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Compact Transformers for Offshore Wind Power Plants Applications

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Abstract. The location of step-up offshore substations for offshore wind power plants forces power transformers to be placed on a platform. This offshore platform means a new cost (avoided in a conventional onshore substation) which grows with the transformer weight and footprint surface. As a result, the weight and footprint surface of transformers are new parameters that must be considered in the optimization process of power transformers for offshore wind power plants. The use of compact transformers should lead to the reconsideration of the platform design criteria as compact transformers can reduce significantly the investment cost [1]. The total cost of the transformer, platform and electrical losses have to be evaluated as a whole in order to find the optimal solution. Up to now, no special value has been given to the most compact solution, but the results show that compact solutions have an important impact into the overall economic evaluation.

Key words

Power transformers, offshore wind power plants, compact transformers, overloads, high temperature insulation.

1. Introduction

Over the last years, hundreds of onshore wind power gigawatts have been successfully installed worldwide. Recently, the wind power farm industry is moving to the sea, where the wind can reach higher speeds than for onshore. For offshore applications, the turbines can reach ratings with fewer restrictions than onshore, which make this technology very attractive. A total of 1150 MW were installed in 2012 and a total of 18 GW are planned to be running in 5 years in European seas [2].

In a conventional onshore substation, the transformer footprint or weight is not a limiting (or conditioning) factor. However, the situation is completely different for an offshore plant installation, as the footprint and weight of the transformer determine the cost of the platform that supports the substation. As a result, transformers for offshore wind power plants have to consider both factors as new restrictions for their designs.

2. Solutions to compact transformers

Several design criteria can help to minimize the overall transformer weight and footprint of the platform. Four of the main factors are evaluated in this work, comparing the conventional solution with an alternative:

- Configuration of the transformer unit: Conventional 3-phase unit versus a bank with 3 single-phase units.
- Cooling system: Standard radiators versus water-coolers.
- Overloading-Rated power of design: Wind power plant rating versus a reduced rated power, based on the expected load, without any reduction of the expected life.
- Insulation system: Conventional cellulosic paper versus aramid paper.

A. *Configuration of the transformer unit*

Redundancy is a must for offshore applications since the cost of any failure can be extremely high due to the difficult access. Redundancy in offshore grid systems is often required to warrant the $N-1$ contingency criterion. This can be achieved with two configurations of the transformer unit:

- A 3-phase transformer unit rated at the wind power plant rating (S_{3T} = S_{WPP}) plus another 3-phase transformer unit (also rated at the wind power plant rating) to warrant the $N-1$ contingency criterion.
- A 3-phase bank with 3 single-phase transformers rated at the wind power plant rating (each single-phase unit rated at the third part of the wind power plant rating, $S_{1T} = S_{WPP}/3$) plus one spare unit (also rated at the third part of the wind power plant rating) to warrant the $N-1$ contingency criterion.

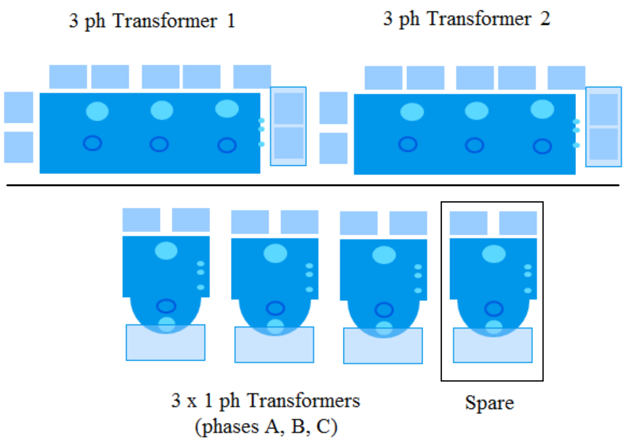

Fig. 1. Three-phase plus spare units and (top) bank of 1-phase transformers plus spare unit (bottom).

