Power flow simulation and visualization of autonomous MicroGrids

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Abstract: Due to decentralized generation power flow situation in low and mean voltage level grids has changed which now complicates estimation of grid condition. A satisfying identification necessitates installation of measurement technique. To find applicable measurement facilities powerful simulation tools focusing new energy sources and changed power flow situation are needed. In this paper the MicroGrid Simulator is introduced. It is a high-performance simulation and visualization tool which can be used for calculating power flow time series of either autonomous or grid connected MicroGrids, dimensioning electrical equipment and energy storage devices or planning MicroGrids.

Keywords: Microgrid, Simulation, Visualization, Renewable energy sources, Nodal load decomposition, Power flow

1 Introduction

The number of small feeders based on renewable energy sources like wind, global irradiance or natural gas has strongly increased during the past years. Because of their limited power these devices primarily feed in low or mean voltage level grids. Contrarily to power supply by means of conventional main power stations the distributed feeding via lots of small producers is called decentralized generation [1].

The increasing amount of decentralized producers results in dramatically changed demands on mean voltage level grids originally planned as distribution grids with one way power flow direction. Energy transportation over a long distance should be avoided because of limited transmission capability resulting in voltage drops and high grid losses. So supplied power is possibly used locally. Mostly offered power, especially power fed by renewable sources, does not match requires of loads. To coordinate energy employment of distributed generation decentralized energy management systems are developed.

A MicroGrid is a cost-effective approach for integrating decentralized generation, increasing reliability and reducing grid losses by regional supply and use of energy. It can be described as a sub grid with the ability to satisfy its demand of energy on its own which means it is able to operate autonomously.

A MicroGrid consists at least of one generator and one load. An additional energy storage device might be useful for load balancing reasons and for peak shaving. A private household with its own power generation (i.e. solar power systems) might be a MicroGrid as well as an industrial network or a mean voltage distribution grid.

In this paper mean voltage (MV) grids are focused.

2 Autonomous MV grids

In the MV level power is mostly fed by renewable energy sources like wind -, solar - and natural gas power systems but as well by conventional CHP devices. The high variability of global irradiance and wind speed results in high demands on control strategy for adjustable sources and loads. In this case energy storage devices like flywheels, SMES or batteries may be helpful.

The topics mentioned in the introduction cause change in MV level grid equipment utilization. Overstresses cannot be detected adequately because for historical reasons measurement technique is sparsely distributed in MV level grids. It is therefore necessary to examine new measurement facilities to satisfactorily identify grid state.

To keep investment cost on a low level examination is done by simulation tools. These tools should be able to calculate time-variant curves (TVCs) of power flow, model feeding behavior of renewable sources like wind or global irradiance and apply methods to sustain grid autonomy. A tool for simulating MicroGrids fed by renewable sources is introduced in this paper: the MicroGrid Simulator.

3 DG sources and loads

Typically electric power of renewable sources is lower than 10 MW so they are connected to a low or medium voltage level grid. To find control strategies for establishing grid autonomy it is necessary to figure out feeding behavior. On the other hand time series of loads have to be examined. A more detailed description of DG sources and loads can be found in [2].

3.1 DG sources

DG sources can be divided into weather dependent and adjustable sources. In this chapter some widespread DG sources are figured.

Wind

Wind is a highly variable phenomenon depending on local factors so its instantaneous value of direction and speed can hardly be calculated. Anyway there are typical characteristic mean TVCs for different heights. As well behavior and appearance of squalls are roughly appreciable. Fig.1 shows TVCs of wind speed in different heights.

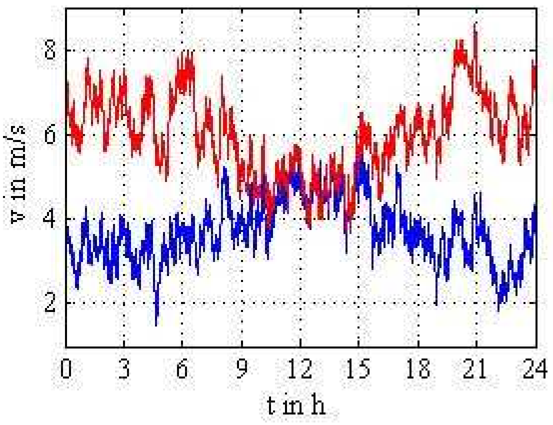

Fig.1 TVC of wind speed within one day

Due to

$$P_{\text{el}} = \frac{1}{2} c_{\text{p}} \rho A v^3 \quad (1)$$

a duplication of wind speed will cause octuple times the original electric power which even enlarges variability.

