MULTIMODAL MICROGRIDS: FLEXIBILITY FOR THE POWER SYSTEM

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ABSTRACT

In this contribution a time constrained mixed-integer optimization framework to access power system flexibility is presented. Linear constraints consider static models of Combined Heat and Power plants (CHP), Power to Gas (PtG) plants and storage systems while AC load flow equations are included as nonlinear constraints.

A case study shows the capability of the framework to coordinate provision of flexibility by multimodal microgrids.

INTRODUCTION

With the increasing amount of fluctuating renewable generation by wind and photovoltaic generators the need for flexibility on distribution grid level increases as well. The use of flexible operating options can be taken into account to avoid grid expansion or curtailment of renewables. Within the past years the concept of multimodal energy systems describing the coupling of energy distribution networks such as power, gas and heat has been in focus of several investigations [1, 2, 3]. This concept offers new options for a flexible operation by accessing coupling technologies such as PtG- or CHP-plants. While most contributions in this area focus on cost minimization the process of accessing flexibility is investigated in this contribution.

MODELS

In the following section the models used in the optimization framework are described. The optimization framework is based on the energy hub concept presented in [2] and [3]. The models of the energy hubs included in the final case study are presented in the first part of this section. In the second part the distribution grid models are described.

Energy Hubs

Several components such as PtG-plant, CHP-plant, PV generator, thermal storage, electric boiler or heat pump, battery storage and electric vehicle charging station can be combined to an energy hub. In this case the hub represents a home energy system connected to multiple energy distribution grids such as power and gas grid. An exemplary structure of an energy hub is depicted in Figure 1.

Combined Heat and Power Plants

In the presented optimization approach a simplified static model of a CHP plant is used. This is sufficient since the regarded time span Δt between two simulation steps is 15 minutes. A further simplification is the assumption of constant efficiencies based on data from the respective datasheet [5].

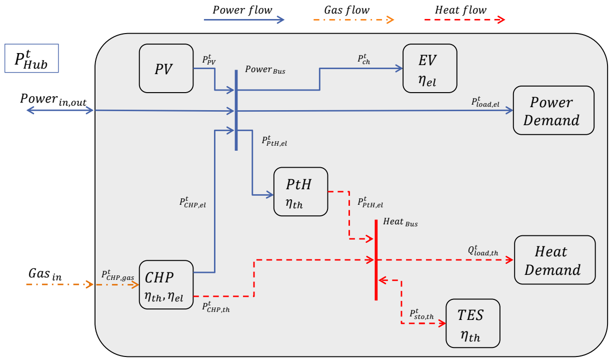

Figure 1: Energy Hub

This leads to the following linear equations using constant efficiencies μ_{th} and μ_{gas} for considered operating points of the plant.

$$P^t_{CHP,th} = \mu_{th} \cdot P^t_{CHP,el} \tag{1}$$

$$P^t_{CHP,gas} = \mu_{gas} \cdot P^t_{CHP,el} \tag{2}$$

A CHP-Plant must be operated at least at 50% of its nominal power. It is possible to switch the plant on and off whenever it is needed while frequent on/off-switching should be avoided regarding the wear parts of the plant. The switching of the CHP-Plant leads to a mixed-integer optimization problem since a binary decision variable $\gamma_{ON,OFF}$ is introduced. Equations (3) and (4) limit the power of the plant to positive values below a certain maximum. To disable operating points below the minimum power equations (5) and (6) are introduced. Both equations have to be satisfied simultaneously. With $\gamma_{ON,OFF}$ being a binary variable the plant can be switched off or operated in the permissible operating range.

$$P^t_{CHP,el} \leq P_{CHP,el,max} \tag{3}$$

$$-P^t_{CHP,el} \leq 0 \tag{4}$$

$$\gamma_{ON,OFF} \cdot P_{CHP,el,min} - P^t_{CHP,el} \leq 0 \tag{5}$$

$$P^t_{CHP,el} - \gamma_{ON,OFF} \cdot P_{CHP,el,max} \leq 0 \tag{6}$$

Power-to-Gas Plant

In the following investigations a simplified linear model of a PtG-plant is used. The plant is only represented by a constant efficiency. Since dynamic effects are neglected this leads to the following equation:

$$P^t_{PtG,g} = \mu_{PtG} \cdot P^t_{PtG,el} \tag{7}$$

A minimum power is included for the PtG-plant as well. This is formulated in the same way as (5) and (6).