Three phase solution has a total of 200% of the maximum generation rating, while the single phase option only needs 133% in order to achieve the *N*-1 contingency criterion. It means that a total of 67% of the rating sum can be removed from the platform.

B. Cooling system.

Radiators are the most extended system in the offshore culture. It is composed by a group of plates joint to the transformer which increase the transformer surface heat transference. The main advantage of this system is that it is independent from the auxiliary system supply. However, radiators are very heavy cooling system.

A water-cooled system is a very compact cooling method to reach high losses dissipation. A typical example is the shell and tube heat exchanger compose by a series of tube inside a shell as indicated in the figure 2.

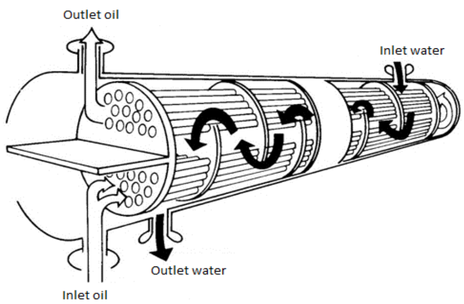

Fig. 2. Water and transformer oil distribution in water coolers.

Liquid refrigerants increase significantly the heat transference. Due to the high efficiency of this system, the number of water-coolers needed is significantly lower and the cooling equipment weight can be reduced significantly.

C. Overloading-Rated power of design

Wind generation plants do not work full time at maximum power since their load depends on the wind source. A typical wind turbine load is indicated in the figure 3.

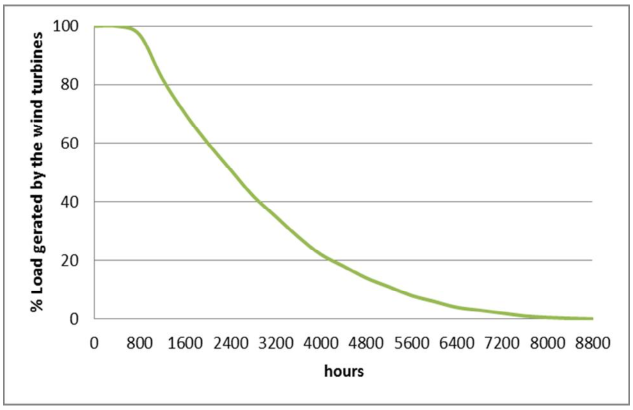

Fig. 3. Expected wind power load curve during the year.

It shows that the maximum rating is only achieved during 10% of the year, the load is below 20% for half of the year and the average load is 33%.

The main concept to determine transformer fatigue is transformer loss of life (IEC 60076-7 [3]), which indicates how the transformer ages due to the different load conditions. When the load increases, the losses in the transformer increase, so too does the temperature in the winding and consequently the insulation ages prematurely. Just the opposite happens when the load is low.

Designing a transformer to work permanently in the most severe scenario (100% load) means that the transformer is overdesigned implying a heavier transformer on the platform.

In order to provide a lighter solution, compact transformers can be designed with a rated power lower than the maximum turbines output power but with an admissible temporary overload as shown in figure 4.

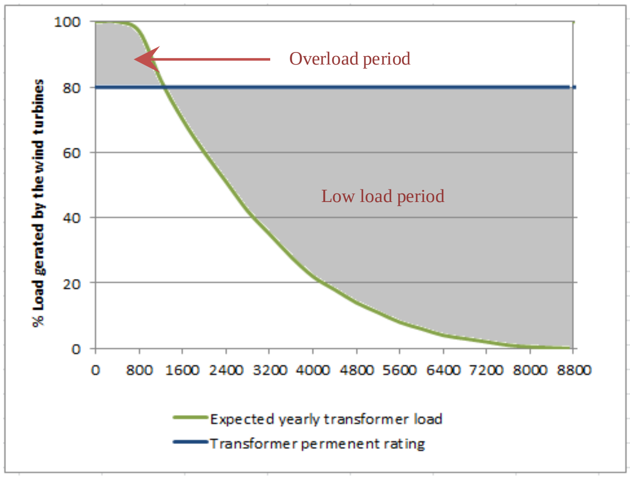

Fig. 4. Wind power load curve during one year vs nominal transformer rating with overload capability.

