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A new method for simultaneous optimizing of wind farm's network layout and cable cross-sections by MILP optimization

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HIGHLIGHTS

- Simultaneous optimization of wind farm's network layout and cable cross-sections.
- Proposed method brings substantial cost savings compared with other methods.
- Usefulness and effectiveness of the MILP optimization was demonstrated.
- Electrical losses need to be taken into account in the design process.
- An absolute optimal solution (GAP = 0) is received in a reasonable computation time.

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ABSTRACT

Internal electrical networks of large wind farms constitute complex and dispersed grid structures. Wind turbines are scattered over vast areas and the total length of cabling infrastructure might reach several dozens of kilometers. Outlays related to cable laying significantly contribute to the entire project budget. Therefore the design process should minimize these expenses considering also operation and maintenance costs calculated over the project lifetime on condition of fulfilment of all technical requirements. An analysis presented in this paper demonstrates that an independent optimization of the twofold problem dealing both with investment and operation costs does not result in the cheapest solution. The analysis confirmed also reliability and effectiveness of application of Mixed Integer Linear Programming method (MILP) to solve this kind of optimization problem. The paper shows that the developed integrated optimization algorithm is efficient and delivers an absolute optimal solution (GAP = 0) in a reasonable computation time. The results obtained for a real wind farm project confirm that the optimal design of a wind farm network can't be determined a priori and the final outcome strongly depends on the configuration of wind turbines (e.g., number of feeders, number of turbines connected to a single feeder, etc.) and technical parameters of cables. Spread over time, discounted costs of energy losses are an integral part of the objective function. The study proves that cost of energy losses impacts on the overall financial results and shouldn't be neglected. The related expenses are roughly at the same level as expenditure linked to cable laying and they heavily influence the final design of the internal network. The results show the possibility of practical use of the proposed algorithm in the wind farm design process.

1. Introduction

The design and construction of a wind farm is a long, multistage procedure. At each of the stages an investor faces economic decisions which aim at producing best technical and economical results taking into account the whole project lifetime. In many instances engineers working on a wind farm design use commercial software tools, which include embedded optimization functionalities. Unfortunately, these tools quite often do not allow for a complex approach including economic aspects in the project optimization, which might contain [1–6]:

- Optimal location of individual wind towers over the geographical area of the wind farm.
- Optimization of the wind farm internal electrical network.

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- Optimal clustering of wind turbines into sections, which defines number of feeders.
- Optimal selection of cable cross-sections both for connections between individual turbines, between feeders and between the entire farm and the electrical substation.
- Optimal selection of power transformers at wind farms' electrical substation.
- Economic optimization of a wind farm daily and hourly operation.

Although each of these problems constitutes a relevant and sometimes decisive factor at a certain stage of a wind farm design process, only integrated optimization of all the above listed problems will result in the best economic gains. This approach is in line with investors' expectations, as they are primarily interested in maximization of their return on investment.

The optimization problem dealing with placement of individual wind turbines and the entire structure of a wind farm has been already well explored. Initially the research focused on maximization of the wind farm productivity, which to a large extent depends on distances between individual turbines and is related to the shadow effect and mechanical interferences within a wind farm. This problem has been addressed in [7–18]. Various optimization methods were proposed to solve this problem. Park and Law [7] propose sequential convex programming for solving the nonlinear mathematical problem. Feng and Shen [8] present a random search algorithm based on continuous formulation. Turner et al. [9] develop mixed integer linear and quadratic optimization formulations. Song et al. [10] use optimization approach based on greedy algorithm. Eroğlu and Seçkiner [11,14] present an ant colony algorithm and propose a particle filtering as a new approach used to optimize the layout model. Pookpunt and Ongsakul [12] use a binary particle swarm optimization with time-varying acceleration coefficients. Emami et al. [16] present a study of wind turbines placement in wind farm with a new genetic algorithm approach.

Kuo et al. [19,20] propose an algorithm that couples computational fluid dynamics with mixed-integer programming to optimize layouts on complex terrains. Furthermore, Rašuo and Bengin [21] consider in their work the topography of the terrain at the wind farm location and Dutta and Overbye [22] analyze an example of large wind farm infrastructure consisting of wind turbine clusters.

