FUTURE STRUCTURE OF RURAL MEDIUM-VOLTAGE GRIDS FOR SUSTAINABLE ENERGY SUPPLY

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ABSTRACT

Due to the fundamental change of the legal framework in Germany [1] and the mandatory targets for renewable energy shares of final energy consumption set by the European Renewable Energy Council [2], the number of distributed renewable generation units in medium-voltage (MV) grids has strongly increased. Especially in rural areas an ongoing dynamic growth of integration of biomass and photovoltaic plants can be expected. In certain situations of injection, parts of rural grids will face overloads and can hardly be operated in line with the technical guidelines.
This paper deals with the renewal effort of a rural 20 kV distribution grid with high proportion of renewable energy sources in the next 20 years. To analyze the future problems of voltage stability, scenarios of renewable energy injection of the years 2015 and 2030 have been created. Concrete recommendations for measures in the MV-grid have been developed. Furthermore general recommendations for planning guidelines of MV-grids with a high proportion of renewable energy sources have been derived.

INTRODUCTION

In the last years the power supply system and the associated industry in Germany changed dramatically and fundamentally. This concerns the generation of electrical power (which switches from centralized generation in nuclear, coal or gas fired power stations to decentralized renewable energy generation) and the distribution systems itself, which have to transport the electrical energy from the decentralized sources to the customers.
The German Renewable Energies Act from 2000 with its amendments [1] supports the installation of renewable energy converters and guarantees remuneration for each injected kWh. Thus, in the last decade the installed power of renewable energy sources in Germany has grown from 11.9 GW to 55.9 GW (Fig. 1).
Particularly in rural regions a high potential for renewable energies is given due to a high availability of areas of arable land for wind turbines and roofs for photovoltaics. So the main requirement of rural MV-grids is to include enormous numbers of decentralized energy generation units like Wind turbines, Biomass power stations and Photovoltaic units with a rated power from 0,1 MW to 2,5 MW in line with the technical guidelines [3] [4].
To enable the expected growth, the grid operators have to increase the capacity of the distributions systems sustainably.

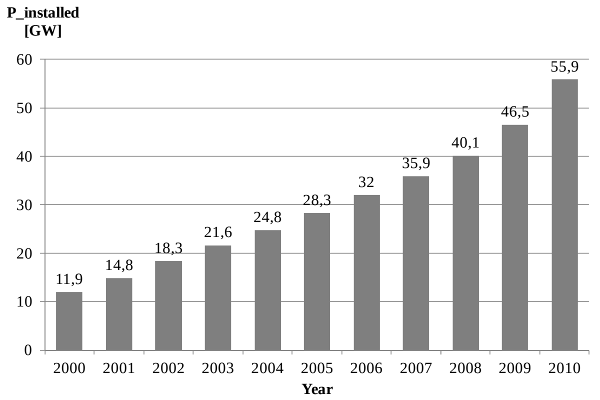

Fig. 1: Installed capacity for electricity generation from renewable energy sources in Germany [5]

SUBJECT OF THE STUDY

In case of injection decentralized energy converters cause a **voltage increase** at their junction point due to the resistance of the lines between the generation unit and the connection point at the main transformer substation to the overlay-grid. Especially in the rural MV-grids overhead-lines with high specific resistance are used to connect many decentralized consumers. This leads to a strong circuit feedback of the generation units and in most cases the voltage increase caused by generation units is higher than in urban regions.
Furthermore the increased number of distributed generation connected to medium- and low-voltage (LV) grids causes **local overloads** of the grid equipment near to the High-Voltage/Medium-Voltage (HV/MV) -transformer substations today and in the future. These overloads occur especially during low-load periods, when the generated energy has to be transported to the higher-level grid.
The particular aim of the study was to derive concrete recommendations for measures to enable the grid operator to run the grid in line with the relevant technical guidelines [3] [4] in the future, considering the situation of injection of renewable energy of the year 2030.

Furthermore universal planning guidelines for rural distribution grids should be developed from the results of the concrete example study.
The analysed grid supplies a rural area in northern Germany of 3,500 sq km with about 3,000 MV/LV-substations via 2,400 km 20-kV-lines (Fig. 2). In 2010 the considered grid contained a load of 135 MW distributed via eight main 110-kV transformer substations and 150 MW of renewable energy injection. The installed power of the 193 renewable energy converters connected to the grid in 2010 was divided as shown in Table 1 The generation units have been installed regarding the German Renewable Energies Act [1] and their junction point cannot be changed in future.
Furthermore nine wind farms with a total power of approximately 100 MW are connected to MV-busbars in the HV/MV-transformer substations.

