Preprints of the 18th IFAC World Congress
Milano (Italy) August 28 - September 2, 2011

Stability Assessment of Isolated Micro-grids Powered by Distributed Combined Heat and Power Micro-units ⋆

Tobias Heß * Philipp Stachel ** Peter Schegner ***

* *TU Dresden, Faculty of Electrical and Computer Engineering, Institute of Electrical Power Systems and High Voltage Engineering 01062 Dresden Germany (e-mail: tobias.hess@tu-dresden.de)*
** *TU Dresden (e-mail: philipp.stachel@tu-dresden.de)*
*** *TU Dresden (e-mail: peter.schegner@tu-dresden.de)*

Abstract: It is expected that combined heat and power (CHP) micro-units will soon play a significant role in the energy supply of private households. To increase the reliability of the system the isolated operation of this micro-grid should be possible. It is assumed that the electrical load is the reference input variable of the local grid to reduce the necessity of electrical energy storages. The produced thermal energy will be stored. The paper presents a study of the voltage and frequency stability in micro-grids powered by CHP micro-units. The simulation model of the micro-co-generation plant is based on a combustion engine and brush-less synchronous generator. The example network represents an urban residential neighbourhood. The electrical household loads are based on probabilistic modelling, with high time resolution. Several scenarios for normal and disturbed operation are defined, which vary in electrical load, number and size of the CHP units and the generation schedule. For these scenarios the stability and voltage limits during normal operation and for selected three phase faults are investigated. The voltage and frequency stability of the micro-grid is determined by dynamic simulations.

Keywords: distributed generation, micro-grid, dynamic models, combined heat and power micro-units, power system stability

1. INTRODUCTION

The worldwide increase in demand for electrical energy, exhaustible resources and the climatic changes are currently the central challenge of the energy system. A discussed and promising approach to these challenges is the development and operation of micro-grids to ensure the shift to decentralized production structures with maximum efficiency, energy security and environmental sustainability. Combined heat and power (CHP) is seen as an integral part of such networks. A CHP power-plant allows predictable and secure control and regulation of power production. Thus they can assist to integrate limited predictable renewable energy sources, such as wind power and photovoltaics. In the Integrated Energy and Climate Programme of the German government CHP units are encouraged. Therefore a high penetration of CHP micro-units in Germany is expected in the next few years.

In this case the isolated operation of the micro grid will increase the reliability of the system. Until now there are only a few experiences with small isolated operated networks with distributed generation. The aim of this paper is to study the stability in such systems.

⋆ The report underlying this project was funded by the Bundesministeriums für Wirtschaft und Technologie under grant number 0327832C. In addition, the project was supported by the Techem Energy Services GmbH and Vattenfall Europe.

Therefore a small residential low voltage network is modelled. To evaluate the dynamic operation behaviour a detailed model of the CHP micro units is created as well as the necessary controllers for islanded grid operation. The stability assessment is then done under normal and disturbed operation with several scenarios.

2. SIMULATION MODEL

2.1 Combined heat and power micro-unit

There are several different technical designs of CHP micro-units. In this paper the CHP is modelled as a micro-cogeneration plant based on a combustion engine and a brush-less synchronous generator is chosen. This design is widely used due to high operational experience, low costs and a low amount of maintenance. The synchronous generator allows operation in an isolated network. The main components of the CHP unit which have to be modelled are (see figure 1):

- combustion engine
- elastic clutch
- generator
- controller for engine and generator

Combustion engine The predominant fuel for cogeneration micro-plants is natural gas. So, gas spark ignition

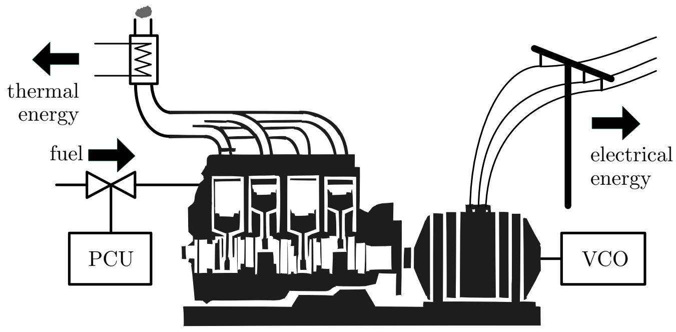


Fig. 1. Schematic of CHP micro-unit with combustion engine, generator, power control unit (PCU) and voltage controller (VCO)

engines are mainly used. Thereby the torque is regulated by a quantity control of the fuel mixture. The amount of mixture with a nearly constant combustion-air ratio is set by a throttle mechanism. The fuel mixture flows into the cylinder and produces the torque, see van Basshuysen (2007).

