) insulation the dielectric losses can be neglected in comparison to the conductor losses, while for a paper-insulated cable these losses are considerable. Typical values for a 630 mm^2, 150kV XLPE cable are: C= 0.17 μF/km, L=0.41 mH/km, and for 630 mm^2, 150kV Paper cable: C= 0.39 μF/km, L= 0.35 mH/km. From this data the electrical parameters in the network model can be obtained.

The maximal power transported through a cable strongly depends on a surrounding soil type. It also depends on a configuration that cables are laid in. In this paper, two different configurations are analysed; trefoils touching and linear with axial separation. The maximal loading currents for XLPE, 630mm^2 cable laid in different configurations are listed in the Table II. As can be seen, the current carrying capability of cables strongly depends on the layout of the cables; the cables should be laid in the soil with sufficient spacing to avoid additional heating.

Table II

	Trefoil touching	Separation 0.15m Cross-bonding	Separation 0.45m Cross-bonding
Current rating [A]	774	842	943

4. Different cable layout configurations

As mentioned above, the layout of the cables and properties of the cables have very big influence on the current carrying capability. Possibility of splitting a three phase cable and use three single phase cables offer some advantages also from the cable capacitance and its capacitive current point of view. In general we can say that the capacitance of the cable is defined by the insulation that is used and stays constant for different cable layouts. On the other hand, the inductances between the cores of the three single cables strongly depend on the cable layout, especially on the distance between the cables. As the distance between the cables increases, the inductance increases as well. The Inductances and capacitances for different distances and cable types are listed in the Table III.

The idea is to use the inductance of the cable to compensate the cable capacitance. This is illustrated in Fig. 6. The figure shows loading conditions (S_{end}/S_n) and cosφ at the end of the cable (shore connection point) as functions of the cable length for two different cable types (Paper, XLPE) and two different cable layouts (trefoil touching, in line with axial distance 0.45m). The power supplied at the beginning of the cable is for all configurations equal to approx. 80% of the cable nominal power; the cosφ used is equal to 1, there is no reactive power supplied from the park. As can be seen, the worst solution is the use of the cables with the paper insulation in the trefoil configuration. Such a cable becomes overloaded for distances little bit longer than 40km. The situation is little bit improved by using the in line configuration. The cables with XLPE insulation achieve much better results even in trefoil configurations. As can be seen, these cables are not overloaded even for distances longer than 120km and the situation is still improved by using the in line configuration.

Table III

Cable Type	Trefoil touching L mH/km	Axial Separation 0.45m L mH/km	C μF/km
XLPE 630 mm^2	0,4	0,78	0,17
Paper 630 mm^2	0,35	0,76	0,39

The selection of the cable with different insulation has the impact on the maximal cable length. The different laying configuration influence is also significant especially for the XLPE cable.

5. The use of the compensation shunts

As mentioned above, AC cables suffer from the capacitance of their insulation. For long cable connections, this capacitance must be compensated to improve the utilisation of the cable and prevent early overloading. This is mostly done by the use of the compensation shunts.

This paragraph evaluates the necessity of the use of the compensation shunts for the cables with XLPE insulation laid in the trefoil configuration. The analysis includes also conditions when a part of the reactive power is supplied from the park itself. Fig. 7, Fig. 8 shows power balance at the end of the cable (shore connection point) for four different wind park configurations. Configurations IV1 (string clusters) and IV2 (star clusters) are wind parks with individual variation of the wind turbine speed. The generators used in this wind parks are equipped with the power electronic converters that can control reactive power at the output and in that way compensate capacitive reactive power of the cable. Different reactive power at the output of the converter is represented by a different cosφ.

The C1 and C2 configuration cannot control the cosφ, which is given by construction of the generator and transformer. The Figures 7 and 8 are therefore valid for this configurations too with assumption that cosφ can still be defined by the design.

