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Optimization framework for distributed energy systems with integrated electrical grid constraints

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HIGHLIGHTS

- Multi-objective optimization framework of distributed energy systems developed.
- Framework combines energy hub, building simulation and distribution grid model.
- Electrical grid constraints integrated by linearizing AC power flow equations.
- Inclusion of grid constraints in the operation schedule reduced emissions 18%.
- Voltage and current variation significantly reduced even with high share of PV.

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ABSTRACT

Distributed energy systems (DES) can help in achieving less carbon-intensive energy systems through efficiency gains over centralized power systems. This paper presents a novel optimization framework that combines the optimal design and operation of distributed energy systems with calculations of electrical grid constraints and building energy use. The framework was used to investigate whether the negative impact of distributed generation on distribution grids can be mitigated and grid upgrades avoided by properly designing and determining operation strategies of DES.

Three new methods for integrating grid constraints were developed based on different combinations of a genetic algorithm and a mixed-integer linear programme. A case study is defined in order to analyze the optimality, accuracy of power flow calculation and solving performance of each method. The comparison showed that each method has advantages and disadvantages and should therefore be chosen based on the application and objectives.

The results showed that the electrical grid constraints have a significant impact on the optimal solutions, especially at high levels of renewable energy use, highlighting their importance in such optimization problems. The inclusion of such constraints directly in the operational scheduling achieved an additional 18% reduction in carbon emissions for a given cost compared to checking the validity of solutions *a posteriori*. Furthermore, by properly designing and determining operation schedules of DES, it is possible to integrated 40% more renewables without grid upgrades.

1. Introduction

1.1. Background

The European Union has set goals of reducing energy consumption, reducing carbon emissions and improving security of supply. This can be achieved by more efficient use of energy, increased share of renewables and/or use of decentralized energy sources. Distributed energy systems (DES) can help meeting the goals by being more efficient compared to centralized power systems. DES can contain fossil based generators but are often predominantly based on local renewable resources. However, such systems can have negative impact on the existing distribution grids if not designed and managed properly. Manfren et al. [1] analyzed the benefits and drawbacks of distributed energy systems. The main strengths are decreased fossil fuel usage, protection against electric

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system failures through use of local renewable resources and optimal operation of different energy carriers (electricity and heat) to meet the energy demands of the built environment. On the contrary, they can have a negative impact on the grid if integration is not properly managed, such as reverse power flow, voltage rise and cable thermal limits. The evaluation of solutions for decreasing environmental impacts needs to take into account the local and global effects of the proposed solutions. Moreover, optimization approaches are necessary to enable successful application in the field of integration of distributed generation and renewable sources in urban areas. Multiple energy technologies, suitable operating strategies to match time-varying energy demands of buildings to renewable energy sources, and operational limits of the energy carrier infrastructure such as electrical grids should be included for the most efficient integration of DES in the distribution grids and for the decreasing environmental impact.

1.2. Previous work

A number of optimization models of distributed energy systems already exist where the objective is to find the optimal design and operation of distributed energy systems according to economic and/or environmental objectives. DER-CAM [2] is an optimization model that determines the optimal capacity and dispatch strategy of distributed generation technologies to minimize global annualized cost on the customer level. Ren and Gao [3] developed a mixed integer linear programming (MILP) model for economic evaluation of DES by selecting appropriate design and operation. Later it was extended to include multi objective optimization considering economic and environmental objectives [4]. Mehleri et al. [5] developed a MILP super-structure model for the optimal design of distributed energy systems, including heating networks. The objective function is the minimization of total annualized cost, and carbon emissions are included as a cost via a carbon tax. Omu et al. [6] developed a model to determine the optimal set of technologies and operation for minimization of annual cost. Holjevac et al. [7] developed a MILP model of a microgrid that determines the optimal microgrid configuration and operation in order to evaluate the flexibility benefits of distributed generation. Chen et al. [8] developed energy management model for determining optimal operating strategies in order to maximize a profit. However, in such publication the constraints of the electrical grid on the integration of local energy sources were not considered, but they assumed the grid to be exogenous and with unlimited capacity. This can lead to solutions that are not possible to integrate in the existing grids and may cause reliability and security issues.