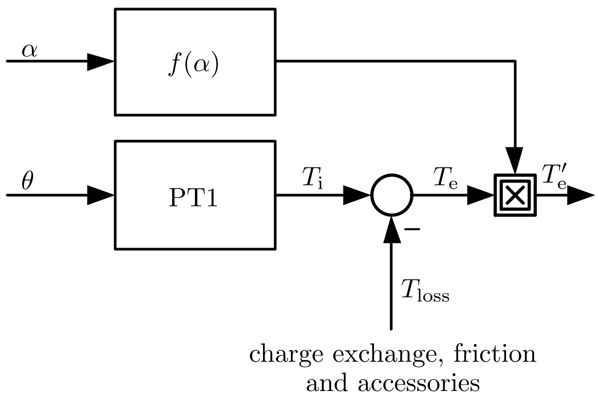


Fig. 2. Signal flow plan of the combustion engine

To model the internal engine process a PT1 element is used to transfer the throttle angle θ to the internal engine torque T_i. The external engine torque T_e is calculated by subtracting a to the engine losses equivalent torque T_loss at the current operation point, which includes the losses of charge exchange, friction and accessories (see figure 2).

Combustion engines produce a discontinuous torque. Each ignition of the fuel mixture in the cylinder creates a powerful torque kick. To model the torque characteristics of the engine the external engine torque T_e is multiplied by a function of the angle of rotation α.

Elastic clutch To homogenise the engine torque for electric power generation, mostly an elastic clutch is used. Figure 3 shows the elastic coupled two-mass system which reproduces the transfer behaviour of the elastic clutch. J_e represents the inertia of the engines rotor. It is affected by the engine torque T_e. J_g stands for the inertia, which is affected by the electrical torque T_el. The elastic clutch is between engine and generator. It is modelled with the spring rate C and damping d.

Synchronous generator To model the synchronous generator the model in DigSILENT Powerfactory is used. It

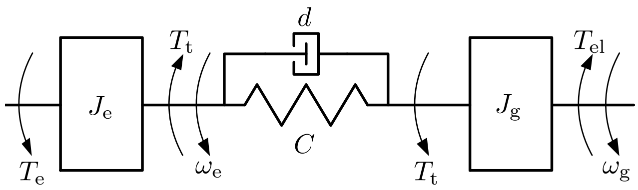


Fig. 3. Schematic of elastic clutch

takes on filed winding and one damper winding on the d-axis and two damper windings on the q-axis into account. The differential equation system of the synchronous generator model thus consists of two motion and four voltage equations, see DigSILENT GmbH (2009). This equation system is a widely used for stability analysis, see Kundur (1994). The model parameters of the synchronous generator are derived from manufacturer's data of small synchronous generator and CHP micro-units.

Controller To realize the stable operation of synchronous generators in the electrical network, voltage and frequency must be controlled. Within this research project following controllers are used and modelled.

- Voltage regulator and excitation control system: For reliability reasons brush-less exciter are usually used in CHP micro-units with synchronous generator. To represent the exciter IEEE Type AC1A is used, which is widely used in stability researches, see IEEE Std 421.5 (2005).
- Reactive power controller: It overlay the voltage regulator in order to achieve a constant power factor or reactive power output. This is used at generators which are not participating in the direct voltage control in the micro grid. The IEEE Var controller Type II is used to model the reactive power controller, see IEEE Std 421.5 (2005) .
- Frequency power controller: To control the frequency, which is equivalent to the active power control, the common two-stage approach with primary and secondary control is used. The controllers are modelled according to Kundur (1994).

Parameters The parameters of the Engine and the Generator are derived from data sheets. The used engine is *MAN E0834 E302* and the generator is *mecc alte ECO 32-3L/4*. The parameters of the controllers are tuned to perform a good step response.

2.2 Low voltage network

On the basis of a small urban residential area the low voltage network and the load of the household are designed. Table 1 gives an overview and the residential area structure. Altogether there are 12 buildings with 320 households. A schematic plan of the residential area with the electrical network is shown in figure 4.