The real power supplied to the cable stays constant for all the configurations. Positive sign of the reactive power represents an inductive character and negative sign and capacitive character. As can be seen, the differences between different park configurations are very small. The distance when reactive power of the cable is fully compensated by reactive power of the park varies quite a lot with the cosφ. For example, for the cosφ equal to 0.9 this distance is approx. 60km. Cable is fully loaded only in the case with cosφ equal to 1 (no reactive power delivered from the parkl) for distance 100km. From that can be seen that if there is some reactive power delivered from the park, then it is not necessary to use compensation shunts for distances up to 100km and even more. It depends what reactive power balance is demanded at the shore connection point. These conclusions are valid only for assumed windpark configurations and may be very different especially if different types of the shore connection cable are used.

6.Conclusions

Inventory of the electrical transmission systems together with the introduction to windpark layouts presented in two case studies is given. The problem of the cable capacitance is briefly explained. The maximal loading of the cables with the paper insulation and the XLPE insulation is evaluated for two different laying configurations. Necessity of use of the compensation shunts is investigated as well.

It is shown, that XLPE cables for long cable connections are much better than paper cables. The advantage is even more obvious when the in line laying configuration is used. It is also shown that the compensative shunts are not necessary for distances up to 120km if XLPE cables are used. This distance covers the range in which all the future offshore windparks are planned. The situation can be even more improved by supplying part of the reactive power from the park itself.

Acknowledgement

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References

[1] P. Bauer, S.W.H.de Haan, M.Dubois: Windenergy and Offshore Windparks, EPE-PEMC 2002 Dubrovnik

[2] DOWEC (www.dowec.nl)

[3] J.T.G.Pierik, M.Damen, P. Bauer, S.W.H.de Haan, Electrical and Control Aspects of Offshore Wind Farms, Researcg report ECN-CX-01-83, 2001

[4] P. Bauer, S.W.H.de Haan, M.Damen, J.T.G.Pierik : Evaluation of Electrical Systems for offshore Windfarms, IEEE IAS Annual Meeting,2000, Rome