The transformer thermal aging at the expected yearly load (green curve) is equivalent to work at full load at a lower rating (blue curve). The loss of life during the overload period is compensated by the increase of life during the low load period in such a way that in both conditions the loss of life is exactly the same.

Since the designed transformer has a lower rating, the winding cross section will be smaller and consequently the transformer dimensions and footprint are decreased.

D. Insulation system

The typical paper used in the transformer industry is Kraft paper. This is composed by cellulose and the maximum hot spot admissible according to the IEC standards is 118ºC (absolute value).

An alternative to this paper is the high temperature insulation paper which is based in aramids. This kind of insulation has a better thermal performance than Kraft paper. The IEC 60076-14 [4] indicates that it can withstand 165°C (absolute value) without damage. It means that this paper can increase the transformer life expectancy.

The IEEE 1276-1997 [5] explains the different life expectancy behavior between both types of papers at a certain winding temperature (Fig. 5). At 130ºC aramid paper can work 700 times longer than cellulose papers.

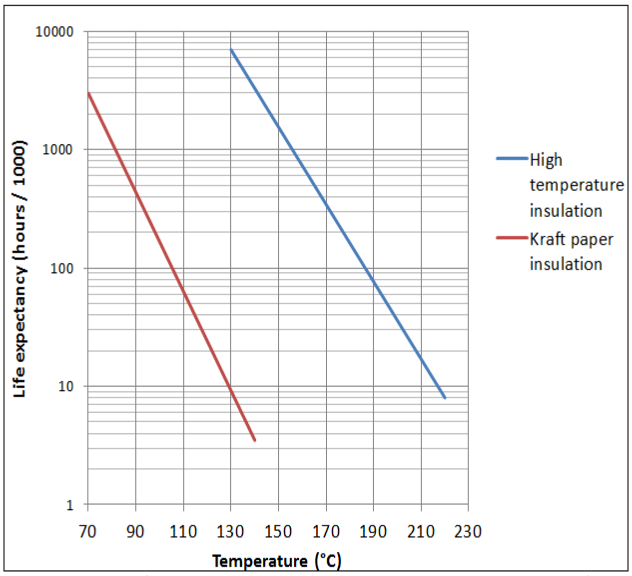

Fig. 5. Kraft paper and high temperature paper thermal life expectancy comparison.

Since this technology can work at higher temperature (165ºC), a solution to provide compact transformers is design units with higher current densities (A/mm^2) allowing reducing the dimensions and weight of the copper windings and consequently the overall transformer weight.

These designs will have higher transformer losses and temperature inside the transformer.

3. Analyzed cases

In order to test the impact of the previously mentioned designs, two different projects have been analyzed:

- Case A. A 200 MVA offshore wind plant.
- Case B. A 1000 MVA HVDC transmission line.

Both evaluations have been done using oil immersed shell form transformers technology. These transformers are designed according the international transformers standards IEC [6] and IEEE [7].

Case A: 200 MVA offshore wind power plant

Figure 6 shows the considered electrical diagram of the offshore wind power plant. Two transformers in parallel share the wind farms load. In case of a failure in one of the transformers, the remaining transformer could deliver the full wind power plant rating as each unit is dimensioned for the total plant capacity.

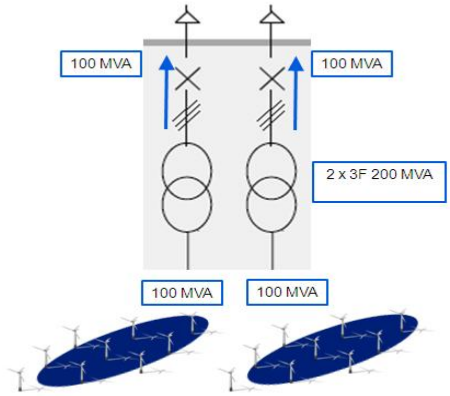

Fig. 6. Case A. Electrical layout of a 200 MVA offshore wind power plant.