Based on the residential area structure in table 1 different household classes are defined. They differ in the number of tenants, in the electrification level and consumer habits. According to this classes a load profile of each household is calculated with a probabilistic load modelling tool in a time base of 30 s see Dickert and Schegner (2010). By shifting each load profile between 0 and 30 s a time

Table 1. Residential area data

Building	House Connections	Flat per Connection	Ø-Area per Flat
L1	4	15	95.2 m^2
L2/L3	3	14	95.2 m^2
L4	6	16	77.3 m^2
W1...W8	1	10	92.8 m^2
Total:	26	320	28 550 m^2

resolution of 1 s is obtained. With this time resolution a dynamic simulation with realistic load alterations will be achieved.

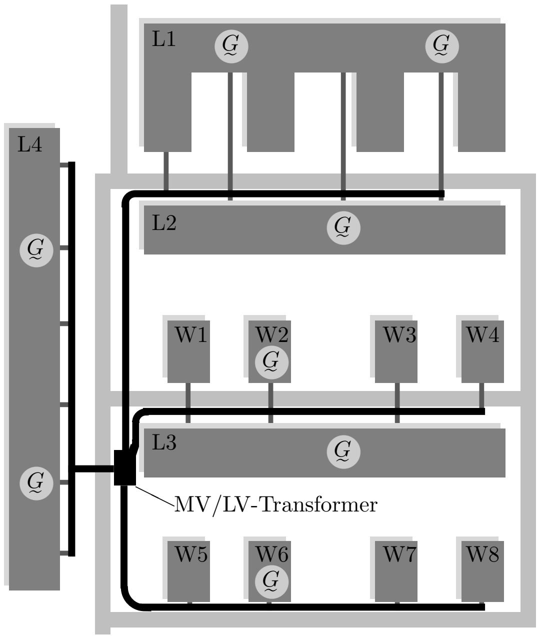


Fig. 4. Schematic of the low voltage network

3. STABILITY ASSESSMENT NORMAL OPERATION

The decentralized network with the model of the CHP micro-unit described in the previous section will be evaluated with dynamic simulation. The calculated voltage and frequency response is compared with the requirements of the EN 50160. The evaluation of the results is done at various scenarios which vary in electrical load, number and size of the CHP units and the generation schedule. The dynamic simulation is executed with an integration step of 100 ms. This integration step is a compromise between accuracy, stability of the simulation, simulation time and memory requirements.

3.1 Evaluation criteria

EN 50160 defines the characteristics of voltage and frequency in public distribution networks. The nominal voltage is $U_n = 230\,V$ measured between phase and neutral. The frequency is $f_n = 50\,Hz$. Following voltage and frequency ranges have to meet in networks without a synchronous connection to the interconnected systems, see EN 50160 (2007):

- *Voltage:* The voltage mean 10 minutes rms values have to fulfil following constraints:

$U_n \pm 10\,\%$	(i.e. 203 V - 253 V)	for 95 % of week
$U_n + 10\,\%/-15\,\%$	(i.e. 195.5 V - 253 V)	all the time

- *Frequency:* The frequency mean value of fundamental measured over 10 s have to fulfil following constraints:

$f_n \pm 2\,\%$	(i.e. 49 Hz - 51 Hz)	for 95 % of week
$f_n \pm 15\,\%$	(i.e. 42.5 Hz - 57.5 Hz)	for 100 % of week

3.2 Simulation scenarios

The decentralized network will be evaluated under different conditions. The simulated period is one week. So the load for weekdays and the weekend is included in the simulation.

Starting from the base case all other scenarios result through variation of load, generation and CHP micro-unit model parameters. The base case is characterized by a representative winter week of the load profile described in section 2.2. It is also the week with the highest electrical load. The loads are set with a constant power factor $\cos\varphi = 0.99$. In this case the decentralized network is powered by maximal eight CHP micro-units with a rated electrical output of $P_{el} = 50\,kW$ (see fig. 4). The following variations are studied:

- *Variation in load*: the loads are also set to the load profiles of summer, spring and autumn respectively. Also a power factor of $\cos\varphi = 0.9$ is applied to the loads.
- *Variation in generation*: In addition to distributed generation by eight CHP micro-units, a scenario is evaluated in which the network is powered by a central co-generation plant with rated electrical power of $P_{el} = 400\,kW$. Furthermore, the scheduling of the power plants is varied.
- *Variation in CHP micro-unit model parameters*: To determine the influence of key parameters of the CHP micro-unit model parameters on the control, the time constant of the motor and the inertia of the rotating parts is varied.

