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Smart Grid Integration of Small-Scale Trigeneration Systems

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Abstract. This paper presents a study on the possibilities for implementation of local heating, air-conditioning and electricity generation (trigeneration) as distributed energy resource in the Smart Grid. By the means of microturbine-based generators and absorption chillers buildings are able to meet partially or entirely their electrical load curve or even supply power to the grid by following their heating and air-conditioning daily schedule. The principles of small-scale cooling, heating and power generation systems are presented at first, then the thermal calculations of an example building are performed: the heat losses due to thermal conductivity and the estimated daily heating and air-conditioning load curves. By considering daily power consumption curves and weather data for several winter and summer days, the heating/air-conditioning schedule is estimated and the available electrical energy from a microturbine-based cogeneration system is estimated. Simulation results confirm the potential of using cogeneration and trigeneration systems for local distributed electricity generation and grid support in the daily peaks of power consumption.

INTRODUCTION

The term Combined Heating and Power (CHP) or cogeneration is used for all power generation systems that use the prime mover exhaust heat for secondary purposes: building heating and hot water production or even for propelling an additional electric generator [1-4]. This concept is well known since decades and is used large-scale power plants for their proper Heating, Ventilation and Air-Conditioning (HVAC) needs, but also for centralized heating of entire urban districts. In this way an overall plant efficiency of up to 85-90% is achievable, although without taking into account the thermal losses between the power plant and the consumers [3].

Micro-CHP are CHP systems with relatively small electric power output (less than 100-120 kW) [5] using fossil or biomass-based fuel designed for buildings located in remote areas. Micro-CHP systems are considered as more efficient than large-scale CHP plants due to the fact that they are located at consumer’s site, which reduces the losses of transferring thermal and electrical energy from the generator to the loads. Prototypes of micro gas turbine-based CHP systems at even smaller scale – designed for a single household, have been developed in the last years [6] which lead to introduction of the term “nano-CHP systems”.

The main principle of CHP systems regardless of their scale is: the heat of fuel combustion is used as prime mover of an electrical generator (in micro- and nano- CHP systems this is done by an internal combustion engine or a gas turbine driving the shaft of an electrical generator). The waste heat (including the exhaust heat of the engine) is used for building heating. By addition of an absorption chiller in the system, the heat can be used for air conditioning of the building, called trigeneration: combined generation of electricity, heating and airconditioning. Most of the micro- and nano CHP generators use for fuel natural gas, methane, Low Pressure Gas (LPG). CHP systems that use fuel derived from biomass are considered as renewable energy-based generators [7].

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As a result of the development of small-scale cogeneration and trigeneration systems, the possibilities of their application in urban areas and integration into the Smart Grid as distributed energy resource are an interesting topic. These systems could provide improved flexibility of microgrids including other types of distributed generators, for example compensation of PV or wind energy fluctuations [1].

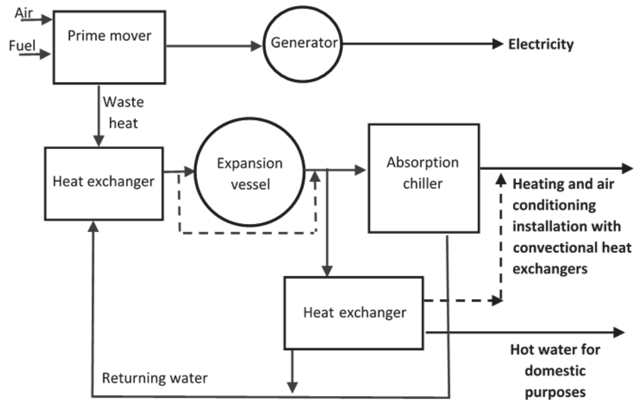

FIGURE 1. Bloc diagram of a trigeneration system

In the Smart Grid architecture, microgrids (called also virtual power plants) are local clusters of loads, energy storage devices, conventional and renewable energy-based generators. Virtual power plants act as a single entity from the grid point of view either as a load or as a generator, capable of autonomous operation and automatic synchronization with the grid. They are also capable of being dispatched by the grid operator.