Table I summarizes the main transformer data considered for Case A.

Table I. – Transformer main data for Case A.

Number	2	Units
Power rating	200	MVA
Windings	2	Units
Rated LV	33	kV
Rated HV	130	kV
Regulation	± 4·2.5	%
Impedance	14	%
Vector group	YNd11	-
HV insulation level	550	kV
HV neutral insulation level	170	kV
LV insulation level	150	kV
Neutral grounding	Rigidly to ground	-

Case B: 1000 MVA HVDC offshore transmission line.

Two lines 1000 MVA HVDC connect two offshore wind power plants. As shown in Fig. 7, each line requires two platforms to place the HVDC regulating transformers: one just prior the rectifier and the second after the inverter.

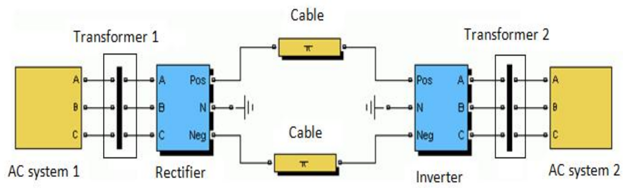

Fig. 7. HVDC transmission scheme between two AC systems.

The main characteristics for this second case are listed in the table II.

Table II. – Transformer main data for Case B.

Number	4 banks + 2 spares = 14	Units
Power rating	333.3	MVA
Windings	3	Units
Rated rectifier voltage	400	kV
Rated inverter voltage	420	kV
Rated Tertiary	20	kV
Regulation	± 8·1.25	%
Impedance	16	%
Vector group	YNynd11	-
Rectifier and inverter insulation level	1425	kV
Neutrals insulation level	150	kV
Tertiary insulation level	150	kV
Neutral grounding	Rigidly to ground	-

4. Technical evaluation of the solutions

Each case will be analyzed independently. A list of possible transformer solution will be provided and compared in order to identify the main features.

Case A: 200 MVA offshore wind power plant.

Table III shows the six considered designs for Case A (of the 16 different possible solution provided in Section 2).

Table III. Transformer designs considered for Case A.

Design	Phases design	Cooling system	Overload Capability	Insulation
A.1	3	Radiators	No	Cellulose
A.2	3	Water-coolers	No	Cellulose
A.3	3	Water-coolers	Yes	Cellulose
A.4	3	Water-coolers	No	Aramid
A.5	1	Water-coolers	No	Cellulose
A.6	1	Water-coolers	No	Aramid

The results of this evaluation are summarized in the table IV, where the five main transformers features of each design (weight, footprint, oil volume, no load losses *(NLL)* and load losses *(LL)* at power plant rating) are showed for comparison.

Table IV. – Technical features of the six designs for Case A

Design	Weight [t]	Footprint [m^2]	Oil Volume [m^3]	NLL * [kW]	Rated / Full LL * [kW]
A.1	2 x 186	2 x 40	2 x 29.8	2 x 57	2 x 247
A.2	2 x 161	2 x 37	2 x 21.5	2 x 57	2 x 247
A.3	2 x 133	2 x 34	2 x 19.3	2 x 51	2 x 386
A.4	2 x 122	2 x 32	2 x 18.0	2 x 42	2 x 517
A.5	4 x 59	4 x 11.5	4 x 8.0	3 x 24	3 x 457
A.6	4 x 50	4 x 8.75	4 x 7.5	3 x 20	3 x 756

*The losses indicated in table IV reflect the operational losses at maximum plant load (not the losses at maximum rating). Single phase units work at full rating, while three phase units share 50% of total load. *LL* depend on the load squared. It means that the three phase transformer will have the one fourth of the losses at maximum plant load.

As indicated in the table IV, three phase transformers (A.1-A.4), the weight, footprint, oil volume and losses of each transformer have to be multiplied by two to take into account both weights and losses (since both transformers are on the platform and both are energized). However, in the single phase designs (A.5 and A.6) the spare transformer is on the platform but it is not energized so the electrical losses of the spare unit are zero.