3.3 Voltage characteristic

Compliance with voltage limits is not a problem in urban low voltage networks, because line or cable lengths are short. Therefore only small voltage drops occurred. Previous studies of distributed generation in electrical networks have shown that the voltage rise caused by distributed generation can exceed the voltage limits in particular at high penetration levels of distributed generation see Einfalt et al. (2009); Hauptmeier (2007); Thomson and Infield (2008).

The results of the simulation done in this research show that no exceeding of voltage limits occur. The maximum voltage deviation is 1 % for the scenario with distributed generation . For central generation the voltage deviation is maximal at 4 %. Thus in no case are the boundaries of the voltage range violated, unlike in the researches of Einfalt, Hauptmeier and Thomson. The main difference compared with this research project is the type of network operation. In contrast to the interconnected operation the power production always has to meet the power consumption in island network operation. Thus lower voltage deviation occurs.

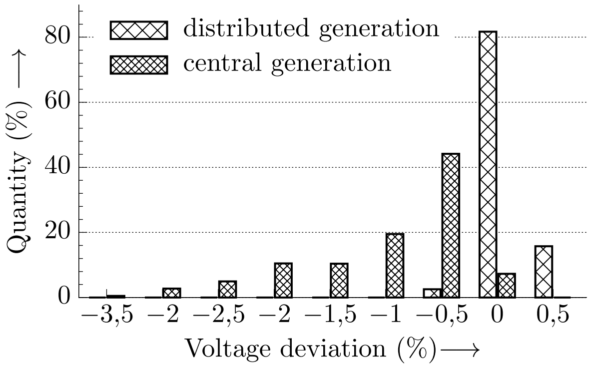


Fig. 5. Distribution function of voltage deviations

To illustrate the voltage deviations at different nodes in the network and over the period of an entire week, figure 5 shows the distribution function of the voltage deviation. As shown in the figure, in the case of central generation higher voltage deviations appear. These occur at high electrical load on the most distant load point form the feeding bus bar in the electrical network. In the case of distributed generation the electric power is produced by the uniformly distributed CHP micro-units in the network, thus at the place where the power is needed. With the resulting lower load flows in the electrical network, the lower voltage deviations are justified.

The simulations have shown that compliance with voltage limits in the modelled network is no problem. Due the distributed generation which meets the load, the required voltage band is even reduced.

3.4 Frequency characteristic

Due to the small rotating masses high deviation from the nominal frequency during load changes is expected. The simulation of the base case shows that the frequency differs by a maximum of 6.1 %. 108 10-second-average values of the simulated week are have a higher deviation than ±2 % from the nominal frequency. This corresponds to 0.002 % of a week. Thus the requirements of EN 50160 are fulfilled.

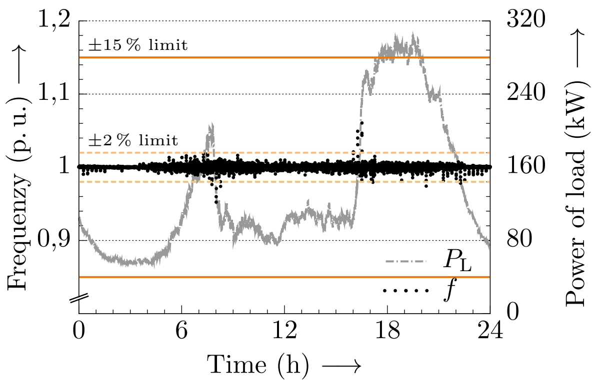


Fig. 6. 10-second-averages of frequency over one day

As figure 6 shows, at high load changes in the network high frequency deviations from nominal frequency also occur. The frequency difference at high load changes is the reverse of the expected direction. When the load degreases a positive frequency difference is expected, but the simulation shows a negative. Thus there is a generation deficit rather than a surplus. This is caused be the shut-down of some CHP micro-units when the load drops. Certainly by adjusting the start-up time and shut-down time a decrease in the frequency deviations can be achieved, but the simulation shows the sensibility of the network to the start-up and shut-down of units.

The standard deviation of the frequency is used to compare the results of the base case to the results of the other scenarios. In the base case the standard deviation is $\sigma_{\mathrm{f}} = 0.3\,\%$. The simulations depict that the frequency deviation depends on the following factors.