Global irradiance

Global irradiance depends on location, orientation, cloudiness, daytime and season. TVCs measured at a continental location of 54 degree of latitude on midsummer and midwinter day are shown in Fig.2. Feeding is limited to a few hours a day and due to inefficiency of photovoltaic modules global irradiance makes a less contribution to power supply than wind energy.

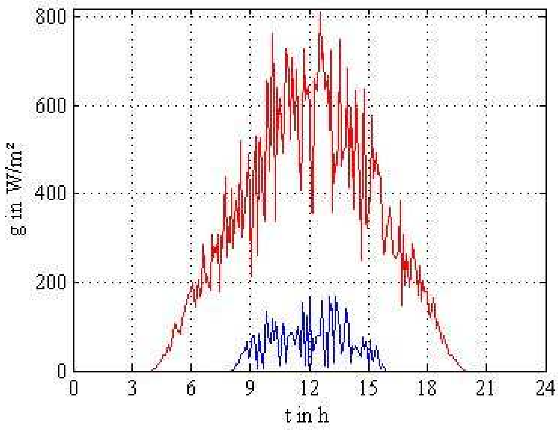

Fig.2 TVC of global irradiance within one day

Adjustable sources

Adjustable sources require independency of outer influence and constant availability of fuel. A short response time is advantageous for control mechanism. In the MV level grid adjustable sources are for example micro gas turbines, natural gas power stations and CHP devices.

3.2 Loads

In the MV level loads are modeled by analytic standard load profiles. The VDEW has announced profiles for eleven different types of loads. The behavior of any arbitrary load can by emulated by cumulating weighted analytic standard load profiles. Fig.3 to Fig.5 show load profiles of household-, industrial- and agricultural dominated loads.