Thermal Energy Storage

To provide flexibility using CHP plants thermal storage systems are needed since power and heat supply need to be decoupled. The technical boundaries of the thermal storage system result in (8) to (11).

$$P_{sto,th}^{t} \leq P_{Sto,th,max} \quad (8)$$

$$-P_{sto,th}^{t} \leq P_{Sto,th,max} \quad (9)$$

$$E_{sto,th}^{t} \leq E_{Sto,th,max} \quad (10)$$

$$-E_{sto,th}^{t} \leq -E_{Sto,th,min} \quad (11)$$

Electric boiler and Heat Pump

For thermal peak loads electric boilers are included in the optimization framework. Assuming a constant efficiency η_B the constraint can be written as:

$$P_{B,th}^{t} = \eta_B \cdot P_{B,el}^{t} \quad (12)$$

The simplified modelling of a heat pump can be formulated in the same way using their temperature dependent coefficient of performance (COP) as their efficiencyη_B.

Renewable Infeed and Load Profiles

For all PV generators a reference profile provided by the grid operator is used. For every hub the time series profile is scaled to the respective peak power.

For the active power demand of households statistical load profiles are applied.

The thermal load profile is derived from standard load profiles of the gas sector. This is possible since gas is only used to provide domestic heat and hot water supply.

Power Distribution Grid

To ensure safe distribution grid operation AC load flow equations commonly used in optimal power flow investigations are included as nonlinear constraints. This includes the nodal balances for active and reactive power as well as the transmission capacity limits for apparent power. Furthermore the operation is limited to the permitted voltage range.

Gas Distribution Grid

In this contribution boundaries resulting from gas grid operation are neglected. Therefore the gas distribution system is included using a single node to determine the overall gas consumption.

$$P_{G,in}^{t} - \sum_{k=1}^{m} P_{G,out,k}^{t} = 0 \quad (13)$$

OPTIMIZATION

In general a nonlinear mixed integer optimization problem has the following form:

$$\min_{x} f(x) \quad (14)$$

Subject to the constraints:

$$Ax \leq b \quad (15)$$

$$A_{eq}x = b_{eq} \quad (16)$$

$$c(x) \leq 0 \quad (17)$$

$$x_{min} \leq x \leq x_{max} \quad (18)$$

$$x_i \in \mathbb{Z}$$

$$x_j \in \{0,1\}$$

$$i \neq j$$

The problem is solved using BONMIN [6] with OPTI-Toolbox [7] for MATLAB. This solver uses the Coin-OR Branch and Cut solver (CBC) and primal dual Interior Point Optimizer (IPOPT) for solving the relaxed problem.

State Vector

The state vector x is a combination of the single state vectors of each time step t.

$$x = [(x^1)^T \; \dots . \; (x^t)^T \; \dots . \; (x^\tau)^T]^T. \quad (19)$$

For each time step the state vector x^t contains the state variables used in the models. This includes continuous variables as well as integer and binary variables of the hub models.

Objective Functions

In every applied case the objective function value is time independent. Therefore the overall objective function is the sum over all time steps. In the optimization framework four different objective functions are applied. The first objective minimizes the operating cost.

$$F_1(x) = \sum_{t=1}^{\tau} C \cdot x^t \cdot \Delta t \quad (20)$$

To determine the possible flexibility provided by the microgrid the total power consumption is maximized (21) and minimized (22).

$$F_2(x) = \sum_{t=1}^{\tau} -P_s \cdot x^t \quad (21)$$

$$F_3(x) = \sum_{t=1}^{\tau} P_s \cdot x^t \quad (22)$$

In case of a need for flexibility the total power consumption is forced to follow a given power demand profile:

$$F_4(x) = \sum_{t=1}^{\tau} (P_s \cdot x^t - P_D \cdot x^t)^2. \quad (23)$$

Constraints

All the models described in the previous sections need to be considered as constraints in the optimization problem. Therefore they need to be formulated according to the general formulation given by (15) to (18). Since the dynamic optimization problem is solved for a prediction horizon τ the constraints need to be included for every time step t.