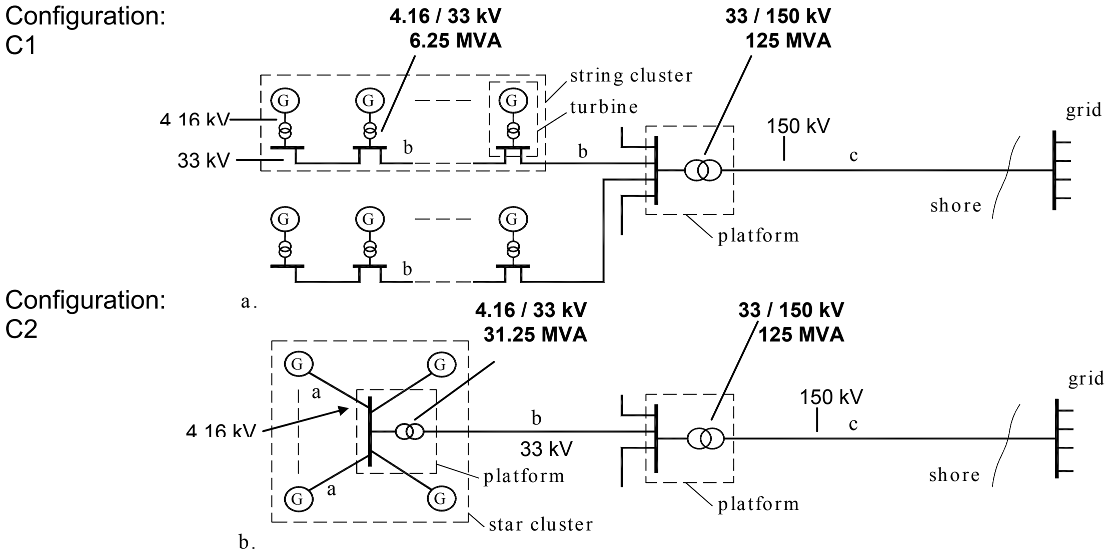

Fig. 4 Constant speed systems

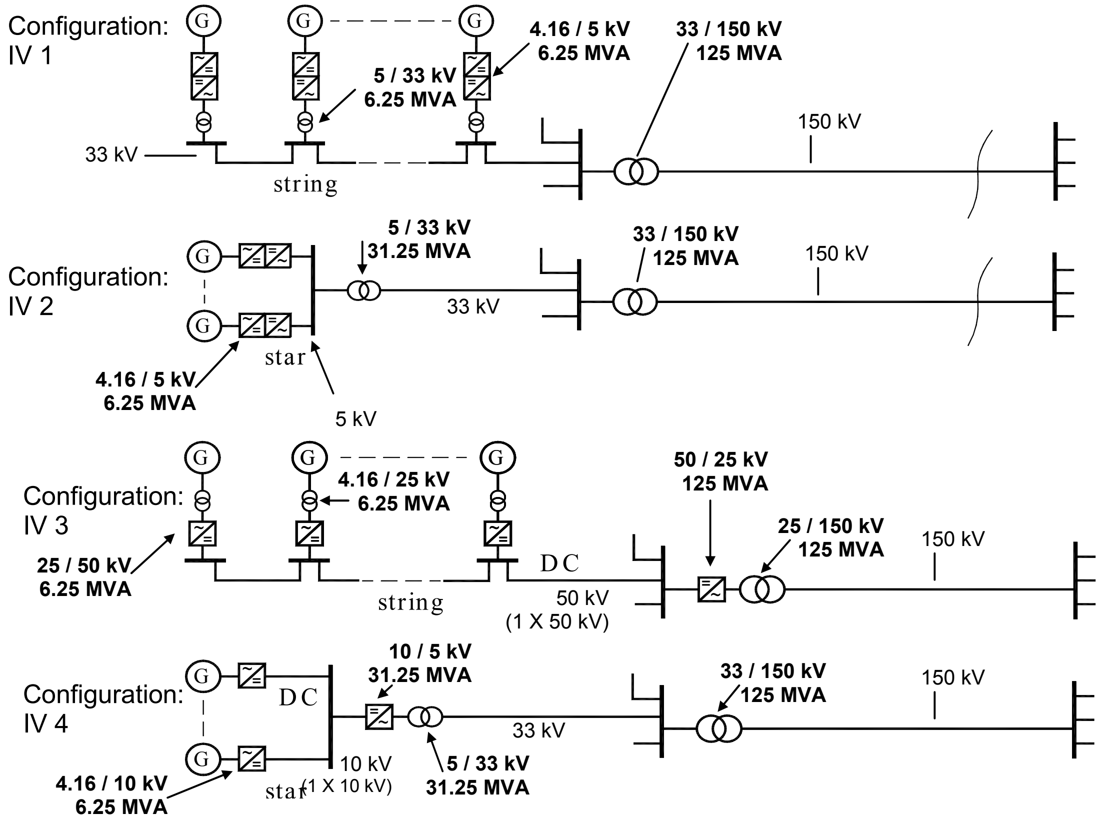

Fig. 5 Individual variable speed systems with back-to-back and multi-terminal DC light system