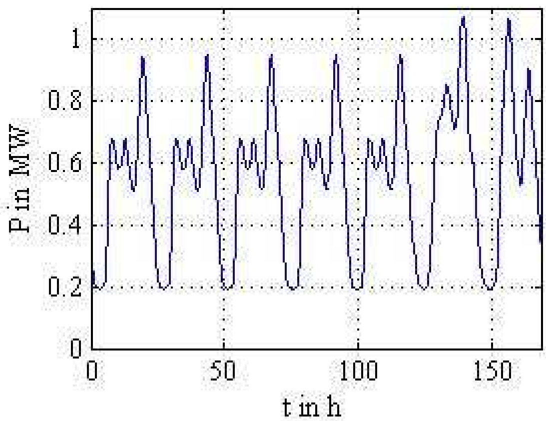

Fig.3 Household dominated TVC within one week

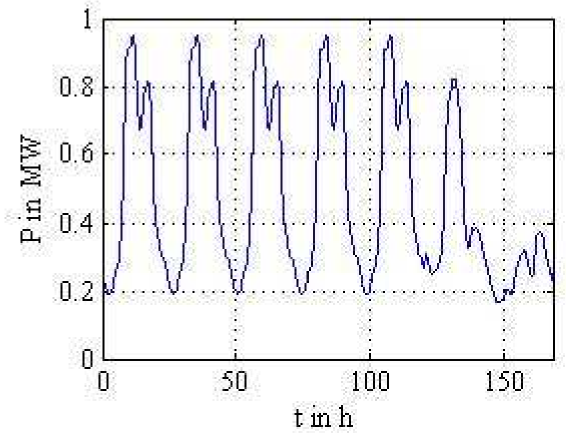

Fig.4 Industrial dominated TVC within one week

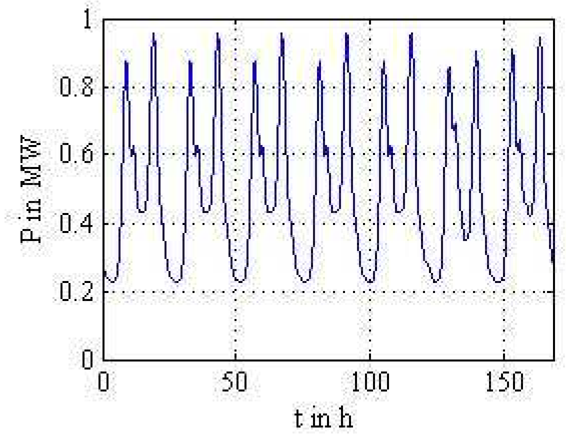

Fig.5 Agricultural dominated TVC within one week

4 MicroGrid Simulator

The MicroGrid Simulator enables users to simply, quickly and intuitively create and modify MicroGrid projects. Electric circuits are easily arranged and parameterized via GUI. Grid size is freely scaleable and can span any voltage level. Parameters of transformers, wires and generators and loads can be stored in an equipment database to quicken parameterization of similar devices.

The behavior of loads and generators are either defined by specific measured time-variant curves or by simulating the physical basics of each device. This is done by synthesizing TVCs of wind speed and global irradiance. Loads are modeled by cumulating weighted analytic standard load profiles. Generators with constant availability of fuel (i.e. natural gas power stations, CHP devices) are used as adjustable sources.

A defining TVC may contain any measurable electric (P, Q, U, I, δ) or non-electric (p, v) measurement category and can be attached to loads, generators, auxiliary and sub grids, storage devices, nodes or terminals. The MicroGrid Simulator is able to read TVCs in XML, Excel and CSV file format.

The simulator uses all synthesized and predefined values to generate a nodal power vector which provides the basis for any power flow algorithm.

4.1 Simulation scenarios

The MicroGrid Simulator offers different simulation scenarios varying in calculation complexity and scope of services.

<u>Power flow</u>

The quick and simple power flow algorithm based on a Newton-Raphson-method calculates nodal voltages, terminal currents and grid losses [3]. It can be used for planning grids and dimensioning electrical equipment. The power flow algorithm is the kernel of the MicroGrid Simulator.

<u>Grid autonomy</u>

Grid autonomy is one possible gain of MicroGrids. To establish grid autonomy for a possibly long time complex control strategies are needed to adjust feeders, loads and energy storage devices. These strategies have to comply with voltage and frequency ranges of tolerance.

The grid autonomy method executes a power flow calculation and tries next to compensate the difference of supplied and used power by adjusting feeders and energy storage devices.

<u>Relay protection</u>

Transformers and lines are equipped with relays. So it is possible to simulate any switching operation effect on the MicroGrid. Relays may be disengaged manually or automatically. In automatic mode the algorithm detects overstressed equipment and tries to disconnect it. Grid integrity is checked before switching.

4.2 Visualization

During simulation all relevant data is shown in the grid plan. Additionally the actual condition of equipment is highlighted in terms of color.

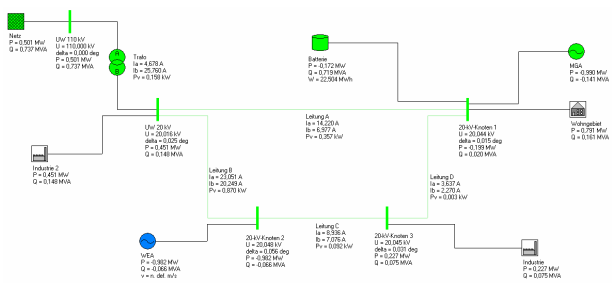

Fig.6 Grid plan during simulation

TVCs of any desired value can be shown online during simulation. For the purpose of demonstration a three dimensional grid view is added showing nodal voltages as well as feeder and load power as arrows.

