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Poster abstract: graph-theoretic model for observability in multi-carrier energy distribution networks

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Abstract The increasing installation of decentralized energy converters merges networks of different energy carriers to a multi-carrier energy distribution network (MEDN). To operate MEDNs efficiently and safe, the state of the network has to be monitored. An economically reasonable approach for monitoring MEDNs is provided by state estimation techniques, which however expect the network to be observable. To the best of our knowledge, we are the first to address the observability on MEDNs. Hence, we introduce a first graph-theoretic model serving as a starting point for introducing structural concepts, such as observability, for MEDNs.

Keywords Multi-carrier networks · Observability · Steady-state · Graph theory

Mathematics Subject Classification 93B18 · 05C90 · 90C35 · 94C15

1 Introduction

Energy distribution networks for different energy carriers—for instance electricity, gas and heat—are traditionally operated separately. However, in recent years the number of decentralized power converters, such as combined heat and power (CHP) plants and novel converter types like power-to-gas plants, increase [4,8]. These converters transform the energy distribution networks towards a multi-carrier energy distribution network (MEDN). The couplings within MEDNs creates potential synergies for the system operation [9].

To operate MEDNs efficiently automated multi-carrier control concepts using available synergies [5–7,9] are required. These concepts are based on online monitoring of the *state* of a MEDN to fulfill important network constraints such as voltage and current limits in the electrical domain; pressure, volume flow and temperature limits in the gas and heat domain. Operational variables that form the network state can be monitored by sensors. However, placing sensors, telecommunication infrastructure and equipment cabinets at each substation of the MEDN would be non-economical since it correlates with the number of network intersection points, pipes and lines.

State estimation offers a promising approach to tackle this problem. In order to perform a state estimation, the network has to be *observable* meaning that all desired operational variables are determinable. The observability of a system can be evaluated by considering the topology of the net-

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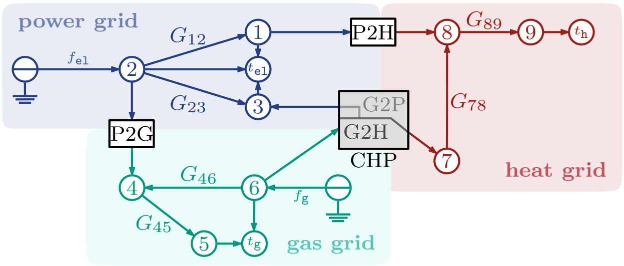

Fig. 1 MEDN with power grid (*blue*), gas grid (*green*) and heat grid (*red*) having $n_V = 18$ vertices including $n_N = 9$ carrier vertices, $n_{V_C} = 4$ converters (P2H, CHP and P2G), and $n_{V_T} = 5$ terminals. Note that the combined heat and power (CHP) plant is subdivided into two converters—the gas-to-power and gas-to-heat converters—adding two converter vertices to V_C. The conductance of each arc $(u, v) \in A$ is given by G_{uv} (colour figure online)

work as well as the types and locations of the measurement points [1]. The observability concept has been well studied for electric networks [1,3]. However, these concepts cannot be directly applied to MEDNs as additional structural characteristics from the cross-domain coupling and the interaction with other energy carrier levels appear. In this paper, we present a first graph-theoretic modeling approach representing a starting point for concepts such as observability in MEDNs.

2 Modeling approach

The coupling of different energy domains has a significant impact on the observability of the entire network. Hence, a cross-domain model is required. To the extent of our knowledge, there are only a few cross-domain approaches available. The most popular approach is the energy hub concept [5–7] using a power-flow-based modeling. However, this model does not contain the operational variables of the network state, e.g. voltage and pressure at vertices. Thus, it cannot be applied in the context of observability.

In our model, we consider the network in steady state, i.e., the system state variables are constant with respect to the time. Figure 1 represents a MEDN considering the electrical `el`, the gas `g` and the heat `h` carrier, which we index with $i \in \{1, 2, 3\}$ and thus, $k = 3$. However, we introduce a more general model allowing an extension towards other carriers if necessary.

We model a MEDN as a graph $M = (V, A)$, where V is the set of vertices representing transfer vertices $V_i \subseteq V$ with carrier $i \in [1, k]$, converters $V_C \subseteq V$, disturbances $V_T \subseteq V$; $A \subseteq \binom{V}{2}$ is the set of arcs representing lines or pipes (see Fig. 1). The vertex subsets are disjoint meaning $\bigcap_{i \in [1,k]} V_i \cap V_C \cap V_T \neq \emptyset$. An induced subgraph $M_i = M[V_i]$ in $M = (V, A)$ covers all arcs $(u, v) \in A$ with both ends $u, v \in V_i$. There are k subnetworks $N_1, N_2, \ldots, N_k$ defined by $N_i = (M_i, s_i, t_i, d_i)$, where the source and sink are two dedicated vertices for carrier i denoted by s_i and t_i with $s_i, t_i \in V_T$, respectively, and d_i as its demand. The source of each carrier represents an energy supply possibly placed in another network layer; the sink models energy consumptions or conversion losses of disturbances. A converter $v \in V_C$ has always conversion losses based on its converter efficiency $\eta \colon V_C \to [0, 1)$. However, the conversion losses are modeled with an arc $(u, t_i) \in A$ at the adjacent vertex $u \in V_i$ having an arc $(u, v) \in A$ to a converter $v \in V_C$ with $i \in [1, k]$. Thus, the number of disturbances in M is at least n_{V_C} resulting in an lower bound for the indegree of all sinks $\sum_{i \in [1,k]} d^-_M(t_i) \geq n_{V_C}$. Though the graph is undirected, we arbitrarily direct the edges for technical simplicity. In addition, we denote the number of vertices $n_V = |V| = n_N + n_{V_C} + n_{V_T}$, where $n_N = \sum_{i \in [1,k]} |V_i|$, $n_{V_C} = |V_C|$ and $n_{V_T} = |V_T|$. A *flow* is a function $f \colon A \to \mathbb{R}$. Assuming a steady-state network, there are no storage effects in any of the carriers [2, p. 152]. Thus, Kirchhoff's laws can be applied on hydraulic networks, too. Consequently, a *physical feasible* flow f on M is a flow complying Kirchhoff's laws.

This graph-theoretic model forms the basis for different structural properties such as observability. In order to obtain an observability criterion, the sensor placement at minimum cost to achieve observability is one of our tasks that we will evaluate on real benchmark sets.

3 Conclusion

In this paper, we provided a graph-theoretic model formulation for multi-carrier energy distribution networks (MEDNs). Compared to existing modeling approaches, we consider the operational variables forming the network state. Thus, this model is the first providing an easy adaption towards different structural concepts. A further endeavors will be done on the observability of MEDNs that is currently non-existent.

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