CHP systems at micro- or nano-scale can be directly integrated in residential, commercial or institutional buildings upgrading the existing centralized heating or HVAC systems [1], [2]. From the consumer point of view this can be beneficial, due to the possibility to sell the excess of electricity to the grid while following their heating load schedule. Moreover, in this way the consumers are able to participate in grid services such as peak load shaving or grid voltage and frequency support. Taking into account the trends in electricity prices, power demand and mass integration of intermittent renewable energy-based generators in low-voltage distribution networks, the implementation of CHP systems can lead to a more flexible and resilient power supply for the consumers and possibly reduce the investments for grid infrastructure reinforcement [1-3].

CHP SYSTEMS BASED ON MICRO GAS TURBINE

Generators driven by a small gas turbine engine are increasingly used for autonomous power supply in remote areas or for backup generators ensuring uninterruptible power supply [4-7]. The principle of operation is as follows: the inlet air (whose temperature is maintained in a narrow range in order to improve engine efficiency) is compressed in a radial centrifugal compressor and after being mixed with the pressurized fuel is supplied to the combustion chamber. The mechanical force generated by the expansion of the burning air-fuel mixture drives a radial turbine mounted on the same axe with the inlet compressor and with a high speed permanent magnet synchronous generator (fig. 2). On some models the electrical generator can also be coupled to the main axe through a gearbox, but often it is directly coupled and its rotational speed is in the range of 60 000 to 180 000 rpm [12]. The high frequency three-phase power is rectified and then converted back to three-phase AC conforming the load or grid requirements.

As presented on fig. 2, the generation control system is capable of automatic switching between autonomous and grid-connected mode (corresponding to grid-forming or grid-support mode). In autonomous mode, the voltage amplitude and frequency references can be configured to suit the load requirements. In grid-connected mode these references are imposed by the grid and the system can be dispatched by references for the generated active and reactive power.

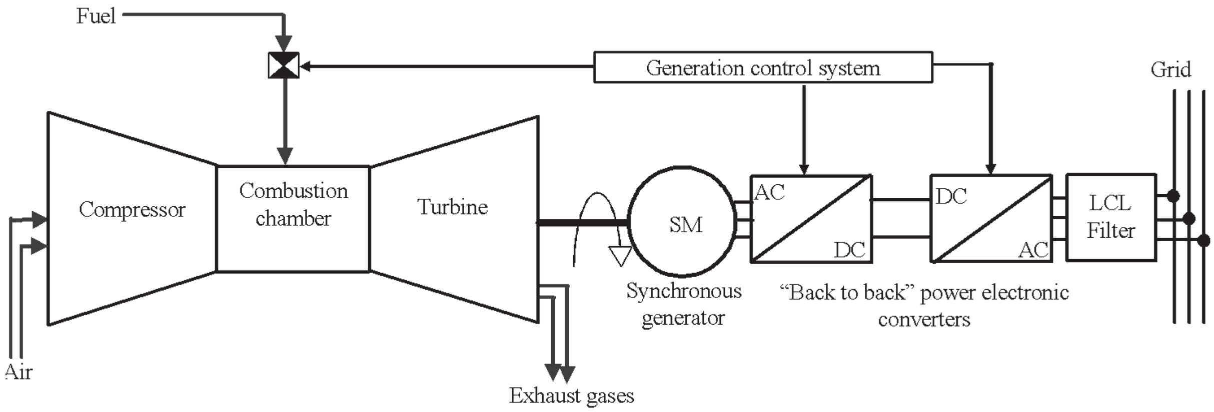

FIGURE 2. Schematic representation microturbine CHP

Micro gas turbines are often preferred rather than diesel groups for autonomous or backup power supply because of their fast response to load changes and lower emissions at partial load. The electrical efficiency of a micro gas turbine is up to 25% and in CHP the overall efficiency can reach up to 80-85% [7].