As a result of the comparison of the considered design criteria, Fig. 8 shows the improvement of the compactness degree for Case A, taking as reference the conventional design A.1.

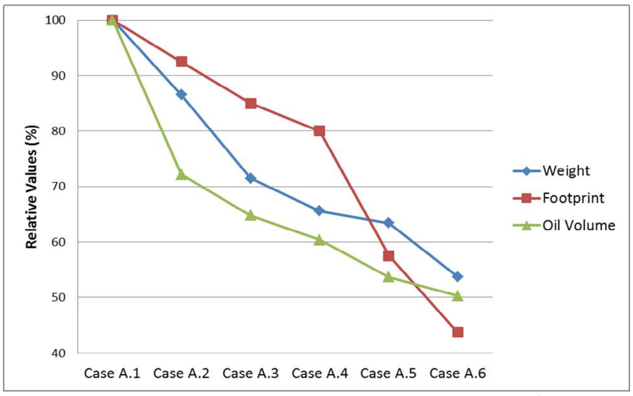

Fig. 8. Compactness improvement in % in Case A referred to the A.1 design.

Each solution improves more significantly one aspect of the transformer compactness:

- Weight: transformer with overload capability.
- Transformer footprint: single phase design.
- Oil volume: the water cooling equipment.

The mixture of all the improvements leads to a reduction of all these aspects to values between 45-55%. However, it also leads to a total transformer losses (*NLL* plus *LL*) increase as indicated in the figure 9.

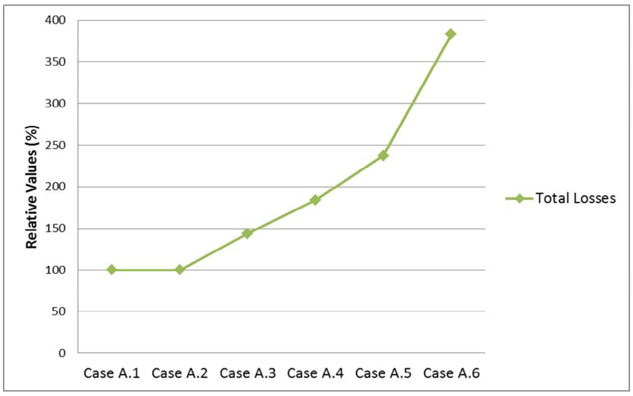

Fig. 9. Transformer electrical losses in operation in % in Case A referred to the A.1 design.

The natural consequence of these designs is the transformer losses rise. The solution which affects more this curve is the single phase designs: from case A.4 to A.6, there is a losses rise of 200% rise.

In order to understand perfectly the indicated results some aspects need to be clarified:

- The only difference between the solution A.1 and A.2 is cooling equipment. Transformer active parts are identical in both cases.
- 3ph with overload design in Case 1 (case A.3) has a rated power of 160 MVA (it can work permanently

at this rating) and can withstand an overload of 200 MVA during the period indicated in Fig. 3. This overload fatigue is compensated with the low load periods when the wind speed is very slow. These calculations are based on the concept of transformer loss of life indicated in the IEC 60076-7 standard and keeping the loss of life as 1 p.u.

- Transformers with overload capability and with high temperature insulation have lower winding cross section implying higher losses at the same rating.
- Single phase designs have three windings: one HV and two LV windings to keep the independency of each wind farm park.

Case B: 1000 MVA HVDC offshore transmission line.

Case B has been evaluated only for single phase solutions since a 1000 MVA three phase design increases significantly the shipping and assembly operations [8]. Nevertheless a total of 12 transformers are required (4 banks of 3 1-phase transformers). Two spare units are added to this evaluation.

For this particular case, four designs have been evaluated. The analyzed designs and the technical features of each design are indicated in the tables V and VI.

Table V. – Analyzed transformers designs for Case B.

