INTEGRATED OPERATION OF AN ENERGY MICROGRID WITH ISLANDED ELECTRICITY NETWORK

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ABSTRACT

An Energy MicroGrid was defined as a Multi-Carrier Energy System serving its local area with all its energy needs. Mathematical models for the networks in the Energy MicroGrids were described. An optimisation model, Integrated Optimal Power Flow (IOPF), for the Energy MicroGrid was formulated.

An approach to operate the Energy MicroGrid as a single integrated system was discussed. This approach was simulated in an islanded Energy MicroGrid system. The simulation results highlighted some of the advantages of this approach.

NOMENCLATURE

Symbols

C	Cost (£)
c	Price (£/kWh)
c_p	Specific heat of water (kJ/kg°C)
F	Fuel input (kW)
L	Length (of a pipe) (m)
$\dot{m}$	Mass flow rate (kg/s)
N	Number of busbars
p	Static Pressure (bar)
P	Active power (p.u. or kW)
Q	Reactive power (p.u.)
R	Resistance (p.u.)
r	Hydraulic resistance (m^2 /kg)
Δt	Time period (h)
T	Temperature (°C)
$\mathbf{V}$	Voltage phasor (p.u.)
X	Reactance (p.u.)
Y	Element of the bus admittance matrix (p.u.)
h	Efficiency
r	Water density (kg/m^3)
Φ	Thermal power (Heat) (kW)
l	Overall heat transfer coefficient per unit length (kW/m°C)

Subscripts

F	Fuel
P	Electric power
Bus_i, Bus_j	Busbars
$Gen\text{-}Bus_i$	Generators connected at Bus_i
$Demand\text{-}Bus_i$	Electric demand connected at Bus_i
$Node_l$, $Node_m$	Node names
$Pipe\text{-}Node_l$	Pipes connected to $Node_l$
$Pipe_{lm}$	Pipe connecting $Node_l$, to $Node_m$
HE	Heat exchanger (connecting a heat load, a heat source, or a thermal store)
Supply	Variable associated with the supply line
Return	Variable associated with the return line
Out-Pipe	Variable associated with the outlet of a pipe
$Pipe\text{-}Node_{l+}$	Pipe supplying $Node_l$ with water
a	Ambient
CHP	CHP
EWH	Electric water heater
Pump	Water pump

INTRODUCTION

The energy supply system in the UK is expected to undergo major changes in response to targets set by the EU [1] and incentives offered by the UK government to support renewable and low carbon technologies [2-4]. These legislations and incentives support micro generation, combined heat and power (CHP) units, and biomass projects.

The support for micro generation schemes will allow electricity MicroGrids [5] to be built in the UK.

District heating systems were recognised to be suitable for biomass applications [6-7]. CHP economics were found to favour communal heat production [8]. These support CHP and biomass for district heating schemes in the UK.

A district heating system and an electricity MicroGrid that supply the same area will be coupled together through equipment such as CHP units, heat pumps, electric heaters, and water pumps. Both networks will also be coupled to the gas network through CHP units. This energy system is hereafter referred to as an Energy MicroGrid.

The Energy MicroGrid is a small Multi-Carrier Energy System [9] that serves all the energy demand of its local area. It comprises all the energy networks supplying this area such as the LV electricity network, the district heating system, and the gas network.

The electricity demand in the Energy MicroGrid is partially met by small scale generators (MicroSources). The rest of this demand is either served via a connection to the main electricity grid, whenever the grid connection is available, or shed whenever the electricity network is islanded.

Heat is produced locally in the energy MicroGrid at a district heating station that contains a CHP unit and an electric water heater, or alternatively a heat pump. The heat produced at the district heating station is supplied to consumers via a double pipeline district heating network.

Previous research suggested that both heating and electricity networks in an Energy MicroGrid should be operated as an integrated system [10]. The control functions for this integrated operation are described hereafter. The benefits that these functions provide were assessed for the case when the electricity network of the Energy MicroGrid is islanded.

