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A goal programming methodology for multiobjective optimization of distributed energy hubs operation

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HIGHLIGHTS

- We address the problem of optimal energy flow in multicarrier networks.
- We consider the effects of interconnected energy hubs on power networks.
- We propose a multiobjective methodology for reliable operation of the energy system.
- The validity of the method has been assessed on the 30 bus IEEE test network.

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ABSTRACT

This paper addresses the problem of optimal energy flow management in multicarrier energy networks in the presence of interconnected energy hubs. The overall problem is here formalized by a nonlinear constrained multiobjective optimization problem and solved by a goal attainment based methodology. The application of this solution approach allows the analyst to identify the optimal operation state of the distributed energy hubs which ensures an effective and reliable operation of the multicarrier energy network in spite of large variations of load demands and energy prices. Simulation results obtained on the 30 bus IEEE test network are presented and discussed in order to demonstrate the significance and the validity of the proposed method.

1. Introduction

The energy grids are, in general, amongst the most reliable systems worldwide. These large interconnected infrastructures, however, are subject to a host of challenges as far as aging assets, generation and transmission expansion to meet growing energy demand, distributed resources and reliability coordination are concerned. In this complex scenario, the large scale deployment of the energy hub paradigm could play a strategic role in supporting the evolution of conventional energy grids toward active, flexible and self healing networks composed by distributed, cooperative and interactive resources.

From a conceptual point of view, the energy hub is a unit where multiple energy carriers can be converted and conditioned. More specifically, they process multiple energy carriers at their input ports and provide certain required energy services (i.e. electricity, heating) at the output ports [1–3]. Consequently, energy hubs could be considered as flexible interfaces between different energy infrastructures (i.e. electrical networks, natural gas distribution systems) and/or energy users (i.e. producers, consumers). Within this interface energy is converted and conditioned by using a wide spectrum of technologies as far as combined heat and power technology, power-electronic devices, and heat exchangers are concerned. These converters allow energy hubs to combine and couple different energy carriers by redundant paths inducing a certain degree of freedom in its supply with several advantages compared to conventional, decoupled energy supply. Many industrial facilities can be modeled according to the energy hub paradigm. They include industrial plants, larger buildings, rural and urban districts, microgrids and isolated energy systems [4,5].

Energy hubs, if properly coordinated and managed, could increase the efficiency of multicarrier energy systems by: (*i*) allowing the large scale penetration of small-scale distributed generation systems; (*ii*) supporting the integration of renewable

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energy sources; (*iii*) reducing system losses and green house gas emissions; (*iv*) increasing the reliability of the energy supply to the customers [6,7].

As a consequence, a significant growth in the number of energy hubs connected to the existing energy distribution systems is expected in the near future.

From this perspective, a crucial issue is how to increase the energy hubs efficiency by properly coordinating their operation. In particular, due to the degrees of freedom established by the redundant connections, various energy vectors and different combinations of them can be used to meet the energy hub load requirements. This flexibility can be properly exploited to optimize the energy hub supply [1,4] since different inputs can be characterized by different costs, availability, and other technical and/or economical criteria.

Many classes of solution algorithms aimed at addressing this problem have been proposed in literature [1–4]. They include linear algorithms, which are based on the linearization of both the objective function and the problem constraints, and nonlinear programming techniques, which deal with problems involving nonlinear objective and/or constraint functions.

These solution methods represent an useful tool only from an user perspective, since they allow the analyst to effectively optimize the operation of a single energy hub without considering its impact on the multicarrier energy network operation.

Consequently the research for alternative techniques aimed at optimizing the operation of interconnected and distributed energy hubs by ensuring an effective and reliable operation of the multicarrier energy network is still an open problem and requires further investigations. We refer to this problem as the optimal energy flow problem.

