HEAT-CONTROLLED COMBINED CYCLE UNITS IN DISTRIBUTION NETWORKS

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Abstract

Electrical distribution networks will face a new challenge in future. Due to new laws actuated by international quests concerning a more efficient use of energy, a launch of various dispersed generation (DG) systems has already begun. This fact will influence today’s energy grids strongly. Installations of dispersed generation facilities will take place more extensively in low-voltage-(LV-) grids, because they realize a cost-effective supply with thermal and electrical energy close to the consumer. In other words, there will be a large number of combined heat and power (CHP) plants spread throughout future residential distribution networks.

Introduction

Although fuel-cell-based energy systems are not yet competitive to other decentralized energy systems, they are conceivable in the near future. Electric distribution networks, fed by CHP-units, will take on new important duties, e.g. an energy transportation in an opposite direction if the consumption is less than the generation of energy. In order to enter the space-heater market, manufacturers provide fuel-cell-based-house-energy-supplies with a heat-control, so that electrical energy is fed into the network according to the domestic thermal demand [1]. This paper focuses on technical aspects of increased dispersed generation in LV-grids by means of CHP. Beside an introduction to existing regulations, simulations of a residential LV-grid are presented. Results of two different scenarios with a varying number of dispersed generation units and different load profiles are pointed out. Finally, solutions are shown how to deal with operation limits such as voltage limits.

General conditions and directives

The operation of CHP-systems in Germany is regulated by a number of different laws, codes and standards, which can be divided into political [2] and technical regulations [3]. The technical regulations include general specifications of CHP systems but also heating specific and electrical norms and guidelines [4]. The most important codes, norms and laws concerning CHP-systems are summarized in table 1. Because the decentralized energy conversion systems will be an important part of the future energy supply, they have to be conform to the German “Energiewirtschaftsgesetz” (EnWG). This law postulates the secure, competitive and ecological use of energy. The advantage of the CHP technology is the simultaneous production of electricity and heat, which is the reason of their high efficiency. In order to force the use of this ecological technology with its higher costs compared to conventional power production, the German Government passed the “KWK”-law that fixes conditions for certification and special rates for electric power from CHP systems.

<table>
<thead>
<tr>
<th>Codes/Norms/Laws</th>
<th>Content</th>
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<tr>
<td>Energiewirtschaftsgesetz (EnWG)</td>
<td>Secure, competitive and ecological energy supply</td>
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<td>DIN VDE 0100</td>
<td>General requirements for protection</td>
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<td>DIN VDE 0102</td>
<td>Calculation of short circuit power</td>
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<td>DIN VDE 0105</td>
<td>Operation of power current equipment</td>
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<td>DIN IEC 38</td>
<td>Standard levels of voltage for European grids</td>
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<td>DIN EN 50160</td>
<td>Voltage characteristics in electrical grids</td>
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<td>E DIN VDE 0126 (draft)</td>
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<td>Specifications for CHP-systems with lifting cylinder</td>
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<td>KWK-Gesetz</td>
<td>Certification and payment regulations for electric power from CHP</td>
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<td>DIN 44574</td>
<td>Electrical room heating</td>
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<tr>
<td>DIN 4701</td>
<td>Heat demand calculation for buildings</td>
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</table>

Table 1: Norms and regulations

In addition to these political conditions, different technical norms exist. First of all general specifications for CHP-systems will be found within the national DIN 6280-14. In fact this norm only contains the specification for CHP systems with lifting cylinder, the most common technology in this area, but it can be used as a basis for other developments like fuel cells. A new international standard project in this area is the IEEE 1561. This guide provides methods and procedures for sizing the major components of hybrid stand-alone energy systems. In order to design the heating part of the CHP-system, it is necessary to calculate the heat demand of the building or of the process in which the facility will be integrated. The corresponding code for buildings is the DIN...
The calculation of power flow is based on load profiles as well as loads. In order to do this, knowledge of electrical and thermal load profiles is mandatory. In detail there has to be a class of different load profiles representing the different seasons of the year as well as different types of weekdays. This paper deals with worst-case situations for the purpose of system planning rather than with an exact modeling of the actual loads of a network. Thus profiles for summer, winter and interim times are used, each of them sub-classified into Sunday- and working-day-profiles (Fig. 1). Interim times with similar load properties include both spring and autumn. Load profiles of Saturdays are implemented as a combination of load profiles of Sundays and working days.

