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Scheduling and control framework for distribution-level systems containing multiple energy carrier systems: Theoretical approach and illustrative example

Laura M. Ramírez-Elizondo *, G.C. (Bob) Paap

Delft University of Technology, The Netherlands

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ABSTRACT

Traditional optimization and control techniques are no longer suitable to account for the interactions introduced by new technologies like combined heat and power units (CHP) and renewable sources. In this paper a general optimization framework and a hierarchical control architecture are presented for systems with multiple energy carriers, i.e. electricity, heat, gas, etc. The proposed framework is based on the energy hub approach and is an extension of previous research done in this field.

Two-level architectures can be adjusted to fulfill the needs of future power systems, where there will be a higher participation of decentralized generation. Nevertheless, the papers generally focus exclusively on electricity flows, even when they include cogeneration units like fuel cells. For this reason the contribution of this paper is to propose a two-level control strategy that can be applied in systems with multiple energy carriers and to provide an illustrative example in which the results of using the strategy can be observed. The complete framework presented in this paper consists of an optimization algorithm and a real-time control algorithm. The optimization algorithm indicates when to turn on and turn off a generation unit and how much power it should deliver at a certain time period. The optimization is done for a forecasted period of 24 h and the real-time control strategy runs continuously to compensate for the mismatches between the scheduled load and the real load by means of control actions.

Introduction

As a result of the growing environmental concerns and the introduction of new technologies, the landscape of power system has been considerably changing during the last years. From the literature review (see section 'Literature review'), it was observed that a two-level architecture can be adjusted to fulfill the needs of future power systems, where decentralized generation will play a more important role. However, most of the control strategies found in the literature only focus on electricity flows. For this reason the contribution of this paper is to propose a two-level control strategy that can be applied in systems with multiple energy carriers (electricity, gas, heat, etc.) and to provide an illustrative example in which the results of using the strategy can be observed.

The complete framework presented in this paper consists of an optimization algorithm that allows the calculation of the *multi-carrier unit commitment* for a forecasted period of 24 h and a real-time control strategy that compensates for the mismatches between the scheduled load and the real load by means of control actions. The multi-carrier unit commitment defines when to turn on or turn off a controllable unit and provides its optimal dispatch (how much power should be produced by the generation unit). The algorithms were programmed in the optimization software for research applications AIMMS [1]. The control algorithms were programmed and tested using MATLAB Simulink.

The *energy hub* is used as the starting point for this work. The energy hub approach was developed as part of the project "Vision of Future Energy Networks – VoFEN" at ETH Zürich. The objective of the VoFEN project was to find optimal structures for energy systems in the future. In the VoFEN project, the interaction and conversion possibilities between different energy carriers were considered to increase the flexibility of energy supply systems.

An energy hub is flexible in supply due to the fact that there are different energy carriers available at its inputs and also by the fact that internal conversion and storage are possible [2,3]. This flexibility allows the use of optimization tools to determine the best way to supply a load, after taking the constraints of the system into account.

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* Corresponding author. Tel./fax: +31 (0)1527 86259/82968.
E-mail address: l.m.ramirezelizondo@tudelft.nl (L.M. Ramírez-Elizondo).

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The paper is organized as follows. Section ‘Basic concepts and definitions’ contains basic definitions related to the framework. Section ‘Literature review’ contains a literature review about control systems for decentralized systems. Section ‘Modeling of multi-carrier energy systems’ presents a summary of work that has been done in relation to modeling systems with multiple energy carriers and control of distribution systems. In section ‘Multi-carrier unit commitment framework’, the *multi-carrier unit commitment* framework is modeled and described. Section ‘Integrated control architecture’ describes the hierarchical control. Later section ‘Dynamic component models and controls’ presents the models that were used to represent the system. Section ‘Simulation results’ shows the results of the simulation. Finally section ‘Conclusions’ presents the conclusion of this paper.

Basic concepts and definitions

Energy hub element

There are three types of *energy hub elements*: direct connections, converters and storage elements [2,3]. Direct connections deliver input carrier α to the output port without converting it into another energy form. Conversely, converter elements transform energy carrier α into a different energy carrier β. Finally, storage elements consist of an interface and an internal (ideal) storage. Through the interface, power in the form of energy carrier α may be conditioned and/or converted into energy carrier γ, which is then stored internally. It is assumed that when a storage element exchanges energy carrier α, the element is considered a storage element of energy carrier α, even if energy carrier $\gamma \neq \alpha$ is stored internally [2,3].

Multi-carrier optimal dispatch

Multi-carrier optimal dispatch is a method to determine an optimal operation policy for a number of converter units processing multiple energy carriers [2].