In areas with cold or moderate winter and hot summer, appliance of CHP systems is even more interesting: in conjunction with an absorption chiller it can be used for heating during the winter as well as air conditioning in the summer (fig. 1). Air conditioning in CHP systems is achieved by adding an absorption chiller to the building heating circuit. The absorption chiller is a device that converts heat in cooling power through evaporation and condensation of its working fluid. The cooled working fluid is then injected in the building's heating circuit and is used for air conditioning by convectional heat exchangers mounted in the rooms. The typical coefficient of performance (COP) of an absorption chiller is around 75%. The room heat exchangers are equipped with thermostats allowing an individual temperature setting in each room. This eliminates the expenses for separate air conditioners in the rooms and allows for the usage of the CHP system during all seasons.

THERMAL PERFORMANCE OF A BUILDING

Modelling and estimation of the heat transfer between a building and its environment is called building thermal performance calculation. For the needs of HVAC system sizing, the building thermal performance is calculated with the highest summer and lowest winter temperatures usual for the area. The difference between the room temperature and the outside air temperature is calculated by considering that all habitable rooms are populated and the inside temperature should be maintained in a range conforming to the regional sanitary norms - in Bulgaria the temperature in inhabited rooms should be between 22 C^0 and 25 C^0 (295,15 K and 298,15 K respectively) and 20 C^0 (293,15 K) in the non-inhabited rooms.

Apart from the temperature difference and the heat exchange with the environment (due to the properties of the construction materials), the thermal performance of a building depends on a number of other factors: design and situation of the building, microclimate in the area, obtained solar irradiation, shading by the surrounding buildings, air infiltration from the outside, ventilation, internal gains due to the inhabitants and the working electrical equipment, etc. [10], [13].

In the case of typical buildings with similar design and located in the same area, an approximation of the HVAC power demand can be calculated relatively easy and with decent accuracy by multiplying the volume of the building envelope by a certain constant (derived from the practice). But if the building is designed conforming to the contemporary tendencies in energy efficiency, the sizing of HVAC system implies individual calculations for each element of the building envelope: outer walls, windows, bottom, roof etc.

The studied building has three identical floors, each of them comprising three flats. On fig. 3 is presented the plan of the second floor.

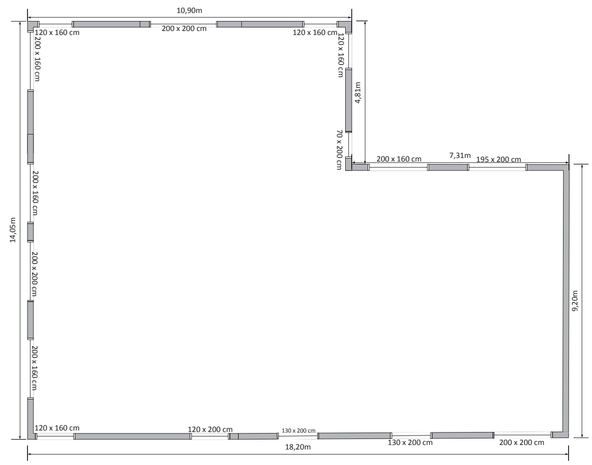

FIGURE 3. Dimensions of the studied building

A thermal conductivity of the outer walls conforming to the actual norms is be adopted - they supposed to have a thermal conductivity less than 0,35 W/m2K (which corresponds to a brick wall with 7cm polystyrene plate mounted at the outside). The inner walls should have a thermal conductivity less than 0,50 W/m2K, the bottom and the ceiling plate - 0,40 W/m2K and the air gap between the ceiling plate and the roof should exceed 0,3 m.

The thermal conductivity of the windows is strongly dependent on the type of glassing installed. The woodwork (supposing that there are no deformations) has an area several times smaller than the glassing, so the thermal performance will be influenced mostly by the glassing installed. In table 1 are presented the thermal conductivities of the usual glassing types. The studied building has windows with double KA-glassing filled with argon.

When the thermal performance of the separate building envelope elements is known, the heat transfer between the building and its environment can be calculated. The thermal conduction of each building envelope element is calculated using the following equation [13]:

$$Q_i = k.S.\Delta T \quad , (\text{W}) \qquad (1)$$

Where k is the thermal conductivity of the corresponding element (W/m2K), S is the surface (m2), и ΔT is the difference between the room temperature and the environment (K). For the bottom plate ΔT is calculated by adopting that the temperature of the earth's surface is constant: 10 C^0 (283,15 K).