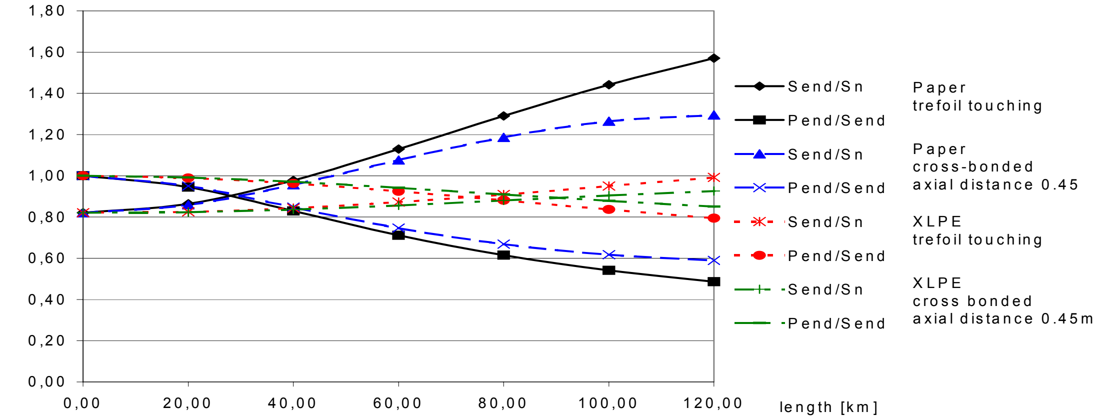

Fig. 6 Power balance of the shore cable connection for windpark C1 and different cable type and layout

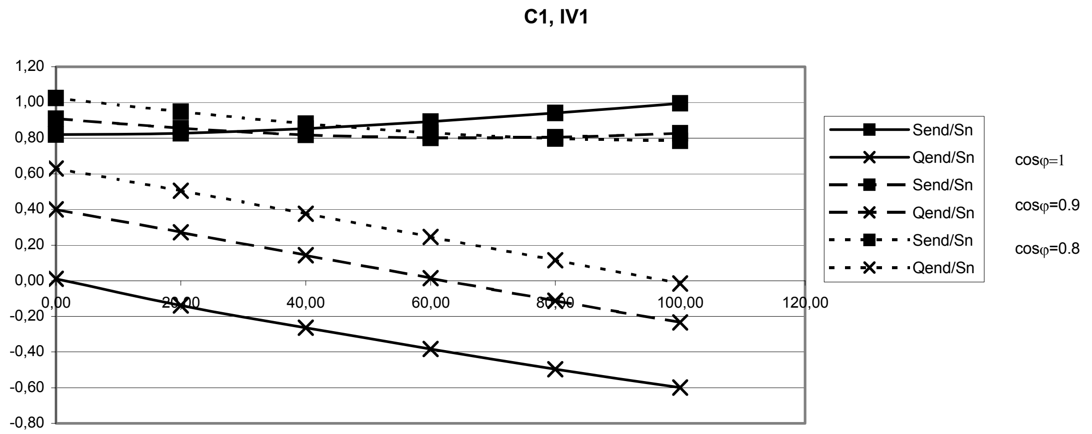

Fig. 7 Power balance of the shore cable connection for windparks C1, IV1 and different reactive power supplied from the park

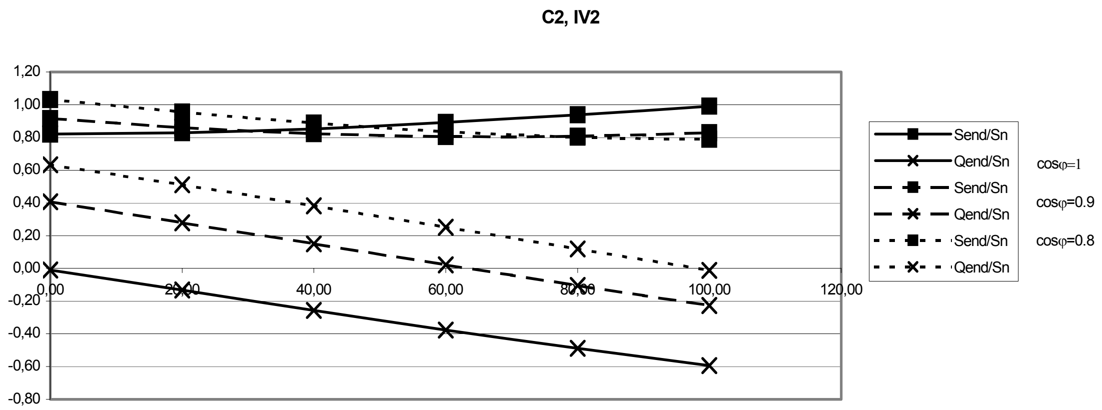

Fig. 8 Power balance of the shore cable connection for windparks C2, IV2 and different reactive power supplied from the park