Optimization Framework

To achieve an efficient use of flexibility an optimization framework is set up (see Figure 2). In a first stage each microgrid (MC 1…N) performs an economic optimization. In addition the available flexibility is calculated using objective functions (21) and (22).
The operator of the main overlaying power network collects the schedules and available flexibility of the microgrids. It is to be mentioned that the operator of the main power network and the operator of the microgrid can be the same company, e.g. a distribution system operator (DSO) operating low voltage and medium voltage grid. In case of a demand of flexibility a re-optimization of the microgrid's schedule is performed using objective function (23). Using this objective the microgrid aims at achieving a certain schedule to support the main power network.

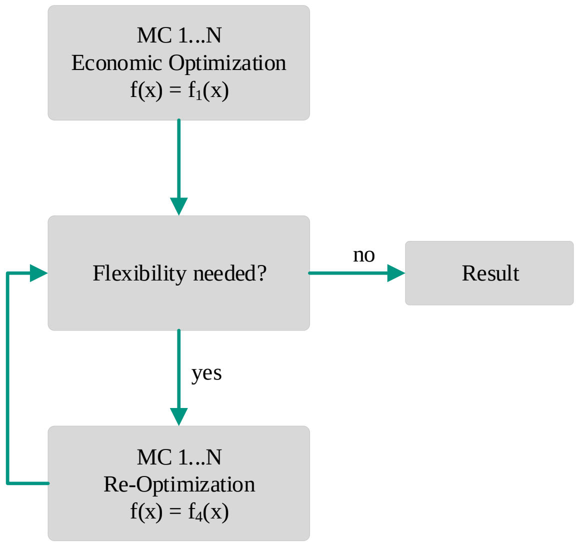

Figure 2: Optimization Framework

CASE STUDY

Based on real low voltage grid data, annual energy consumption values and temperature measurement of 2014 a case study is performed. The investigations focus on a small microgrid. A radial low voltage network which is depicted in Figure 3 is assumed.

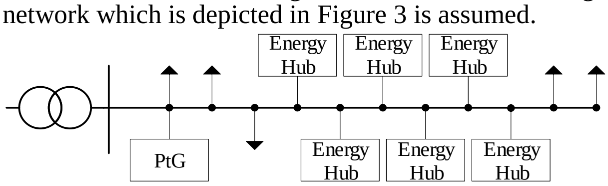

Figure 3: Exemplary Microgrid

The microgrid is connected to six energy hubs with different load profiles, a PtG-plant and five non-controllable loads. The models of the energy hubs and the PtG-plant are parameterized as shown in Table 1. The non-controllable loads are modelled using synthetic load profiles [8].

Table 1: Case Study: Parameter

PARAMETER	VALUE	UNIT
POWER TO GAS		
EL. POWER	37.5	kW
EFFICIENCY	64	%
MINIMAL POWER	11.25	kW
ENERGY HUB		
ANNUAL POWER CONSUMPTION	15000	kWh
ANNUAL HEAT CONSUMPTION	50000	kWh
CHP POWER (EL)	2.5	kW
CHP EFFICIENCY (ELECTRICAL)	32.2	%
CHP EFFICIENCY (THERMAL)	62.7	%
POWER TO HEAT	8	kW
THERMAL STORAGE: POWER	12	kW
TS: CAPACITY	30	kWh
TS: INITIAL STATE OF CHARGE	50	%
PV GENERATOR	3	kW

In the first stage of the following case study the economically optimal operation strategy is determined. In addition the flexibility potential is calculated minimizing and maximizing the power at the slack bus.
In the second stage an external request to increase the overall load is investigated. Since the operation of CHP-plants highly depends on the heat demand a winter and a summer scenario are addressed.

Economic Optimization and Flex-Potential

In the first stage the economic optimization and the calculation of the possible flexibility are performed. Since the cost of natural gas is lower than the feed-in remuneration for CHP-plants the economic optimum is the same as the minimum of the power consumption at the slack bus. This is exemplarily shown in Figure 4. The microgrid can only provide flexibility by increasing the load while still meeting its power and heat demand.

