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Practical determination of HVAC - HVDC Hybridization ratio for Offshore Transmission network Architectures through technico-economic considerations

Adrià Pibernat ROSES, Bruno FRANCOIS
Univ. Lille, Centrale Lille, Arts et Metiers Paristech, HEI, EA 2697 – L2EP, Laboratory of Electrical Engineering and Power electronics, F-59000 Lille, France
bruno.francois@ec-lille.fr

***Abstract*— Transmission network architectures between an offshore wind farm and the grid in shore are analyzed. Models of HVAC, HVDC and hybrid transmission systems are developed in order to determine losses, costs and voltage drops according to the offshore distance and the transmitted power. An optimization framework is presented to order required calculation subroutines and process technico-economic analysis. The optimal hybridization ratio to set the power transfer between HVDC and HVAC transmission networks is then found. For comparisons, the connection of 300 MW offshore wind farm with a 100 km distance is studied.**

***Index Terms*— Transmission Systems Planning, Offshore wind farm, transmission system, high voltage direct current, HVDC, high voltage alternating current, HVAC, architecture and hybrid transmission and optimization.**

I. INTRODUCTION

In the most developed countries of Europe, the main wind resources available in land have been exploited since a long time. Nowadays only few areas in shore are available for wind farms but are not interesting solutions due to the low wind speed, the high cost of the system or environmental problems. Moreover a huge enlargement of the installed onshore wind power capacity installed is not expected for next years. Most of this new capacity will be the substitution of old wind turbines by new ones with a higher power capacity.

Offshore wind farms present better advantages compared with classical wind farms in shore [1]:

- More powerful and more frequent wind resource;
- Large available areas;
- Low visual impact for population;
- Small environmental impact.

Therefore many new offshore wind farms are under construction and a continuous increasing is expected in the next decade [26]. Large projects are planned around the world as: the Blekinge Offshore AB (Sweden) of 2,5 GW which is awaiting a decision [2], the Southwest Offshore Wind Project (South Korea) will have the same size and it is waiting for the approval of the South Korean Government [2] and the Moray Firth (United Kingdom) with 1.3 GW [2].

However offshore wind farms are needed more investments than onshore farms because of undersea cables, components of offshore wind turbines as tower sections, nacelles and blades, maintenance costs. So every technical details should be well calculated to gain maximum efficiency and minimum cost [25]. Optimal architectures for transmitting powers from far away offshore wind farms to the onshore grid are tackled in this paper with a focus on the decrease of operating costs. A lot of key factors should be considered, such as, investment, operation cost, stability, reliability, etc. Here, optimality is considered according to voltage drops, losses and costs and in function of the transmitted power and the offshore distance length in order to highlight interesting architectures and their corresponding designs.

Offshore distribution networks for wind generation connection are not considered [23, 24]. Here, the main interest is focused on hybrid architectures of offshore transmission networks combining advantages of high voltage alternating current (HVAC) and high voltage direct current (HVDC) (fig. 1). Moreover, new possibilities and facilities for the grid operator appear for the operation management as:

- an improved reliability as a partial rerouting of the power is still possible in case of fault,

- the availability of the frequency at the offshore station (from the HVAC lines) and so the possibility to vary the power injection onto the HVDC lines according to the national generation/consumption imbalance following a classical droop characteristic.

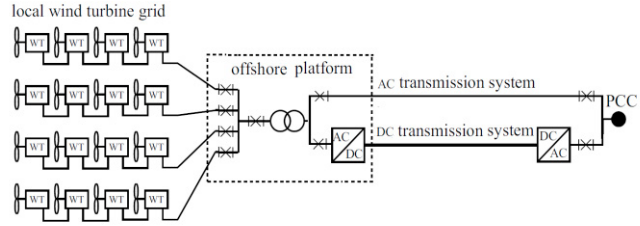

Figure 1. Overview of an hybrid transmission system

Anyway the power size and length of such hybrid transmission system must be previously studied to define a realistic framework for interesting industrial offshore

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applications. The issue is to develop technical and economic models for integration into a model based decision support tool for future transmission offshore project. in order to minimize capital costs, satisfy constraints imposed by the offshore site and assess the future profitability of the transmission power network.

The second and third part of this paper present modelling equations, which are used for the technical-economic analysis of HVAC and HVDC architectures. Then a parametrized modelling of a hybrid transmission network is detailed in the fourth part. Assumptions and the framework of the economical modelling are focused on the fifth part. Then in part six, the design tool is used in order to determine best hybrid architecture parameters (hybridization ratio of power transmission, distance length, transmitted power) according to losses and economic criteria.

II. Modelling of a HVAC Transmission Network

HVAC transmission systems are based on three main components: the three-core HVAC submarine cable, the offshore/onshore transformer and the reactive compensation equipment. They are modeled in order to assess power losses.

