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Estimation of investment model cost parameters for VSC HVDC transmission infrastructure

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ABSTRACT

Investment model cost parameters for VSC HVDC transmission infrastructure continue to be associated with high uncertainty and their validity remains a crucial challenge. Thus, it is the key objective of this analysis to identify a new cost parameter set providing better investment cost estimates than currently available cost parameter sets. This parameter estimation is based on a previously conducted review of investment model cost parameters including its collection of existing cost parameter sets and project cost reference data. By using a particle swarm optimisation, the overall error function of the review's evaluation methodology is minimised to obtain an optimal parameter set. The results show, however, that the optimised parameter sets are far from being realistic and useful, which is why an improved overall error function is developed. Effectively penalising negative and near-zero cost parameter coefficients, this new overall error function delivers a realistic and well-performing cost parameter set when being minimised. In fact, the new parameter set produces better cost estimates for back-to-back, interconnector, and offshore wind connection projects than any of the existing cost parameter sets. Therefore, it is a valuable contribution and shall be considered in future grid investment analyses involving VSC HVDC technology.

1. Introduction

Voltage Source Converter (VSC) High Voltage Direct Current (HVDC) is the most suitable technology for future super grids and offshore grids in Europe [1,2]. While multiple investment analyses of future offshore grid topologies have already been conducted (e.g. [3]), the subject of implementing integrated power grids continues to be an important research topic. As the optimisation algorithms used for assessing investment decisions in offshore grid infrastructure rely on a cost model and corresponding parameter sets, the validity of those parameter sets plays a crucial role.

However, it has been established in [4] that the cost parameter sets which have been widely used by academia and policymakers show significant variations from study to study. They indicate a high level of uncertainty both when comparing them against each other and when evaluating them against reference cost data from realised VSC HVDC projects. Acknowledging the fact that there are multiple and valid reasons for diverging cost estimates obtained with those parameter sets, a new parameter set based on the reference cost data for realised projects is needed to improve the validity of future grid investment and evaluation studies. Therefore, by drawing on the collected parameter sets and reference project cost data in [4], a new parameter estimation approach will be explored in this context to determine a new investment cost parameter set for VSC HVDC projects which can be used in transmission expansion studies.

In the remaining part of this article, Section 2 summarises the cost model and parameter information for the following parameter estimation. Section 3 introduces the particle swarm optimisation methodology which is used to compute the new parameter sets through error minimisation. Two optimised cost parameter sets based on the error function from [4] are presented in Section 4. Section 5 develops an extended overall error function including the new realness category. In Section 6, the final cost parameter set obtained from minimising the new overall error function is presented. Section 7 discusses the obtained comparison and evaluation results and Section 8 concludes the study.

2. Fundamentals

This section contains a summary of the most important information, equations, and tables from [4], which are essential for the optimisation approach of this article. In addition, a new

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Nomenclature

Abbreviations

B2B	back-to-back
ITC	interconnector
OWC	offshore wind connection
PSO	particle swarm optimisation
QEF	quadruple error function
R	realness
TEF	triple error function

General

$\lceil real \rceil$	ceiling of *real*($\lceil real \rceil = \min\{n \in \mathbb{N}_0 \mid n \geq real\}$)
$\|set\|$	cardinality of *set*

Indices and sets

$f \in F_i$	set of branches within project i
$g \in G_i$	set of nodes within project i
$h \in H_i$	set of offshore nodes within project i
$i \in I_j$	set of projects within category j
$j \in J$	set of project categories ($J = \{$B2B, ITC, OWC$\}$)
$k \in K$	set of cost parameter sets
$q \in Q^k$	set of cost parameters of parameter set k
$z \in Z$	set of categories including realness ($Z = J \cup \{$R$\}$)

Cost parameters and variables

B_0^k	fixed cost for building a branch with cost parameter set k (M€)
B_{lp}^k	length- and power-dependent cost for building a branch with cost parameter set k (M€/GW km)
B_l^k	length-dependent cost for building a branch with cost parameter set k (M€/km)
$C_{\mathrm{est},i}^k$	estimated investment cost for project i (M€)
$C_{\mathrm{ref},i}$	reference investment cost for project i (M€)
$C_{\mathrm{ref},i}^{\mathrm{con}}$	reference contracted cost for project i (M€)
N_0^k	fixed cost for building a node with cost parameter set k (M€)
N_p^k	power-dependent cost for building a node with cost parameter set k (M€/GW)
S_0^k	fixed additional cost for building an offshore node with cost parameter set k (M€)
S_p^k	power-dependent additional cost for building an offshore node with cost parameter set k (M€/GW)