Parameters of the network calculation

In order to assess the impact of DG on distribution networks, power flow and short circuit calculations are performed. Regarding the calculation of power flow, several parameters, apart from the ones concerning the network and the DG-plants themselves, are necessary. In this study the Newton-Raphson-scheme is used to calculate the power flow. Two different modes of operation of DG-facilities are considered. On the one hand DG is considered to mainly deliver a household’s demand of electrical power leaving thermal energy as byproduct (DG in current controlled mode). On the other hand it is used to deliver a household’s demand on thermal energy (heat orientated mode) leaving electricity as spin-off.

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Fig 1: Classes of load profiles used

Concerning the electrical load profiles a set of existing load profiles is used [6]. Figure 2 shows the electrical load profile for a winter-weekday. For thermal load, a simple model has been created for a typical 3-person-household. These parameters lead to an average characteristic for the calculations with a real distribution network. The model includes the thermal energy demand for heating purposes and for hot water. Due to the variety of existing building types, the model can only be applied on system-studies rather than for a single object. It represents a system-wide average value with respect to a three-person-household but not an exact function of the local thermal load. For this reason only the set-point-reduction of the heating system at night has to be modeled, omitting the periodical switching events occurring in a heating-system. Figure 3 shows the thermal load-profile calculated for a winter-weekday. The jumps at 6:00 a.m. and 11:30 p.m. are a result of the set-point-reduction at night. The peaks at 8:00 a.m. and 10:00 pm are caused by hot water demand for washing purposes. These peaks can be found in weekend load profiles as well. In this case they will occur closer to midday.

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Fig 2: Electrical load profile on winter-weekdays

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Fig 3: Thermal Load profile on winter – weekdays

Calculating the power flow, the same electrical load profiles are used for loads and DG in current controlled mode; in the latter case they were inverted. The derived thermal load profiles are assigned to DG-facilities in heat-controlled mode.

Purpose of calculations

Power flow calculation should attract interest on possible overload situations in the distribution network. Another point of interest is the voltage levels found within the networks. Due to DG they are not exclusively dependent on the feeder voltage any more, but also determined by the level and local distribution of power fed by DG. Thus the voltage levels are to be checked detecting any possible violation of the limits stated by existing norms. If so, means of voltage regulation have to be found, either by addition of passive elements to the network, by variation of the parameters of the dispersed plants or by introduction of a voltage control system. A third point of interest is the overall amount of dispersed generated power. It has to be determined if there is any power fed back into the medium voltage grid. In this case the maximum amount of back-fed power can be considered as most important value for studying the effects on medium voltage grids due to operation of DG. This is not subject to this study leaving the values as base for future studies.

In addition to power flow calculation, short circuit calculation is pursued as well. As a result of this calculation the subtransient short circuit $S_{\text{St}}$ and the subtransient fault current $I_{\text{K}}$ related by
The installations of DG systems occur over a long period of time. Hence a smooth transition to a high penetration level of DG will take place. For this reason three different scenarios are considered representing the different levels of DG (Fig 6).

In the scenario “some DG” 28 dispersed generation units are placed in 7 randomly chosen regions of the distribution network. In case of the “many DG”- scenario, a DG unit is placed in parallel to any load but street lighting. Except for the reference scenario without any DG at all, all scenarios are sub classified by the operational mode of the DG-plants, which are either heat- or current-oriented modes. In any subclass all DG-units are assumed to operate in the same mode. In case of the heat-controlled-mode there is a distinction in “unlimited electrical power” and “electrical power limited up to 5 kVA” corresponding to an additional burner for heating purposes. This is also possible for current-controlled-mode, but obsolete as the maximum demand of electrical energy of a household peaks at about 4 kW.