MODELLING OF THE ENERGY MICROGRID

The electricity network was modelled by the AC load flow equations described in [11]. These equations are the active and reactive power balance equations at all busbars, Equation (1); and the network equations, Equation (2).

$$P_{Bus_i} + \mathbf{j}Q_{Bus_i} = \left(\sum P_{Gen-Bus_i} - \sum P_{Demand-Bus_i}\right) + \mathbf{j}\left(\sum Q_{Gen-Bus_i} - \sum Q_{Demand-Bus_i}\right) \quad (1)$$

$$P_{Bus_i} + \mathbf{j}Q_{Bus_i} = \mathbf{V}_{Bus_i} \sum_{j=1}^{N} Y_{Bus_i Bus_j} \mathrm{V}_{Bus_j} \quad (2)$$

The district heating system was modelled by a set of hydraulic, heat transfer and power balance equations. These equations are based on the models described in [12-13].

The pipeline networks were modelled by their node equations, Equation (3); and pressure loss equation, Equation (4). Each of the supply and return pipeline networks were modelled independent of the other [12-13]. Both networks were coupled at nodes where loads and heating stations are connected. At these nodes, water discharged from one network is equal to water supplied to the other.

$$\sum \dot{m}_{Pipe-Node_l} = 0 \quad (3)$$

$$p_{Node-l} - p_{Node-m} = r_{Pipe_{lm}} \dot{m}^2_{Pipe_{lm}} \quad (4)$$

Heat loads, heat sources, and heat storage were assumed to be connected to the network via heat exchangers. Only the network side of the heat exchanger was modelled. The equation representing this side is given by Equation (5).

$$\Phi_{HE} = c_p \dot{m}_{HE}\left(T_{Supply-HE} - T_{Return-HE}\right) \quad (5)$$

The temperature of the water at a node is equal to the average value of the temperature of the water flowing into the node from each pipe weighted by the mass flow rate of the water of this pipe as given by Equation (6).

$$T_{Node_l} = \frac{\sum \dot{m}_{Pipe-Node_{l+}} T_{Out-Pipe-Node_{l+}}}{\sum \dot{m}_{Pipe-Node_{l+}}} \quad (6)$$

The water temperature at the inlet of a pipe is equal to the water temperature at the node supplying this pipe. As water moves along the pipe, its temperature drops exponentially [13]. A linear approximation of this exponential decay, Equation (7), was used to calculate the temperature at the outlet of the pipe.

$$T_{Out-Pipe} = \begin{cases} \left(T_{In-Pipe} - T_a\right)\left(1 - \dfrac{l_{Pipe} L_{Pipe}}{c_p \dot{m}_{Pipe}}\right) + T_a & \dfrac{l_{Pipe} L_{Pipe}}{c_p \dot{m}_{Pipe}} \le 1 \\ T_a & \dfrac{l_{Pipe} L_{Pipe}}{c_p \dot{m}_{Pipe}} > 1 \end{cases} \quad (7)$$

The equipment in the district heating station, shown in Figure 1, was assumed to be a CHP unit, an electric water heater, and a water pump. The CHP unit and the heater were modelled by their efficiencies, Equations (8), (9), and (10). The pump was modelled by its performance equation, Equation (11). These equations couple the models of heat and electricity networks.

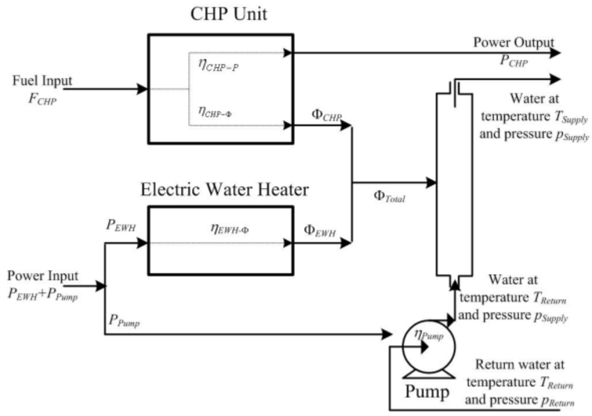

Figure 1. Equipment in the district heating station.

$$P_{CHP} = h_{CHP-P} F_{CHP} \quad (8)$$

$$\Phi_{CHP} = h_{CHP-\Phi} F_{CHP} \quad (9)$$

$$\Phi_{EWH} = h_{EWH-\Phi} P_{EWH} \quad (10)$$

$$P_{Pump} = \frac{\dot{m}_{Pump}\left(p_{Supply-Node_i} - p_{Return-Node_i}\right)}{r\, h_{Pump}} \quad (11)$$

