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Optimal dispatch of large multi-carrier energy networks considering energy conversion functions

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Abstract

An integrated coordination of multi-carrier energy networks including gas, heating, cooling and electricity can increase the flexibility, efficiency and sustainability of energy systems. The optimal dispatch of such systems is complicated by the non-convex nature of their energy conversion processes. Although these processes can be represented in mixed-integer linear programmes, real-time constraints of an online dispatcher may not be satisfied. In this paper, two approaches for alleviating this problem are developed and compared: one is based on a relaxed mixed-integer linear formulation and the other on mathematical optimization with complementarity constraints. Simulation results on realistic systems demonstrate that both approaches solve large multi-carrier dispatch problems efficiently. The mathematical optimization with complementarity constraints is computationally less intensive but the relaxed mixed-integer linear formulation is numerically more robust.

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1. Introduction

The need for energy efficiency measures, carbon emission reductions and the growth of distributed energy systems have sparked research in the operational optimization of energy systems. In particular the dispatch (unit commitment) of multi-carrier energy systems or energy hubs has gained attention as many degrees of freedoms can be exploited to increase efficiency and to access new types of energy storage [1]. In this paper, the focus is on the combined dispatch of electrical distribution grids and decentralized district heat networks.

Energy conversion processes are crucial to this endeavour. In most recent work on multi-carrier energy networks, the energy conversion has been regarded as a constant efficiency. With the adoption of small distributed modulating

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heat-pumps and combined heat and power plants, the specific properties of energy conversion processes cannot be ignored. Generally, the models of these processes involve non-convex constraints and are therefore impossible to address using efficient convex optimisation methods such as linear programming.

The non-convex characteristics of the heating, ventilation and cooling equipment have been included in model predictive control schemes with a focus on single building control via relaxation methods [2] and sequential quadratic programming [3]. The works of [4] and [5] represent these processes with a piecewise affine representation and use mixed-integer linear programming (MILP) to find a solution. This approach works adequately only if the systems to be optimised are not very large.

In the case of control of multi-carrier networks with a multitude of components, the computational load of the underlying dispatching problem can exceed the real-time requirements and faster methods are needed. Decreasing the computational load of mixed-integer linear programming is a part of ongoing research. By showing that the energy conversion function is mostly concave, a simplified MILP model is presented that only requires a binary variable per time step. Furthermore, [6] has proposed a novel optimisation technique based on inverse parametric optimization (IPO) and mathematical programming with complementarity constraints (MPCC). Any piecewise affine function can be reformulated in the MPCC framework as shown in [7]. This property can be used to solve the energy dispatch as a MPCC by formulating the energy conversion processes as inverse parametric optimization problems. The two methods are compared for a realistic full-scale multi-carrier energy network.

2. Multi-carrier energy network models

2.1. Multi-carrier nodes

A multi-carrier network, such as the one depicted in Fig. 3, consists of a set of nodes $\mathcal{N}$ of any energy carrier (gas, electricity, heat, cooling, hydrogen), a set of network links, a set of grid feeders G, a set of energy conversion systems P that connect the multi-carrier nodes, a set of loads L and a set of storage systems S. Over a horizon $T \in \mathbb{Z}^+$, demand and supply are balanced at every node $i \in \mathcal{N}$ and for every time-step $k = \{1, 2, ..., T\}$ in the multi-carrier network:

$$\sum_{p_{out} \in P_i} p_{out,k} - \sum_{p_{in} \in P_i} p_{in,k} + \sum_{s_{out} \in S_i} s_{out,k} - \sum_{s_{in} \in S_i} s_{in,k} + g_{i,k} - \sum_{l \in L_i} l_k = 0 \tag{1}$$

where $p_{in,k}$, $p_{out,k} \in \mathbb{R}$ are the input and output streams of a conversion system linked to node i, $s_{in,k}$, $s_{out,k} \in \mathbb{R}$ are the storage streams linked to node i, $g_{i,k} \in \mathbb{R}$ is a grid link and $l_k \in \mathbb{R}$ are loads at node i. P_i, S_i and L_i denote the sets of decision variables of the conversion devices, storages and loads connected to node i.

2.2. Energy conversion systems

Combined heat and power plants (CHP) and heat pumps (HP) are useful components of decentralised energy systems. The outputs of these energy systems can be modulated and controlled according to demand. Energy conversion systems are often subject to minimum load constraints and part-load efficiency variations. For simplicity, we consider only single input/output energy streams; generalisation to multiple input or output streams is possible. In this context, an energy conversion unit can be thought of as a function $f : \mathfrak{R} \rightarrow \mathfrak{R}$ mapping the input to the output energy stream. The efficiency (for CHPs) or coefficient of performance (for HPs) is then defined by $\epsilon = f(p_{in})/p_{in}$.

The minimum and maximum outputs of the energy system limit the conversion to a certain range. In the case of CHPs, the function in this range is often convex due to the increasing efficiency [4]. The electric power to heating power conversion of heat pumps is often concave [8], as shown in Fig. 1(a). The CHP curve shown is based on [9]. The heat pump coefficient of performance was calculated using the method from [10]. A polynomial fit of the conversion function reveals the degree of convexity. The second order coefficient of the polynomial fit indicates whether the function is convex (negative coefficient) or concave (positive coefficient) in the operating range of the system. It is important to note that a convex energy conversion function or a negative intercept of the polynomial fit can both lead to an efficiency that increases with the load factor (Fig. 1(b)). Sections 3.1 and 3.2 explain how the energy conversion process is integrated into the optimization framework.