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Results of power flow calculation

The highest utilization of network elements arises from load profiles of a winter workday. Table 1 shows worst-case results when limits are exceeded.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Overloaded elements</th>
<th>Voltage violation &gt; 10%</th>
<th>Voltage violation &gt; 20%</th>
<th>Maximal work load of transformer 1 [kVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No DG</td>
<td>Lines, Transformer</td>
<td>X</td>
<td>X</td>
<td>77.84 (+)</td>
</tr>
<tr>
<td>Some DG</td>
<td>+ aux. burner</td>
<td>X</td>
<td>X</td>
<td>50.18 (+)</td>
</tr>
<tr>
<td>Some DG</td>
<td>- aux. burner</td>
<td>X</td>
<td>X</td>
<td>124.06 (-)</td>
</tr>
<tr>
<td>Qthermal</td>
<td>+ aux. burner</td>
<td>X</td>
<td>X</td>
<td>410.81 (-)</td>
</tr>
<tr>
<td>Much DG</td>
<td>+ aux. burner</td>
<td>X</td>
<td>X</td>
<td>369.03 (-)</td>
</tr>
<tr>
<td>Qthermal</td>
<td>- aux. burner</td>
<td>X</td>
<td>X</td>
<td>1195.95 (-)</td>
</tr>
</tbody>
</table>

Table 2: Overview of load flow results

A positive (negative) algebraic sign means a classical (reverse) direction of electric power flow through the transformer, that is from medium voltage to low voltage level (resp. vice versa). Electric power flow changes its direction, when the supplied power of DG exceeds the demand of energy. The first value with a reversed power flow appears in the 3rd line in table 2, when some decentralised energy systems are installed (value (-) 124.06 kVA). However, in this situation no elements are overloaded and no voltage violations appear. If the output is not limited to 5 kW for every energy supply system (case: few number of DG without auxiliary burner), then first line overloads and voltage band violations (> 10%) appear. This scenario is pessimistic.
because a relatively huge amount of energy 410.81 kVA flows in reverse direction into the medium voltage level. An overloaded element is the bus bar at the end of line 1.1. This problem can be solved by a different topology: lines 1.2, 1.3 and 1.4 can be disconnected from transformer one and be connected to transformer two or the second transformer feeds the network additionally (meshed system). Calculations show, that a change to a meshed topology reduces the load of bus bar EL 1 from 110 % to 80 %.

The last two lines of table 1 lead to the strongest overloads and voltage band violations especially for the last case (lots of DG without auxiliary burner), where 17 kW at every household interconnection are supplied. The scenarios make clear, that an auxiliary burner is necessary not only for a heating system itself but also for a sensible electric network connection. Otherwise an expensive network reinforcement would be necessary to allow massive electric power infeed.

Results of load flow calculations show, that massive injected real power leads to exceeded voltages. A further alternative is an additional reactive power consumption in order to reduce this effect. The scenario “Many DG with auxiliary burner” was chosen. Critical nodes are situated at the end of line 1. In one calculation the injected real power is set to 0 kW and the reactive power is set to 5 kVAr (DG as a real reactive load). The effect is a small reduction in voltage of only 1.2 V. If a real voltage control should be implemented, then the amount of controllable reactive power must be higher and several DG units have to be coordinated. In another calculation 8 DG units were set to 5 kVAr reactive power and the voltage could be reduced from 107 % to 104 %. Reactive power, which is consumed on low voltage levels leads to additional losses, if it has to be transported through medium voltage levels. Nevertheless, network operators have various possibilities with DG units e.g. a control of the injected real and reactive power and so a limited control of voltage.

**Short circuit calculation**

Two realistic values of short circuit power ($S_{k,min}=20$ MVA and $S_{k,min}=500$ MVA) are chosen at the medium voltage level. It is assumed, that the power electronic converters of DG units are capable for overload and have a subtransient short circuit current of three times of their nominal current. The calculations should just provide a hint, which difficulties may occur.