Design	Phases Design	Cooling System	Overload Capability	Insulation
B.1	1	Radiators	No	Cellulose
B.2	1	Water-coolers	No	Cellulose
B.3	1	Water-coolers	Yes	Cellulose
B.4	1	Water-coolers	No	Aramid

Table VI. – Technical features of each design for Case B.

Design	Weight [t]	Footprint [m^2]	Oil Volume [m^3]	*NLL* [kW]	*LL* [kW]
B.1	14 x 310	14 x 31	14 x 48	12 x 123	12 x 562
B.2	14 x 302	14 x 28	14 x 43	12 x 123	12 x 562
B.3	14 x 255	14 x 26	14 x 37	12 x 115	12 x 912
B.4	14 x 242	14 x 25	14 x 33	12 x 113	12 x1229

As in the Case A, the spare units are not energized so they do not have any electrical consumption.

5. Economical evaluation of the solutions

TOC evaluation

Two types of costs can be identified in a transformer project:

- *Initial investment:* This refers to the cost which has to be invested prior running the transformer in the plant. Regarding the offshore transformers, there are two main components: transformer and platform.
- *Operational costs*. There are some costs associated to the transformer life regarding some features like transformer efficiency or maintenance.

Total ownership cost (*TOC*) is defined as the initial investment plus the operational costs [9]. To find the most economical solution, the table VII has to be evaluated:

Table VII. – Offshore transformer *TOC* evaluation.

	Investment		Operational		*TOC*
	Transformer	Platform	Losses	Maintenance	
Design 1	…	…	…	…	…
Design 2	…	…	…	…	…
Design 3	…	…	…	…	…

Evaluated parameters

In order to economically evaluate the indicated technical performance, the following criteria have to be analyzed:

- *Weight*. The overall weight of the transformer has been penalized by considering an additional cost [10] in order to cover the additional amount of material and complexity needed to manufacture the platform. These costs take into account only the weight difference between each design and the lightest option (for this last option the relative platform weight cost is 0€).
- *Losses cost*. The designs with higher losses will increase the operational costs due to the efficiency reduction. The considered losses unitary cost has been 5 k€/kW.
- *NLL* are very constant since they depend mainly on the voltage and frequency system which are normally very stable. However, *LL* depend on the transformer load squared and the load varies during the yearly demand. In order to perform a real losses evaluation the *LL* that have to be evaluated are the average *LL*, not the losses at maximum rating. The resulting average of *LL* during the year is 24% of the maximum *LL*.
- *Maintenance costs*. They are assumed to be very similar in all the proposals so they have been removed from the evaluation.

Case A: 200 MVA offshore wind power plant.

Fig. 10 shows a comparison of the losses and platform cost for Case A. The less compact transformers (A.1 and A.2) have higher acquisition cost due to specially the impact of the weight. A.6 design achieves an investment cost reduction of 4.3 M€.

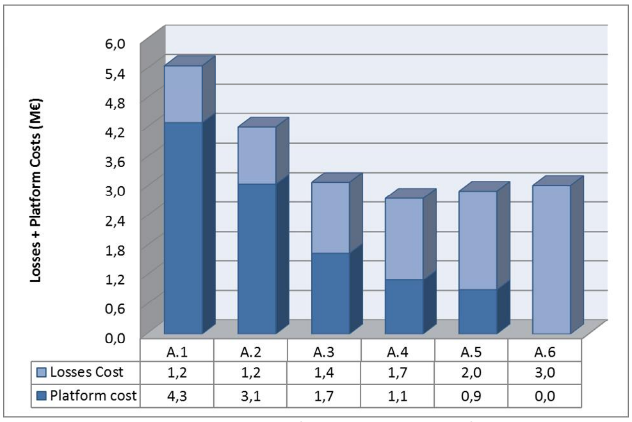

Fig. 10. Losses and platform costs in M€ for Case A.