TABLE 1. Thermal conductivity of common glassing types

Single glassing	5,9 W/m^2K
Double glassing	2,9 W/m2K
Double KA-glassing	1,7 W/m2K
Double KA-glassing filled with argon	1,5 W/m2K
Triple KA-glassing	1,4 W/m2K
Triple KA-glassing filled with argon	1,2 W/m2K

The cumulative thermal conduction of the entire building envelope is then obtained using the following equation:

$$Q_{tot} = \sum_{i=1}^{n} Q_i \quad , \text{W} \qquad (2)$$

The thermal conduction of the building envelope calculated at the lowest usual winter temperature in the region: -18 C˚(255,15 K) is the amount of heating power necessary for only maintaining the given temperature reference in the rooms. The maximum installed heating power should be higher than that because the heating installation should be able to raise the room temperature up to the abovementioned reference even if they have not been inhabited for a few days.

According to [4] and [13]. The required heating power can be estimated by multiplication of the building thermal conduction by a sizing factor (1+z) where z has a value between 1,15 and 1,25:

$$Q_{heating} = Q_{tot}(1+z) \text{ , W} \tag{3}$$

Calculation of the building's heating power demand for other temperatures and room temperature references is performed in the same way by modifying Δt in equation (1) for all building envelope elements except of the bottom plate, because the earth surface temperature is considered constant.

An approximation of the worst-case cooling power demand during the summer is calculated by the same equations by adopting an outside temperature of 35 C˚. The absorption chiller efficiency η chiller should be taken into account – for this study it is considered 75%. Also the internal heat gains Q gains due to human activity (table 2) and electrical appliances (refrigerators, computers, lighting etc.) should be taken into account. The values in table 2 are given for an average person (whose skin surface is 1,8 m^2). The estimate of the building cooling power demand is:

$$Q_{cooling} = \frac{Q_{tot}(1+z)}{\eta_{chiller}} + Q_{gains} \text{ , W} \tag{4}$$

TABLE 2. Average heat production of the human body

Activity	Power, W
Sleeping	60
Resting	80
Sitting, normal office work	100
Mind-intensive work	150
Walking	200
Workout	250

By using the correlation between the heating/cooling power demand and ΔT and available hourly meteorological data, the daily thermal load curve of the studied building is obtained. On fig. 4 are presented the estimated thermal load curves of the studied building for four days: a summer day with hot and moderate temperatures and a winter's day with cold and moderate temperatures.

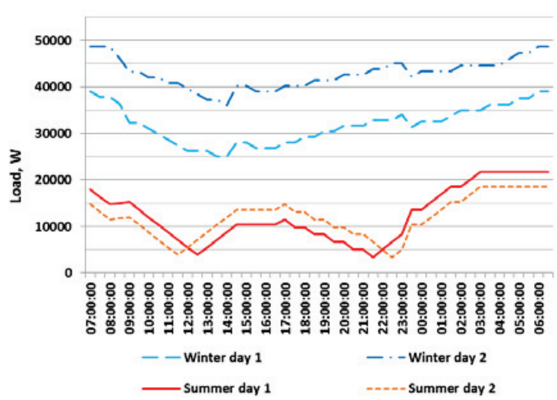

FIGURE 4. Estimated daily thermal load curves (heating or air conditioning) of the building

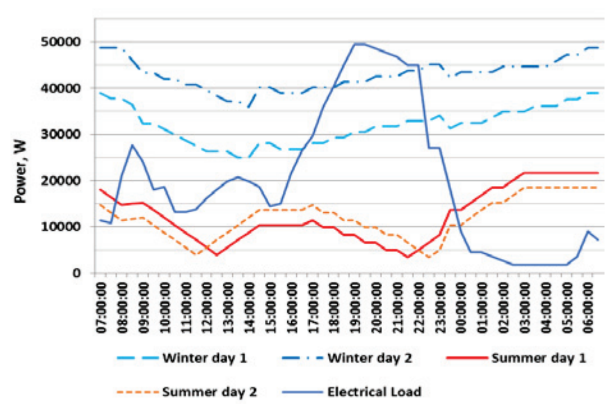

FIGURE 5. Available power from CHP generation and a common daily electrical load curve of the studied building

POTENTIAL OF MICRO-CHP SYSTEMS FOR DISTRIBUTED GENERATION

A micro-gas turbine CHP system with rated electrical output of 30kW has an electrical efficiency of 25% at nominal load [13] and recoverable exhaust heat of 60kW, in other words 50% of the total thermal power supplied to the combustion chamber. The partial load characteristics of micro-gas turbine CHP systems have already been discussed in previous works [7, 8, 11]. Considering that the system follows the thermal load, the available electrical power was simulated. The results are presented on fig. 5 along with the electrical load curve of the studied building.