First of all, the influence of the variation of the short circuit power of the medium voltage level on the short circuit power of the low voltage level is studied. Relations of $S_{k,max}^+/S_{k,min}=25$ on medium voltage level are reduced to $S_{k,max}^+/S_{k,min}=1.8$ on low voltage level. Another result is, that the short circuit power decreases with an increase of distance to the infeed, and that short circuit currents of the DG units do not have a strong effect on the total short circuit power.

The relation of short circuit power on low voltage side to short circuit power produced by DG units is around 10 at the beginning of a line and decreases to around 1 to 2.5 at the end and leads to the consequence that power quality problems will probably occur at the end of long lines. A new limit $\varepsilon$ can be implemented and be set to $\varepsilon = \frac{S_{k,DG}}{S_{k,Net}} \leq 0.5$ which helps to evaluate certain scenarios better. In the test network the cases with a supply of lines 1.2 to 1.4 with transformer two and a meshed system are analysed. The situation at the end of line 1.2 in a meshed topology is a factor $\varepsilon=0.568$. Regarding the assumed factor, a disconnection from the left part of the network and a connection to transformer 2 would be the preferable solution. Other modifications within the network (new lines, etc.) seem to be uneconomic.

The results can be summed up as followed:

- area-wide installations of DG units lead to a feedback of electrical power from low to medium voltage levels
- area-wide installation of CHP-DG units without modifications in the network topology are only possible when power generation is limited (e.g. $P_{DG} \leq 5$ kW) and auxiliary burners are used
- Overloads occur mainly at the end of radial network topologies and can be remedied with simple changes in topology
- Voltage band violations do not appear while using many DG units, but voltage increases are relatively high compared to the reference calculation (no DG)
- Reactive power supply of a single unit has a small influence on voltage
- Reactive power consumption at low voltage level leads to a higher and unwished reactive power transfer via the transformer
- Consumption of reactive power (for a reduction of voltage) and injection of real power have to be cleared
- High variations of short circuit power on medium voltage side are transformed to a small range of short circuit power on low voltage side
- Interferences produced by DG units appear mainly at the end of radial network lines, where the ratio of short circuit power of DG units to the short circuit power of the network is much higher than anywhere else in the network

**Conclusions and outlook**

There are many motivations for an application of decentralised energy supply systems. A more efficient and economic use of energy, cost pressure due to liberalization and a substitution of old power plants are main reasons.

Today’s fuel cell systems do not yet operate economically. There is a call for action for fuel cell systems particularly with regard to readiness for marketing. Changes will occur, when fuel cell systems will be mass-produced and costs can be reduced.

Fuel cell systems which generate thermal heat and electrical power at the same time and their application in a house-energy-supply-system are basic ideas for the realized load flow calculations. It is assumed that the facilities are heat controlled in order to discharge the heat and to prevent an overheating of the whole supply system. If the supplied real power does not exceed 5 kW, only elements in wide-stretched dead-end feeders are overloaded. In this exemplary network, this problem can be solved by a change to a meshed topology.
The nominal voltage increased to around 7% and was within the limits according to IEC 38. The influence of reactive power consumption on voltage, while all decentralized power supplies consumed 5 kVar each, is relatively small. Additional energy supply in the low voltage network has a neglecting effect due to the dominating influence of the short circuit power in the medium voltage network. Calculations with the exemplary network makes clear, that short circuit power decreases at the end of long lines and that circuit feedbacks may appear.

Future investigations will concentrate on:
- Plant management of several decentralized energy systems in order to control voltage with reactive power consumption/injection
- Single phase connection to electrical network and resulting unsymmetries
- Models of thermal loads have to be improved
- Coordination of decentralized systems in order to realise an operation management and a protection system
- Protection systems in separate networks
- Operation of islanded low voltage networks.

Further work has to be done on this field of research and the forthcoming field tests of fuel cell based decentralized energy supply systems will show, which difficulties have to be cleared before these devices can be installed on a big scale.

**Literature:**
[4] T. Wiesner: "Technical Aspects of Wide Area Integration of DECS into Distribution Networks (German only)", Dissertation at the University of Dortmund, Dortmund, Germany, 2001