The thermal and electrical efficiencies of the CHP were assumed to vary linearly with the supply temperature of the CHP [12]. This is shown by equations (12) and (13) where $h_{CHP\text{-}\Phi 0}$, $h_{CHP\text{-}P0}$, and k are constants.

$$h_{CHP-\Phi} = h_{CHP-\Phi 0} + kT_{CHP-Supply} \quad (12)$$

$$h_{CHP-P} = h_{CHP-P0} - kT_{CHP-Supply} \quad (13)$$

THE INTEGRATED OPTIMAL POWER FLOW

Optimal Power Flow (OPF) has been used as a tool of transmission system analysis and optimisation [11]. Recently, OPFs has been formulated for integrated studies of gas and electricity systems [14-15].

In this research, an Integrated OPF (IOPF) that optimises the operation of the heat and electricity networks in a Multi-Carrier Energy System was formulated in the form:

Minimise:

Σ Operational costs

Subject to:

Power balance constraints;
Heat and electricity networks constraints;
Heat source constraints; and
Generator constraints.

The objective function of the IOPF was chosen to be the cost of energy, C_{Total}, needed to meet the demand. Linear cost functions were assumed. Fixed costs, including capital and maintenance costs, were not considered. The objective function considered is given by Equation (14).

$$C_{Total} = \sum_{Time}\left(\sum_{CHP} c_F F\Delta t + \sum_{MicroSources} c_P P\Delta t\right) \qquad (14)$$

Equations (1) to (13) were used as the equality constraints for the IOPF.

The inequality constraints for the electricity network are: the thermal limit of the lines, the maximum active power output of generating units, the thermal limit of the generator, and the voltage magnitude constraints.

The inequality constraints for the district heating network are the minimum pressure difference between the supply and return lines at nodes where heat loads or storage are connected, the range of the CHP supply temperature, and the rating of the CHP.

INTEGRATED OPERATION OF THE ENERGY MICROGRID

The Energy MicroGrid was assumed to be operated as an integrated system. The district heating network, which couples the heat and the electricity networks, was operated to support both networks. This was achieved using the following control options:

Supply temperature control: The supply temperature setting of the CHP unit was allowed to vary in order to change the thermal and electrical efficiencies of the CHP unit in response to the availability of heat and electricity resources. It was also varied in response to the balance between hydraulic and thermal losses as an increase in the supply temperature increases thermal losses and reduces hydraulic losses in the pipes.

Electricity and heat load following: The CHP was not restricted to follow heat demand. This was to allow it to respond to any shortage in electric power.

Control of the electric water heater: The electric water heater was used to convert any surplus electricity into heat. This was to balance electricity demand and generation without curtailing electricity generation.

Control of thermal storage: Thermal storage was used to decouple heat production from heat demand. This was to allow optimising the operation patterns of the CHP and to prevent any surplus heat from being wasted.

CASE STUDY

The different control options of the Integrated Operation were modelled in the IOPF. This IOPF was then applied to the model Energy MicroGrid network shown in Figure 2. The parameters of this network are found in [10] and [16].

The IOPF was used to optimise the operation of the Energy MicroGrid for one day on half hourly time steps. The LV network was assumed to be islanded. Two cases were simulated.

Non-Integrated Operation

For the first simulation, it was assumed that the Integrated Operation was not being used. Neither an electric heater nor thermal storage was assumed available. The CHP unit was operated at constant supply temperature and was set to follow heat demand.

The electricity generation available for the CHP and the MicroSources is shown in Figure 3 by the line plots. The area plots in the same figure show the generation scheduled by the IOPF. The difference between the area plot and the line plot of a certain MicroSource is the generation curtailed. About 360 kWh of electric energy was curtailed and about 51.8 kWh of demand was shed.