- *Real power load* In the scenarios with lower load (spring and summer) the frequency deviations are slightly smaller. So the standard deviation in the simulated spring week is $\sigma_{\mathrm{f}} = 0.28\,\%$ and respectively $\sigma_{\mathrm{f}} = 0.26\,\%$ in the summer week.
- *Rotating mass on the electrical network* As expected the a higher rotating mass will decrease the frequency deviation. So if the rotation mass is doubled for every generator the standard deviation of the frequency results in $\sigma_{\mathrm{f}} = 0.18\,\%$
- *Time constant of the combustion engine* τ_e With the time constant of the combustion engine subsequent parameter adjustments in the frequency power controller are possible. In the base case the time constant is $\tau_e = 0.5\,\mathrm{s}$. In the szenarion with a time constant of $\tau_e = 0.1\,\mathrm{s}$ the standard deviation of the frequency is $\sigma_{\mathrm{f}} = 0.01\,\%$ and respectively $\sigma_{\mathrm{f}} = 0.82\,\%$ in the scenario with a time constant of $\tau_e = 1.0\,\mathrm{s}$. This illustrated the high dependency of the results to this parameter. Thus the exact value of this time constant is important for the simulation. For further research it is necessary to determine this parameter exactly e.g. through measurements on CHP micro-units.

4. STABILITY ASSESSMENT UNDER DISTURBED OPERATION

To evaluate the stability of the micro grid under disturbed operation, the critical clearing time (CCT) is calculated for three phase faults at different locations in the network. This is done for several scenarios with different load and generation configuration.

4.1 Evaluation procedure and scenarios

The CCT is defined as maximal fault duration for which the system remains transiently stable. In this paper the network is evaluated as unstable if the frequency in the network could not maintained or an out of step signal occurs. When one generator is out of step in the power system the generator protection will trip it. In this simulation the out of step signal is generated when the absolute rotor angle of one generator exceeds 360 deg.

In a dynamic simulation a three-phase fault is applied to one house connection. After a defined time the fault is cleared. The load and/or the generation if present at this house connection is tripped at the same time. To determine the CCT the fault clearing time in the simulation is increased until the system loses stability. This is repeated for all house connections in the network.

The simulations are done for several scenarios in which load and generation are varied. The total load was increased in 6 steps between the minimal load of 56 kW and the maximal load of 325 kW (see table 2). For the generation the following scenarios are reviewed:

- *Scenario A*: This scenario is based on the base scenario of the simulation under normal operation. To supply the load a maximum eight distributed generators are installed. To ensure economical operation of the isolated grid only as many CHP micro units are in service to fulfil the load balance.. Thereby a reserve of at least 50 kW is included. The power controllers are set to primary control for all generation units and to secondary control for 2 units.
- *Scenario B*: In this scenario the periodic torque generation of the combustion engine is neglected. All other settings are identical to scenario A.
- *Scenario C*: In this scenario the distributed generation is replaced by one central CHP unit with a rated power of 400 kW.

4.2 Results

The results of simulations are shown in table 2 and figure 7. The table shows the minimal CCT of all evaluated bus bars in one scenario. Figure 7 illustrate the CCT at all analysed bus bars for one load case.

Table 2. Overview of load scenarios and results

load (kW)	number of generators in service [1]	minimal CCT (s) Scenario A	B	C
56	3	0.19	0.19	> 1
99	3	0.09	0.09	> 1
156	5	0.15	0.15	> 1
201	5	0.12	0.12	0.84
306	8	0.13	0.13	0.18
325	8	0.14	0.14	0.15

The evaluation shows that the periodic torque of the combustion engine has no influence to the CCT. The scenarios A and B have the same results (see table 2 and figure 7). The minimum CCT of all load cases is 90 ms. It results at the load case where fewest generators are in service with high loading. Thus the rotating mass and the rotor angle reserve are minimal. In the other cases, the minimum CCT is greater than 100 ms.

In the case of central generation (scenario C) the highest CCTs were achieved. But in the case of high loading the CCT is quite similar to case of distributed generation.