On the other hand, a lot of work has been done in analyzing impact of distributed generation on distribution grid constraints. Calvillo et al. [9] assessed the effects of cable thermal limits on optimal distributed energy resources planning; cable thermal limits are based on maximum energy transfer between households and not on AC power flow calculations. Thomson and Infield [10] looked at the potential technical effects of micro combined heat and power (CHP) on distribution grids for predefined capacities without optimization of operation. Cossent et al. [11] quantified the impact of distributed generation on distribution network costs in three real distribution areas with predefined capacities and no optimization of operation. Liu et al. [12] analyzed impact of CHP, heat pumps and electric boilers on electricity and heat networks. Power flow study was solved using Newton-Raphson iterative method. Mancarella et al. [13] proposed a methodology to model and assess the impact of distributed generation on distribution networks; the capacities of distributed generation are predefined. Baetens et al. [14] developed a tool for simultaneous simulation of thermal and electrical systems at feeder level. Thomson and Infield [15] performed load-flow analyzes for the widespread integration of photovoltaics in distribution systems with predefined capacities and no optimization of operation. Navarro-Espinosa and Mancarella [16] performed high resolution analysis of impact of heat pumps on low voltage networks by solving power flow in OpenDSS. In aforementioned publications there is no optimization included. The capacities are predefined and the power flow study is performed afterwards and cannot influence design or operation. This may provide less efficient solutions and unnecessary grid upgrades.

Integrating AC power flow equations in their original form in the optimization model so that they influence both the design and operation is only possible with a nonconvex mixed integer nonlinear program formulation. However, incorporation of nonconvex constraints leads to a high chance that the global optima are not reached and the solution gives local optima. Moreover, even though there have been recent advances in new solver there is still no efficient solver for such problem which makes the solving computationally demanding and very difficult for larger problems. One of the other approaches used to include power flows in the optimization model is to express them as energy balance for each line or even area as done in [17–21]. In distribution grids with large share of distributed generation, power flows are not necessarily only unidirectional and the inclusion of intermittent sources using energy balance for power flows can lead to incorrect state estimation which can have negative impact on distribution and even transmission grids [22,23].

Another approach is to linearize power flow equations to efficiently integrate them and use them in the optimization problems. The most common linearization of AC power flow equations is DC power flow. However, it assumes that reactive flows are equal to zero and that all voltages are close to nominal value. Also, certain properties of the grid have to be met such as resistance/reactance ratio. As consequence they do not provide any information about voltage magnitudes, reactive power flows and branch, and are not applicable in the distribution grids but are usually applied in transmission lines [24,25]. For distribution grids, linearized AC power flows are required where information about voltages, currents and both active and reactive power flows at each line for each timestep is known [26]. To authors knowledge linearized AC power flows have not yet been combined with the optimal design and operation of DES in any previous work. By obtaining voltages, currents and both active and reactive power flows at each line, it becomes possible to integrate DES in the distribution grids so that the reliability and power quality of the system and the grid is ensured. Also, large voltage fluctuations, exceeding cable thermal limits and transformer limits can be avoided. In that way, additional costs such as upgrade of the grid or replacement of equipment can be avoided.

In conclusion, existing optimization models that find the optimal design and operation of distributed energy systems do not take distribution grid constraints into account and assume that the grid can integrate any amount of local sources. On the other hand, the distribution grid limits are taken into account separately from determining the design and operation of DES, or by combining them in the optimization models in simplified form which does not give all required information. This may lead to inadequate solutions, grid instability, and additional upgrades and maintenance costs.

1.3. This paper

In this paper we present a novel optimization framework that incorporates the optimal design and operation of DES with electrical grid constraints (based on AC and linearized AC power flow). The framework advantages over existing literature are shown in Table 1. The framework is applied to a case study to analyze the