A. HVAC Cable

The HVAC submarine cable is modelled as a π model with two capacitances (C_1 and C_2), one inductance (L_1) and the resistance (R_1) without taking in consideration the dielectric losses [3] (Fig. 2). The corresponding modelling equations with subscripts *in* and *out* for respectively input and output electrical variables are:

$$Z = j\omega L_1 + R_1 \quad (1)$$

$$Y = j\omega C_1 = j\omega C_2 \quad (2)$$

$$I_z = I_{out} + \frac{Y}{2} V_{out} \quad (3)$$

$$V_{in} = V_{out} + Z I_z \quad (4)$$

$$V_{in} = \left(1 + \frac{ZY}{2}\right) V_{out} + Z I_{out} \quad (5)$$

$$I_{in} = I_z + \frac{Y}{2} V_{in} \quad (6)$$

$$I_{in} = Y\left(1 + \frac{ZY}{4}\right) V_{out} + \left(1 + \frac{ZY}{2}\right) I_{out} \quad (7)$$

The equations below can be represented in a matrix form:

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{out} \\ I_{out} \end{bmatrix} \quad (8)$$

With

$$A = \left(1 + \frac{ZY}{2}\right) \qquad B = Z$$

$$C = Y\left(1 + \frac{ZY}{2}\right) \qquad D = \left(1 + \frac{ZY}{2}\right)$$

Losses in the AC cable ($Pl_{AC\ Cable}$) in MW are expressed as:

$$P_{in} = real(3 \cdot V_{in} \cdot conj(I_{in})) \quad (9)$$

$$P_{out} = real(3 \cdot V_{out} \cdot conj(I_{out})) \quad (10)$$

$$Pl_{AC\ Cable} = (P_{in} - P_{out}) \cdot n_{cables} \quad (11)$$

n_{cables} is the number of cables. The voltage drop (VD_{AC}) in % is expressed as:

$$VD_{AC} = \left(\frac{(V_{in} - V_{out})}{V_{out}}\right) \cdot 100 \quad (12)$$

Parameters of cables are coming from ABB datasheets [4], [5]. The inductance and the capacitance are linear but the resistance is not linear because it depends on the current. The AC resistance of the cable is expressed as:

$$R_{AC} = R_{DC} \, . \, (1 + \gamma_s + \gamma_p) \quad (13)$$

γ_s is the skin effect factor, which is calculated by using the IEC 60287 "Calculation of the continuous current rating of cables" [20] by:

$$\gamma_s = \frac{{x_s}^4}{0.8 \cdot {x_s}^4 + 192} \quad (14)$$

$${x_s}^2 = \frac{8 \cdot \pi \cdot f_{grid} \cdot 10^{-7}}{R_{DC}} \quad (15)$$

f_{grid} is the frequency of the grid, x_s is the resistance effect factor and R_{DC} is the DC resistance.

The proximity effect (γ_p) is determined by using the same IEC 60287 [6]:

$$\gamma_p = \frac{{x_p}^4}{0.8 \cdot {x_p}^4 + 192} \cdot \left(\frac{d_c}{s}\right)^2 \cdot \left[0.312 \cdot \left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{{x_p}^4}{0.8 \cdot {x_p}^4 + 192} + 0.27}\right] \quad (16)$$

$${x_p}^2 = \frac{8 \cdot \pi \cdot f_{grid} \cdot 10^{-7}}{R_{DC}} \quad (17)$$

d_c is the diameter of the conductor, s is the space between conductors.

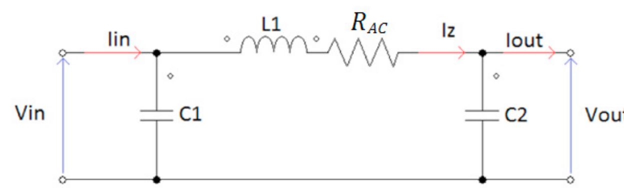

Figure 2. Three-core HVAC submarine cable electrical circuit

R_{DC} is the DC resistance of the cable at a specific temperature (T).

$$R_{DC} = R_0 \, . \, (1 + \alpha(T - T_0)) \quad (18)$$

R_0 is the DC resistance at 20 ºC, α is the temperature coefficient of the material (= 0.00386 for copper), T_0 is 20 ºC. $T(ºC)$ is the temperature of the cable. Fig. 3 shows the temperature variations for three different cross sections (400, 630 and 1000 mm^2) depending on the current.

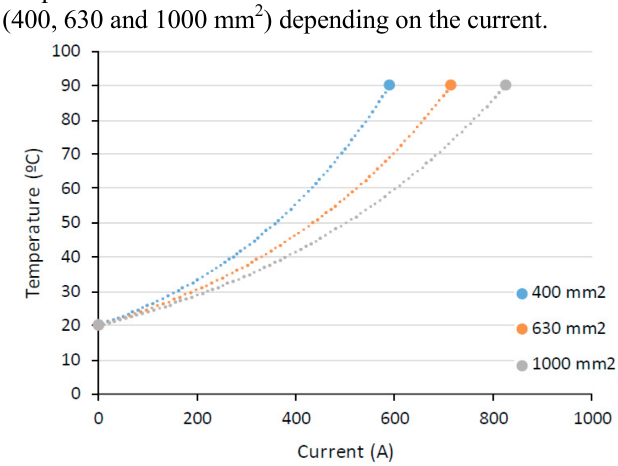

Figure 3. Temperature in function of the current in the cable