On fig. 6 are presented the building's electrical load curves for the case study as seen from the grid operator point of view: a negative load means that the entity is acting as a generator, supplying power to the grid. The considered electrical appliances in one apartment with their peak power consumption are given in Table 3.

From these estimated curves it is visible that installation of CHP systems in urban districts can reduce distribution grid congestion during periods of peak load.

Based on this case study and meteorological data for one year, an estimation was performed of the monthly energy consumption for heating/cooling along with the cogenerated electrical energy by the CHP system. Results on fig. 7 demonstrate that during all seasons users could benefit from the CHP system by covering partly their power consumption and selling power to the grid.

TABLE 3. Electrical appliances rated power in a common household

Appliance	Power, W
Kitchen furnace	3 000
Water heater (boiler)	2 000
Lighting	350
PC	250
Refrigerator	200
TV	50

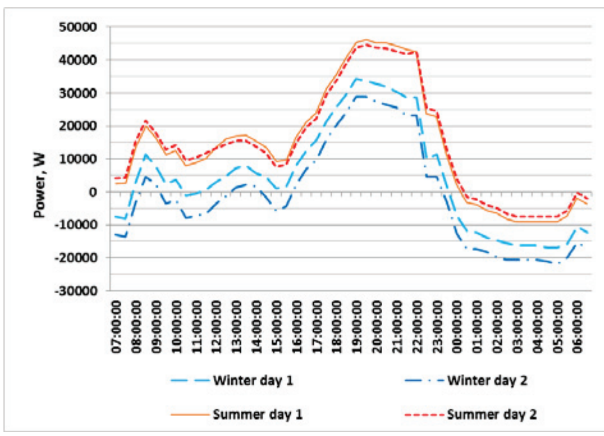

FIGURE 6. Resulting load curve of the studied building from the grid point of view

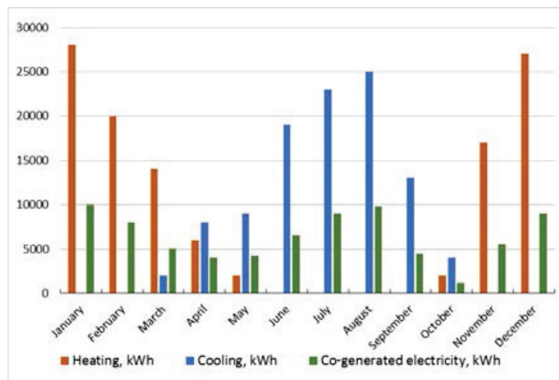

FIGURE 7. Monthly estimated heating and cooling energy consumption and the available electrical energy, generated from a CHP system

CONCLUSIONS

Micro-cogeneration and trigeneration systems are a recent concept, although the same principle is used in power plants and has been proven beneficial for centralized heating and power generation for decades. The scale reduction of CHP systems due to the development of micro gas turbine-driven generators made possible their application in urban buildings. By addition of an absorption chiller in the system it is able to serve for air conditioning, heating and power generation. A case study for CHP in a residential building is presented in this paper. First, the building heating/air-conditioning power demand is estimated for proper sizing of the system. Then by using hourly meteorological data for two summer and winter days the building thermal load curves are estimated. Using partial load characteristics of micro-CHP systems, the available electric power in thermal load following mode is obtained. The results demonstrate that, depending on the season and temperatures, a CHP system can produce enough electrical power to supply partially its electrical load and even sell power to the grid. The hourly thermal and electrical load curves demonstrate that the usage of building-integrated CHP systems can reduce the electrical consumption and grid congestion during peak hours.

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