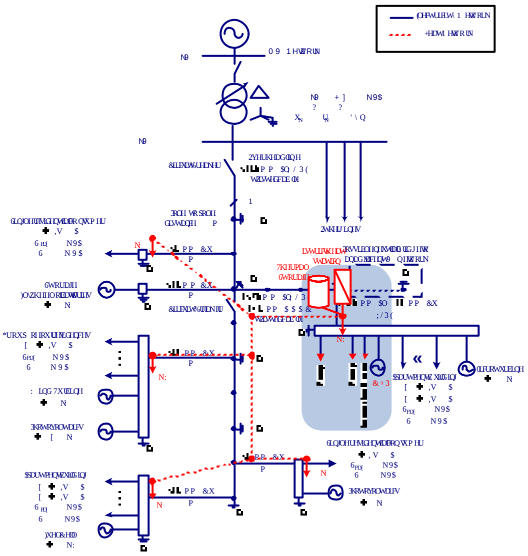

Figure 2. The test system of the Energy MicroGrid

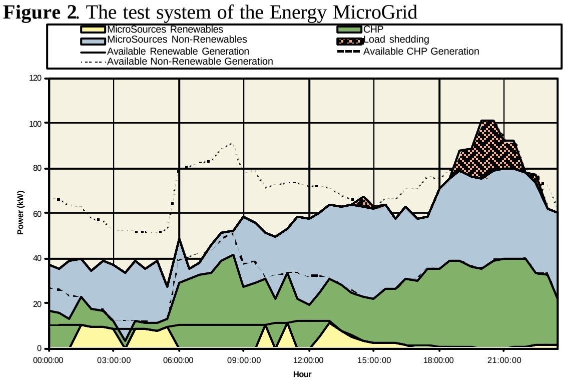

Figure 3. Electricity generation in the Energy MicroGrid. Non-Integrated Operation.

Integrated Operation

For the second simulation, both an electric heater and thermal storage were assumed available. The CHP output was not restricted to follow heat demand and the supply temperature setting of the CHP was optimised by the IOPF.

The supply temperature of the CHP unit, Figure 4, was reduced during periods of low heat demand to reduce thermal losses. It was also reduced during periods of high electricity demand to increase the electrical efficiency of the CHP in order to reduce load shedding. When there were surplus electricity resources and the heat demand was high, the supply temperature was increased to reduce the electricity output of the CHP.

Electricity generation in the Energy MicroGrid is shown in Figure 5. The difference in total generation between Figure 4 and Figure 7 reflects electricity converted into heat by the electric heater. Figure 7 shows a reduction of the demand that was shed to 3.9 kWh and reduction in the generation curtailed to 3.5 kWh.

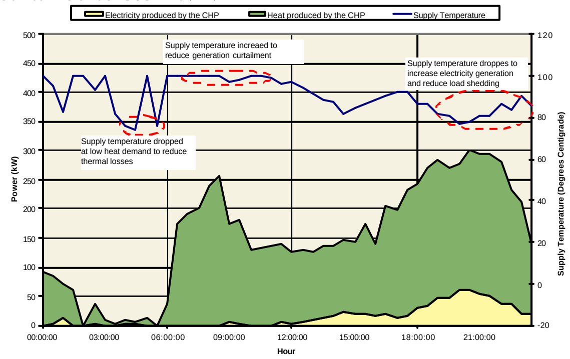

Figure 4. The outputs and the supply temperature of the CHP. Integrated Operation.

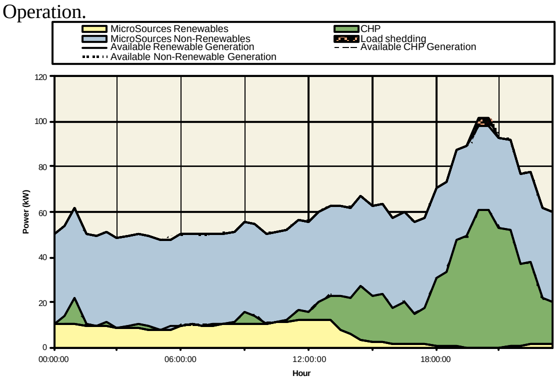

Figure 5. Electricity generation in the Energy MicroGrid. Integrated Operation.

CONCLUSION

An Energy MicroGrid was defined. Models for steady state and optimisation of this Energy MicroGrid were formulated.

An approach for operating the Energy MicroGrid as an integrated system was described. This include operating the CHP for electricity load following, allowing the supply temperature of the CHP to vary in response to the availability of electricity resources, converting any surplus electricity into heat, and the use of thermal storage to decouple heat production from heat demand.

Integrated Operation was simulated in an Energy MicroGrid test system with its electricity network islanded. The results indicated that this approach reduces the mismatch between local electricity generation and demand. This minimises generation curtailment and load shedding

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