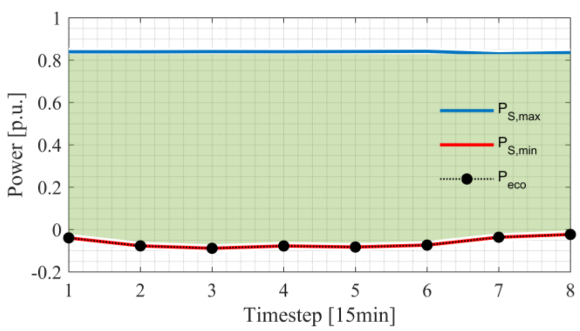

Figure 4: Flexibility potential (winter)

Provision of Flexibility

In the second stage a need to access flexibility is assumed. This can be caused by high shares of renewable infeed on medium voltage level. In the following simulations a request for increased power consumption is assumed for time step three to five. In every other time step the microgrid can follow its economic optimum. This is shown in Figure 5 and

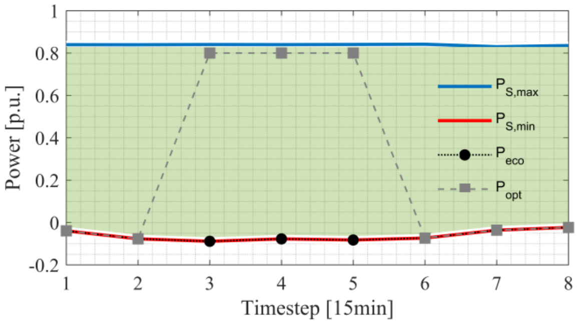

Figure 5: Load demand (winter)

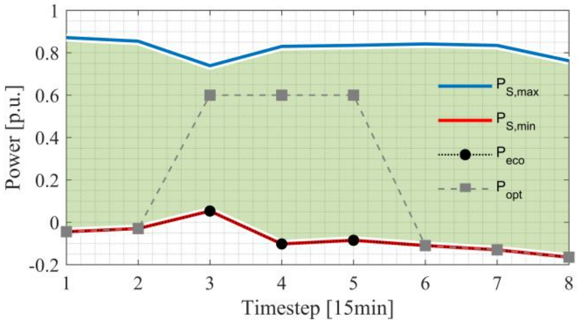

Figure 6: Load demand (summer)

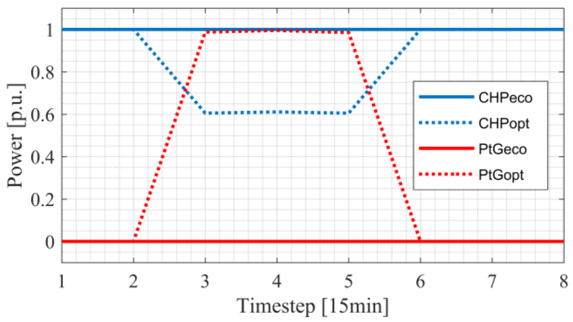

Figure 7: Provision of flexibility (winter)

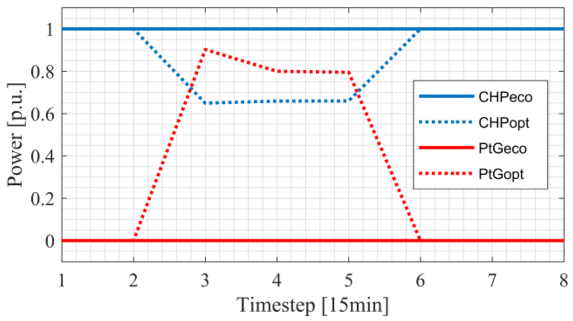

Figure 8: Provision of flexibility (summer)

Figure 6 for winter and summer scenario. As Figure 7 and Figure 8 show the load increase is achieved switching on the PtG-plant while the power of the CHP-plants is reduced. The results show that the multimodal microgrid is able to provide the requested flexibility for the main power network. To ensure a safe microgrid operation the provision of flexibility is coordinated internally.

CONCLUSIONS AND OUTLOOK

In this contribution a nonlinear mixed integer optimization approach based on the energy hub concept is presented. The results show that multimodal microgrids offer flexibility in their operation scheduling to support the main power network. To ensure safe operation of the microgrid the provision of flexibility is coordinated within the multimodal microgrid's components such as CHP- and PtG-plants. The coupling of multiple energy sectors such as power and gas offers new options of flexibility to deal with the fluctuating nature of renewable energy sources.
Further components like electric vehicles can be integrated in the optimization framework easily. Thus aspects like charging scheduling or Vehicle-to-Grid-services can be included in future investigations.

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