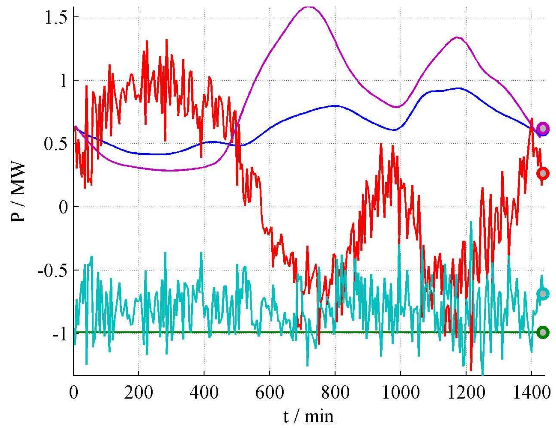

Fig.7 Time series during simulation

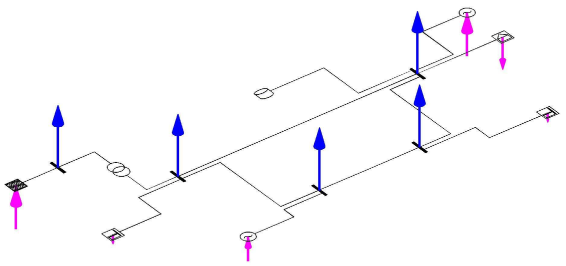

Fig.8 Three dimensional grid view

4.3 Export possibilities

All MicroGrid projects and simulation results are stored in XML format. Results may be converted to XLS or CSV format to be used for further calculation in Excel or MATLAB. Nodal admittance matrix, nodal-terminal-incidence-matrix and terminal admittance matrix can be stored in CSV format. Pictures of the grid can be saved as BMP or JPG image file.

4.4 Remoting

Instead of using predefined time series the MicroGrid Simulator is able to capture measured values online via web service. The values have to be transmitted in XML format and may contain the same electric and non-electric measurement categories as the predefined TVC.

4.5 Decomposition of nodal loads

As mentioned above loads connected to the MV level grid can be modeled by cumulating weighted analytic standard load profiles. The MicroGrid Simulator offers the possibility to disassemble a given active power time series to get weighting factors i.e. load composition.

Decomposition is done by a least-squares-algorithm minimizing the difference between measured and calculated load.

$$\Delta \boldsymbol{p} = \boldsymbol{p}_{\text{calc}} - \boldsymbol{p}_{\text{meas}} = \left[\boldsymbol{p}_1 \ \cdots \ \boldsymbol{p}_{11}\right]\boldsymbol{w} - \boldsymbol{p}_{\text{meas}} = \boldsymbol{L}\boldsymbol{w} - \boldsymbol{p}_{\text{meas}}$$
$$= \begin{bmatrix} p_1(t_{\text{Start}}) & \cdots & p_{11}(t_{\text{Start}}) \\ \vdots & & \vdots \\ p_1(t_{\text{End}}) & \cdots & p_{11}(t_{\text{End}}) \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_{11} \end{bmatrix} - \begin{bmatrix} p_{\text{meas}}(t_{\text{Start}}) \\ \vdots \\ p_{\text{meas}}(t_{\text{End}}) \end{bmatrix} \quad (2)$$

$$\frac{\partial f}{\partial \boldsymbol{w}} = \frac{\partial\left(\Delta \boldsymbol{p}^{\mathrm{T}} \Delta \boldsymbol{p}\right)}{\partial \boldsymbol{w}} = \boldsymbol{0} \quad (3)$$

$$\Rightarrow \boldsymbol{L}^{\mathrm{T}}\boldsymbol{L}\boldsymbol{w} - \boldsymbol{L}^{\mathrm{T}}\boldsymbol{p}_{\text{meas}} = \boldsymbol{0} \quad (4)$$

Consequentially the weighting factor vector $\boldsymbol{w}$ can be calculated as follows

$$\boldsymbol{w} = \left(\boldsymbol{L}^{\mathrm{T}}\boldsymbol{L}\right)^{-1}\boldsymbol{L}^{\mathrm{T}}\boldsymbol{p}_{\text{meas}} \quad (5)$$

5 Simulation scenario examples

In this chapter the grid shown in Fig.6 is used to demonstrate some simulation scenarios and visualization abilities.

<u>Simple power flow</u>

In power flow mode energy storage devices are disengaged if they are not attached to a measurement device or a TVC. The utility grid is defined as slack to provide power balance.

Power time series of all loads, generators and grids are shown in Fig.7. Fig.9 displays nodal voltages of all mean voltage level nodes during simulation.