Wind farm layout problem is well discussed in literature, but most of it concerns only optimal turbine location, maximizing farm energy output. Guirguis et al. [23] present genetic algorithm to show the effectiveness of non-linear mathematical programming in solving continuous-variable the Wind Farm Layout Optimization problems by utilizing exact gradient information of the problem's objective and constraints. Turner et al. [24] use Jensen's wake decay model to represent multi-turbine wake effects. Authors develop mixed integer linear and quadratic optimization formulations and apply them to several exemplary layout cases. Gao et al. [25–27] propose the optimal wind turbine layout configurations with an economic analysis and monthly power generation for offshore wind farm in Hong Kong. Optimization is done by Multi-Population Genetic Algorithm.

Herbert-Acero et al. [28] present a review of existing methods for optimization of wind farm grid infrastructures and suggesting prospective research activities in that area.

Investors and future farm owners are mostly interested in maximizing wind farm energy production. This problem may be solved in the design phase by use of previously described methods optimizing the location of the turbines in respect of better utilization of wind energy. An equally important problem is the optimization of the wind farm operation to maximize overall profits. Siahkali and Vakilian [29] present a new approach for solving the generation scheduling problem. Moyano and Lopes [30] describes an operational optimization strategy to be adopted at the wind park control level, that enables defining the commitment of wind turbines and their active and reactive power outputs.

González et. al. [31–33] use an Evolutive Algorithm for wind farm optimal overall design. The algorithm's objective is to optimize the profits given an investment on a wind farm by maximize the generation of energy and minimize the power losses. Recently observed growing interest in the renewable energy and soaring number of wind projects has drawn even more attention to optimization of wind farm grid infrastructure. More and more frequently researches acknowledge the key role and potential of advanced optimization of internal networks and methods for wind farm coupling with public networks. González-Longatt et al. [34] apply genetic algorithms to optimize infrastructures of large offshore wind farms. For a similar task Neagu and Georgescu [35] recommend conventional algebraic graph theory algorithms. In works published by Klein et al. [36], the authors solve the problem with Mixed Integer Linear Programming (MILP) method. All these works, however, focus on optimization of wind farm cabling with a single objective - minimization of overnight investment costs. In consequence, such optimization is limited exclusively to minimization of the total length of all branches of the internal network.

Although Bauer and Lysgaard [37] present an approach based on MILP method combined with additional heuristics, taking into consideration cost and cross-section of cables, the proposed optimization of the infrastructure was limited to the preselected types of cables and predefined configuration of network sections. Fagerfjall [5] and Fischetti [38,39] have progressed with more advanced optimization models, based also on MILP methods, but without considering technical constraints and energy losses. Both papers made efforts to combine separate optimization procedures into one integrated calculation algorithm. Lumbreras and Ramos [40] propose Benders' decomposition strategies for solving the problem of the optimal design of the electrical layout for an offshore wind farm.

Cerveira et al. [41] were one of the first authors, who considered limitations related to specific cable design series, with both cross-sections and prices modeled using integer variables. Additionally the authors included engineering constraints in the proposed algorithm, but at the same time ignored costs related to energy losses. Pemberton et al. [42] offer a Genetic Algorithm based optimization method for onshore applications and demonstrates how an optimal wind farm cable network design solution can be reached in terms of minimum cost, minimum power losses and maximum reliability. Chen et al. [43] present method which can be used to generate the network model based on fuzzy c-means and binary integer programming methods. The objective of this optimization is to minimize the investment costs of cable connection and the transmission power losses. Hou et al. [44–47] show the effect of taking into account energy losses in the optimization of network configuration of the wind farm. Authors use few different algorithms: minimum spanning tree (MST), dynamic minimum spanning tree and algorithm based on the concept of MST and further improved by adaptive particle swarm optimization algorithm. Finally, Pillai et al. [48] present optimization model, which considers both selected technical requirements and costs of energy losses, however, due to negligence of temporal aspects of intermittent operation of a wind farm, the way the energy losses are accounted for in regular operation of the wind farm is ineffective.

The above review of the most relevant scientific publications shows that the existing methods for optimization of wind farms' electrical network are not completely satisfactory. Selection of the network topology is a complex task. On the one hand, the optimal layout of the network should minimize the length of connections between wind turbines within the farm and to the point of