Technical parameters and variables

$\hat{P}_j$	maximum power rating for a single installation within category j (GW). In case of a back-to-back system, this is twice the system rating (two fully rated converters at one node).
$l_{\mathrm{OHL},f}$	overhead line section length of branch f (km)
$l_{\mathrm{SMC},f}$	submarine cable section length of branch f (km)
$l_{\mathrm{UGC},f}$	underground cable section length of branch f (km)
l_f	total equivalent line length of branch f (km)
p_f	installed power rating of branch f (GW)
$p_{g/h}$	installed power rating at node g/h (GW). In case of a back-to-back system, this is twice the system rating (two fully rated converters at one node).

Deviations and errors

ϵ_R^k	unscaled root-mean-square realness error for cost parameter set k (–)
$\epsilon_{q,\mathrm{EXP}}^k$	relative exponential deviation of parameter q for cost parameter set k (–)
$\epsilon_{q,\mathrm{LOG}}^k$	relative logarithmic realness deviation of parameter q for cost parameter set k (–)
$\epsilon_{q,\mathrm{REL}}^k$	relative realness deviation of parameter q for cost parameter set k (–)
A	constant scalar realness error scaling factor (–)
D_i^k	project investment cost estimation deviation of project i for cost parameter set k (–)
D_j^k	category investment cost estimation deviation of category j for cost parameter set k (–)
E_{QEF}^k	overall root-mean-square error of four category errors (quadruple error function) for cost parameter set k (–)
E_{TEF}^k	overall root-mean-square error of three category errors (triple error function) for cost parameter set k (–)
E_{R}^k	root-mean-square realness error for cost parameter set k (–)
E_q^k	realness error of cost parameter q for cost parameter set k (–)
$E_{j/z}^k$	category root-mean-square error of category j/z for cost parameter set k (–)

parameter set notation is introduced as it is convenient for all subsequent considerations.

2.1. Cost model

A linear uniform cost model has been defined in [4]. It provides an approximation of the investment cost associated with offshore grid HVDC infrastructure and yields a reasonable accuracy regarding long-term large-scale transmission expansion studies (e.g. [45]). The cost model is based on [46–48].

Bear in mind that a mixed-integer linear cost model yields significant benefits for long-term large-scale transmission expansion planning problems and the optimisation algorithms solving them, as computation time and convergence face severe challenges when more complex cost models are applied.

Since the main equations explained in [4] are inevitable for the subsequent calculations, they are repeated in this subsection. The linear uniform cost model for VSC HVDC transmission investments is defined by Equations Eqs. (1–6):

$$C_{\mathrm{est},i}^k = \sum_g^{G_i} N_g^k(p_g) + \sum_f^{F_i} B_f^k(l_f, p_f) + \sum_h^{H_i} S_h^k(p_h) \quad (1)$$

$$N_g^k(p_g) = N_p^k \cdot p_g + \lceil \frac{p_g}{\hat{P}_j} \rceil N_0^k \quad (2)$$

$$B_f^k(l_f, p_f) = B_{lp}^k \cdot l_f \cdot p_f + \lceil \frac{p_f}{\hat{P}_j} \rceil \left(B_l^k \cdot l_f + B_0^k \right) \quad (3)$$

$$S_h^k(p_h) = S_p^k \cdot p_h + \lceil \frac{p_h}{\hat{P}_j} \rceil S_0^k \quad (4)$$

$$\hat{P}_{\mathrm{B2B}} = 4\ \mathrm{GW} \quad \hat{P}_{\mathrm{ITC}} = 2\ \mathrm{GW} \quad \hat{P}_{\mathrm{OWC}} = 2\ \mathrm{GW} \quad (5)$$

$$l_f = l_{\mathrm{SMC},f} + \frac{5}{4} l_{\mathrm{UGC},f} + \frac{2}{3} l_{\mathrm{OHL},f} \quad (6)$$

It is important to stress that the installed power rating (p_g, p_h) corresponds to the total power rating of all converters at a node, which is twice the system rating for a back-to-back system (contains two fully-rated converters). This is the reason why $\hat{P}_{\mathrm{B2B}}$ is twice the size of $\hat{P}_{\mathrm{ITC}}$ and $\hat{P}_{\mathrm{OWC}}$.