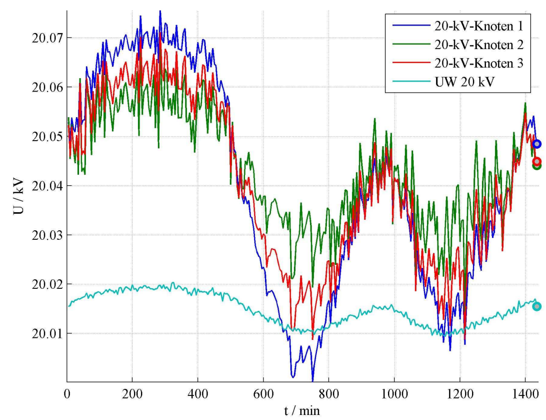

Fig.9 Nodal voltages

Grid autonomy

In grid autonomy or MicroGrid mode adjustable sources and energy storage devices are controlled for the purpose of keeping power exchanges with utility grids as small as possible.

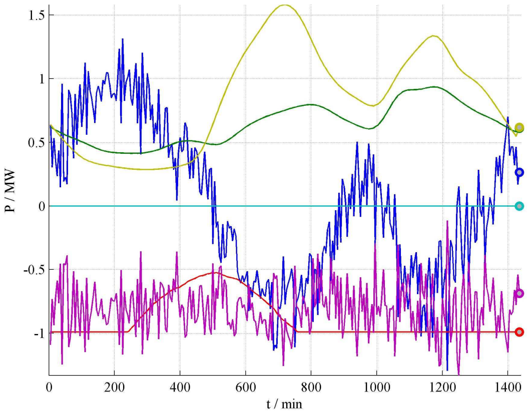

Fig.10 Power time series during MicroGrid mode

Fig.10 shows that the battery can balance wind variability and the fed power of the adjustable device (MGA) is reduced temporarily.

Relay protection

In relay protection mode switches are pictured as small boxes in the grid plan at the ends of wires as shown in Fig.11. A black box represents a closed switch. In automatic mode relays are disengaged if nominal power is exceeded and grid integrity would not be violated by switching. As well they are reengaged automatically as soon as possible.

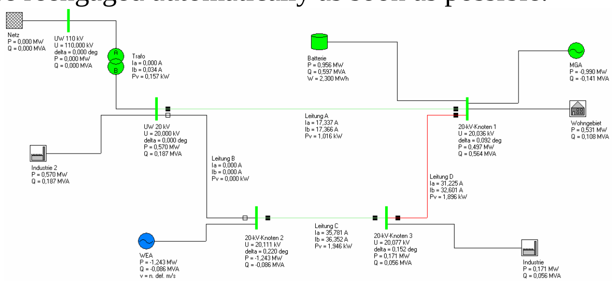

Fig.11 Grid in MicroGrid relay protection mode

Fig.12 shows power flow time series during relay protection mode simulation. After 550 min line B is overstressed and switched off. After 700 min it is switched on again. Protection of line B recurs after 1050 min.

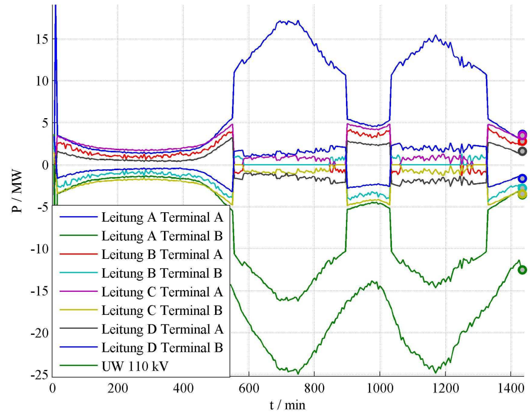

Fig.12 Power flow time series

6 Conclusion

The MicroGrid Simulator is a new and powerful tool to simulate, analyze and visualize power flow and equipment condition time series in MicroGrids and distribution grids of any size and voltage level.

It is able to synthesize wind speed and global irradiance time-variant curves and so it can model feeding behavior of renewable energy sources. The MicroGrid Simulator introduces a control strategy to adjust feeders and loads for the purpose of grid autonomy.

The tool provides many simulation scenarios like power flow, grid autonomy and grid protection and offers various visualization possibilities.

The MicroGrid Simulator supports different data sources and data formats and can easily be integrated into distributed computing processes.

During further development of the tool among other simulation scenarios and new models of electric equipment the integration of grid condition identification and short-circuit calculation is planned. Just as well probabilistic power flow calculation of grids fed by renewable energy sources might be useful and is to be integrated.

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