Following this direction, in this paper we propose a solution based on the theory of multiobjective goal attainment optimization. In details we show as the optimal asset of the energy hubs network which (*i*) meets the loads, (*ii*) minimizes the energy costs and (*iii*) assures a robust and reliable operation of the multicarrier energy network can be formalized by a nonlinear constrained multiobjective optimization problem. Since these design objectives conflict with each other, the solution of such the optimal energy flow problem hasn't got a unique solution and a suitable trade off between the objectives should be identified.

To address this problem, one of the most common solution approach is based on the weighted global criterion method in which all objective functions are combined to form a single utility function. The main limitation inside these techniques in solving the optimal energy flow problem is that the weighting coefficients of the objective function do not necessarily allow trade-offs between the objectives to be expressed especially when the objectives are competing and the number of objectives increases. Further on the weighting strategies suffer of the so-called convexity problem that, in some cases, does not allow the analyst to explore the whole solutions space.

To fix this issue a solution paradigm based on the multiobjective goal attainment methodology is here proposed. The insight principle is to solve the optimal energy flow problem by firstly minimizing each objective function. This asks for the solution of a proper number of constrained scalar optimization problems characterized by different objective functions and the same set of equality and inequality constraints. The obtained solutions (also known as utopia points) are then processed by a goal attainment based programming technique aimed at identifying the final trade off solution.

Simulation results obtained on the 30 bus IEEE test network will be presented and discussed in order to prove the effectiveness of the proposed methodology in the task of solving the optimal energy flow problem in spite of large variations of load demands and energy prices.

2. Multicarrier energy network modeling

2.1. Electrical power network

Electrical power system modeling asks for the calculation of the steady-state voltage phasor angle and magnitude for each network bus for a given set of parameters (i.e. load demand and real power generation). Based on this information, all the variables characterizing the actual power system operation point (i.e. the real and reactive power flows on each branch and the power losses) can be computed.

In details, the input (output) variables of the electrical power system model are typically: the real and reactive power (voltage magnitude and angle) at each load bus; the real power generated and the voltage magnitude (reactive power generated and voltage angle) at each generation bus; and the voltage magnitude and angle (the real and reactive power generated) at the slack bus.

The equations used to solve this problem are the real power balance equations at the generation and load buses, and the reactive power balance at the load buses. These equations (also known as power flow equations) can be written as:

$$\begin{aligned} P_i^{SP} &= V_i \sum_{j=1}^{N} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad i \in nP \\ Q_j^{SP} &= V_j \sum_{k=1}^{N} V_k Y_{jk} \sin\left(\delta_j - \delta_k - \theta_{jk}\right) \quad j \in nQ \end{aligned} \tag{1}$$

where:

- N is the total bus number;
- nQ is the list of the buses in which the reactive power is specified;
- nP is the list of the buses in which the active power is specified;
- P_i^{SP} and Q_j^{SP} are the real and reactive power injections specified at i-th and j-th bus;
- $\overrightarrow{V} = V_i \angle \delta_i$ is the i-th bus voltage (in polar coordinates);
- $\overrightarrow{Y}_{ij} = Y_{ij} \angle \theta_{ji}$ is the ij-th element of the bus admittance matrix.

Due to the nonlinear nature of the power flow equations, numerical methods are employed to obtain a solution that is within an acceptable tolerance [8].

2.2. Natural gas network

The natural gas network is mainly composed by a system of pipelines with a set of production fields, processing plants, transportations and markets nodes [9].

In our study we assumed that each production node is equipped by a compressor which allows the gas to be injected into the network at a pressure level that can be fixed within certain limits, depending by the compressor and the physical pipeline proprieties.

The natural gas is delivered to the energy hubs by one or more transportation pipelines. For the sake of simplicity we assumed that the gas pressure cannot be increased in the transportation nodes, i.e., there are no compressors available in these nodes.

According to these hypothesis, we can model the flow q in each pipeline in function of the inlet (p_{in}) and outlet (p_{out}) pressure by the nonlinear Weymouth equation:

$$q = k\sqrt{p_{in}^2 - p_{out}^2} \tag{2}$$

where k is a constant factor whose value depends by the physical properties of the pipeline [10].

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