Figure 8 shows the frequency at a fault with a clearing time of 100 ms. The characteristic of the frequency is quite unusual. Normally the generators with rated power of more than 1 MW will increase speed if a fault occurs because there is no or less real power load during the fault. In this simulation there is a high frequency drop when the fault occurs and all frequency limits are exceeded. This

[1] In scenario C the power is generated by one central generator

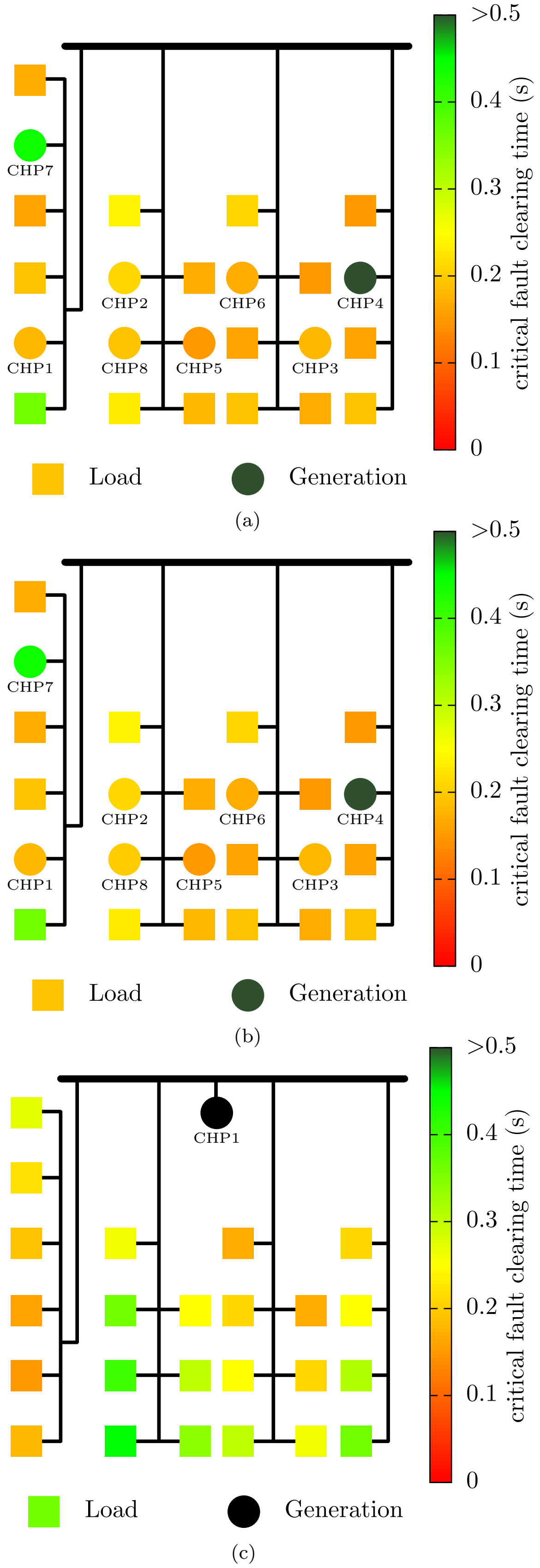


Fig. 7. CCT at different fault locations at load of $P_L = 325\,kW$: (a) scenario A; (b) scenario B; (c) scenario C

is caused by the high stator resistance of the generator. The chosen generator for the CHP micro units has stator resistance $R_s = 52\,m\Omega$. In case of terminal short circuit