Multi-carrier unit commitment

Multi-carrier unit commitment was introduced in [4] as the computational procedure that makes scheduling decisions in advance about the units that must be committed to supply a forecasted load in energy systems containing multiple energy carriers. The procedure determines the sequence in which the start-up and shut-down of the units (energy hub elements) should be executed as well as the optimal dispatch of each committed unit at each time period.

Participation factors

As a result of the execution of control actions, when a mismatch exists between the predicted demand and the actual demand, the units involved participate at compensating this mismatch. A *participation factor* defines the percentage in which each of the units has to participate in order to reduce the error that is produced by the mismatch.

Law of conservation of energy in an open system

For the system considered in this work, the total energy change per unit of time [W], or power, is equal to the result of adding the power that flows into the system in the form of γ, given by $\phi_{\mathrm{m},\gamma_{\mathrm{in}}} u_{\gamma_{\mathrm{in}}}$ [W], the power that goes out of the system, given by $\phi_{\mathrm{m},\gamma_{\mathrm{out}}} u_{\gamma_{\mathrm{out}}}$ [W]), the power added Φ_{in} [W] and the heat exchanged with the surroundings per unit of time Φ_{out} [W]:

$$\frac{dE}{dt} = \phi_{\mathrm{m},\gamma_{\mathrm{in}}} u_{\gamma_{\mathrm{in}}} - \phi_{\mathrm{m},\gamma_{\mathrm{out}}} u_{\gamma_{\mathrm{out}}} + \Phi_{\mathrm{in}} - \Phi_{\mathrm{out}} \tag{1}$$

where $\phi_{\mathrm{m},\gamma_{\mathrm{in}}}$ [kg/s] is the mass flowing into the system, $\phi_{\mathrm{m},\gamma_{\mathrm{out}}}$ [kg/s] is the mass flowing out of the system, u [J/kg] is the specific internal energy and t [s] is time. The total energy E [J] and the specific internal energy u [J/kg] can be expressed by:

$$E = \rho V c T \tag{2}$$

$$u = cT \tag{3}$$

where ρ [kg/m^3] is density, V [m^3] is volume, c [J/(K kg)] is specific heat capacity and T [K] is temperature. Eq. (4) results from substituting the energy and specific internal energy expressions in (1). It is assumed that no mechanical power is being added ($\Phi_{\mathrm{in}} = 0$) and that the input and output mass flows are the same ($\phi_{\mathrm{m},\gamma_{\mathrm{in}}} = \phi_{\mathrm{m},\gamma_{\mathrm{out}}} \phi_{\mathrm{m},\gamma}$):

$$mc\frac{dT}{dt} = \phi_{\mathrm{m},\gamma} c_\gamma (T_{\mathrm{in}} T_{\mathrm{out}}) - \Phi_{\mathrm{out}} \tag{4}$$

where m [kg] stands for mass ($m = \rho V$). If the system is stationary, the heat exchanged with the surroundings Φ_{out}, denoted from now by Φ_{q}, is equal to the heat transferred by the mass flow $\phi_{\mathrm{m},\gamma}$:

$$\Phi_{\mathrm{q}} = \phi_{\mathrm{m},\gamma} c_\gamma (T_{\mathrm{in}} T_{\mathrm{out}}). \tag{5}$$

Heat conduction

Heat conduction occurs when heat is transferred by interactions between atoms/molecules, but there is no transport of atoms or molecules themselves [5]. The equation that describes the heat conduction process is:

$$\Phi_{\mathrm{q}} = \frac{\kappa}{d} A \Delta T \tag{6}$$

where Φ_{q} [W] is heat transferred per unit of time, κ [W/(m K)] is the thermal conductivity, d [m] is the thickness of the wall, ΔT [K] is the temperature difference that drives the heat transfer phenomena and A [m^2] is the area of the wall.

Heat convection

Heat convection occurs when heat is transferred through the transport of material. The equation that represents this process is given by:

$$\Phi_{\mathrm{q}} = UA\Delta T \tag{7}$$

where Φ_{q} [W] is the heat transferred per unit of time, U [W/(m^2 K)] is the heat transfer coefficient, A [m^2] is the area and ΔT [K] is the temperature difference that drives the heat transfer phenomena.

Literature review

This section summarizes several papers and reports where control architectures for distributed power systems are proposed. Most of the architectures have two-level hierarchical configurations and only take electrical parameters and electrical interactions into account. For example, in [6] a droop control method is applied on a system that contains renewable energy generators and storage. In [6], the first level is called PQ Droop Control Method and the second level is called Management of the Distributed Power Station. The first level manages the power output of each unit separately, while the second level monitors the whole system and controls the set-points of the units depending on the state of charge of the battery. The control is designed for two operating conditions: normal interconnected mode and emergency mode. In both cases the control unit optimizes the power output of the