If the operational costs are added, the economic advantage of compact transformers is reduced but still more attractive. The costs of option A.1 and A.2 are significant higher than the rest. The costs of solutions A.3 to A.6 are near (2.8-3.1 M€) but with different platform and losses percentage for each design.

The optimal solution is the design A.4 (three phase design with aramid insulation) since it is a compact design but the losses are not as high as in the single phase designs.

Case B: 1000 MVA HVDC offshore transmission line.

In acquisition terms, the option B.4 (aramid paper design) saves a total of 23.8M€ in initial investment due to the extreme transformer weight reduction.

In *TOC* basis, the solution B.4 (aramid insulation) is also the most economical solution. However, B.4 and B.3 has similar costs. Solutions B.1 and B.2 have higher costs due to the cost of the platform.

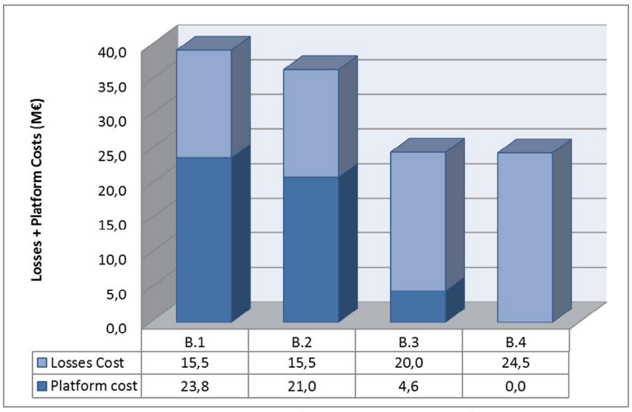

Fig. 11. Losses and platform costs in M€ for Case B.

Results can vary depending on the considered formula for the losses capitalization. A complete evaluation is done performing the same economical evaluation but for different cases: 2, 5 and 8 k€/kW (Fig. 12).

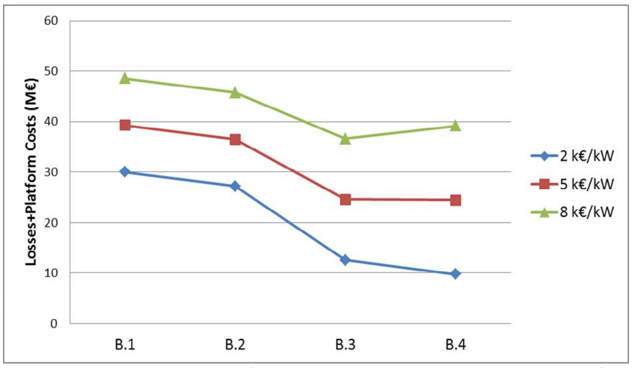

Fig. 12. Losses and platform costs in M€ at 2, 5 & 8 k€/kW for case B.

If losses capitalization is high, the curves tend to decrease smother. The platform cost is kept constant, but operational cost due to the transformer electrical losses increases sharply. Anyhow, for high losses cost (8k€/kW), compact solutions (B.3 and B.4) are still the better choice since the costs are lower than B.1 design.

6. Conclusions

Offshore wind power plant manufacturers have to decide between the different power transformer designs, not only based on standard transformer solutions with capitalized losses evaluation, but also on the transformer weight and footprint to find the optimal solution: minimum total cost of the whole offshore substation (transformer plus platform).

As shown in the previous figures, the more compact the transformer is, the higher the losses are. High efficiency transformers have huge weight that makes this solution less attractive in acquisition terms.

Compact transformers are in the opposite direction to low losses transformer so the electrical losses associated to the transformer are higher. Taking into account the losses cost, compact transformers still are more interesting economically speaking.

An accurate value of cost of losses (due to the demand load reduction) and of the platform (due to the transformer weight) will definitely help to determine the best solution.

The evaluation has been done using the weight. However, the footprint and the oil volume are key factors to be evaluated as well.

The cost due to the transformer weight has a higher impact than losses cost. As a result, the use of compact transformers (with high temperature insulation or transformer with overloading capability) can be a useful instrument to achieve optimal solutions.

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