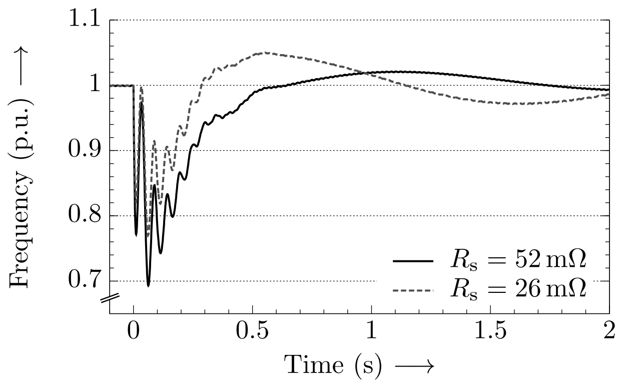
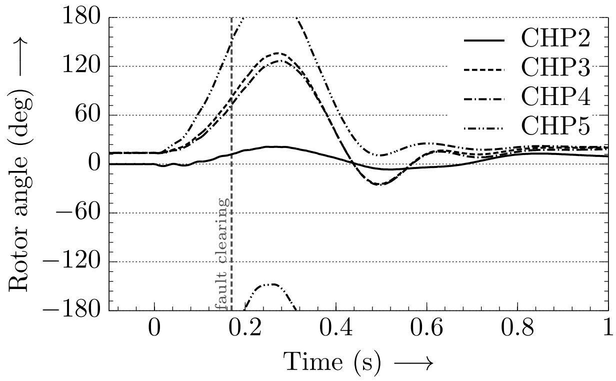
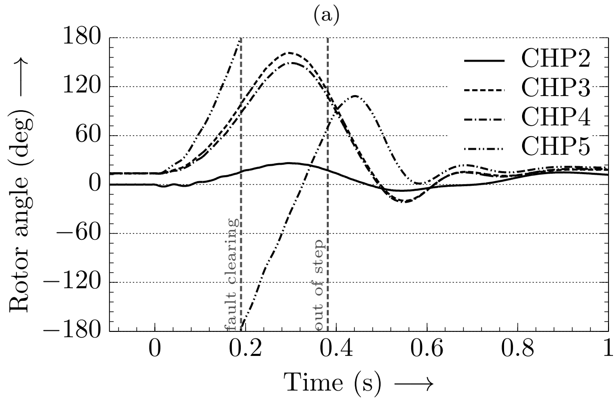


Fig. 8. Frequency during a fault for different values of the stator resistance

the sub-transient short circuit current I''_s is 1.3 kA which causes losses in the stator of 264 kW. This is five times higher than the nominal power of the generator. To meet the allowed frequency during a fault the stator resistance has to be lower (see figure 8). So the demand on a small generator in CHP micro-units has to be higher.



(a)



(b)

Fig. 9. Rotor angle deviation to the reference machine over time: (a) Stable case with fault clearing time of $t_f = 0.17\,s$; (b) Unstable case, out of step detection with fault clearing time of $t_f = 0.19\,s$

Figure 9 shows the rotor angel deviation to the reference machine of the generators for (a) a stable case and (b) an unstable case. It shows in the unstable case that the out of step signal occurs but the system still maintain stability. So the question is how many pole slips a generator of the micro co-generation plant can withstand. If an absolute rotor angle deviation of more than 360 deg is possible the CCT could be higher.

5. CONCLUSION

This paper presented a study of the voltage and frequency stability in micro-grids powered by CHP micro-units. The simulation model of a CHP micro-unit was developed as well as an example network of an urban residential neighbourhood. The electrical household loads are based on probabilistic modelling, with high time resolution. The evaluation was done for several scenarios.

The results show that the isolated operation is basically possible in CHP powered micro-grids. In normal operation the frequency and voltage fulfils requirements of EN 50160. The simulation of disturbed operation with three phase faults shows, that a fault clearing in 90 ms is necessary to insure a stable operation.

The investigation identifies development potential for a small generators which are used for disturbed generation. If the generator can withstand more than one slip the CCT for three phase faults could be increased. To reduce frequency deviation during faults the stator resistance of small generators has to be reduced.

REFERENCES

Dickert, J. and Schegner, P. (2010). Residential load models for network planning purposes. In *Modern Electric Power Systems 2010*, paper 04.1. Wroclaw, Poland.

DigSILENT GmbH (2009). *Technical Documentation – Synchronous Generator*, 5. edition.

Einfalt, A., Tiefgraber, D., Haidvogl, H., and Czermak, K. (2009). Netzintegration von Mikro-KWK-Anlagen. *e & i Elektrotechnik und Informationstechnik*, 126(3), 105–110.

EN 50160 (2007). Voltage characteristics of electricity supplied by public distribution networks.

Hauptmeier, E. (2007). *KWK-Erzeugungsanlagen in zukünftigen Verteilungsnetzen –Potenzial und Analysen–*. Dissertation, Universität Dortmund.

IEEE Std 421.5 (2005). IEEE recommended practice for excitation system models for power system stability studies. IEEE Power Engineering Society.

Kundur, P. (1994). *Power system stability and control.* EPRI power system engineering series. McGraw, New York.

Thomson, M. and Infield, D.G. (2008). Modelling the impact of micro-combined heat and power generators on electricity distribution networks. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 222(7).

van Basshuysen, R. (2007). *Handbuch Verbrennungsmotor: Grundlagen, Komponenten, Systeme, Perspektiven?* Vieweg, Wiesbaden, 4. edition.