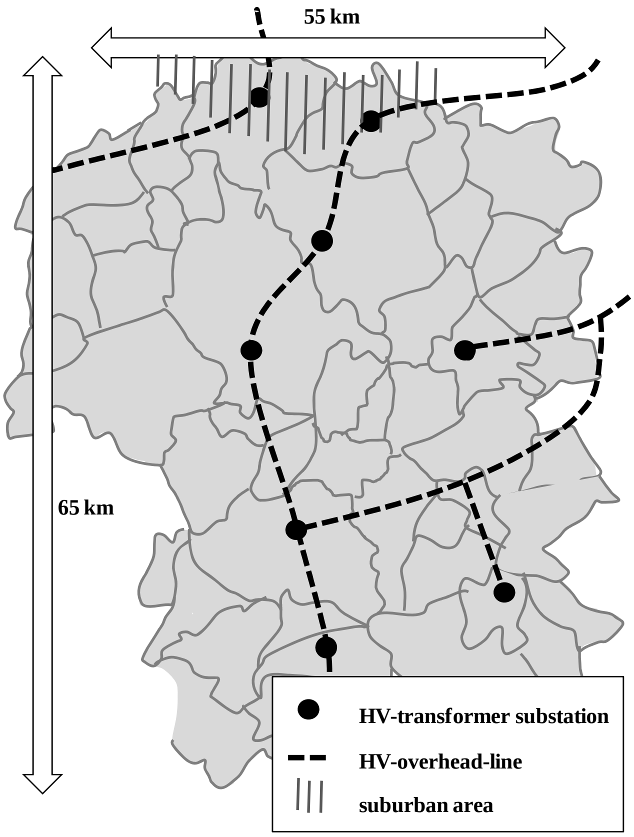

Fig. 2: Area of analysed MV-grid.

Table 1: Installed power of renewable energy converters in the analyzed grid (2010)

	# units	P_{TOT} [MW]	Ø P [MW]
Biomass	93	44,4	0,48
Photovoltaics	28	11,1	0,40
Wind turbines	72	98,5	1,37

ASSESSMENT METHOD AND SCENARIOS

Determination of voltage increase

Under normal operating conditions of the grid, the magnitude of the voltage changes caused by all generating plants with a point of connection to a MV-grid, must not exceed at any junction point a value of 2 % within this network as compared to the voltage without generating plants [3]. In exceptional cases the distribution system operator may warrant a deviation of the 2% value.
The voltage changes are determined by means of complex load-flow calculations comparing the voltages with and without decentralized generation at each busbar in the MV-grid.
In this consideration, generation units connected to other grid levels are not taken into account. The assessment of the circuit feedback of these generation units is defined in separate guidelines [6].

Determination of overloads

The maximum permanent loads of the grid equipment have been investigated in worst-case situations of weak load of consumers and high injection of generations plants in all voltage levels subordinated to the HV/MV-transformer substations (i.e. MV-busbar in substation, MV-grid, MV/LV-busbars of local substations, LV-grid). Generation plants connected to the LV-grid have been considered by reducing the sums of the loads in the local MV/LV-substations, implying a massively increasing number of generation plants (especially photovoltaics) in LV-grids.

Adherence of permitted voltage range

Within the scope of the study was to determine whether the permitted voltage range in the MV-grid is respected. DIN EN 50160 [4] gives the borders $U_{Nominal}$ +10% and $U_{Nominal}$ -10%, which have been tested for the original and modified grid structures by considering situations of full load and full injection (in all voltage levels).

Development of scenarios

Scenarios of renewable energy injection of the years 2015 and 2030 have been created. They are representing the expected situations of renewable injection of biomass, photovoltaics and wind and are based on internal investigations and prognosis. Furthermore they are considering the development of the MV- and LV-loads until 2030 (Table 2).
The average rated power of **biomass plants** will be at approximately 250 kW per generation unit. In the developed scenarios 142 additional biomass plants mostly installed in rural areas have been foreseen. In total 35.5 MW of biomass injection will be installed in the considered grid until 2030.
Photovoltaics with approximately 350 kW_p each will be included in rural and in urban parts of the analysed grid. In the scenario 2030 additional 35.0 MW of distributed

generation by photovoltaics have been foreseen.
Until 2030 no additional **wind** priority sites have been foreseen (as of December 2010). Assuming, that the existing wind turbines will be repowered extensively, the rated power of the wind turbines locally installed in the MV-grid have been increased by the factor 1.7 for the scenario 2030.
The demographic development and the rural-urban migration are leading to a decreasing number of electrical house connections in the considered area. Furthermore improvements in energy efficiency will contribute to a decrease of the **maximum loads** in LV-grids of about 10%.

Table 2: Load / renewable injection in scenario 2030

	Expectation 2030	Ø P [MW]
Biomass	+ 35,5 MW	250 kW
Photovoltaics	+ 35,0 MW	350 kW_p
Wind	+ 70% / + 69 MW	-
Load	- 10%	-

EXAMPLE CALCULATION

The presented example grid shows impressively the effect on voltage change considering the developed scenario of the year 2030 and the recommended measures for operating the grid in line with the mandatory guidelines [3] [4].

Original grid structure

Fig. 3 displays the example grid with of approximately 70 km of MV-lines. It is operated in a closed loop, supplying a total load of 3.3 MW at approximately 50 MV/LV-substations (i.e. LV-grids). In 2010 the example grid contains 12.5 MW of renewable energy injection via eight wind turbines, three powerful biomass plants and two photovoltaics (grey in Fig. 3 / Fig. 4).

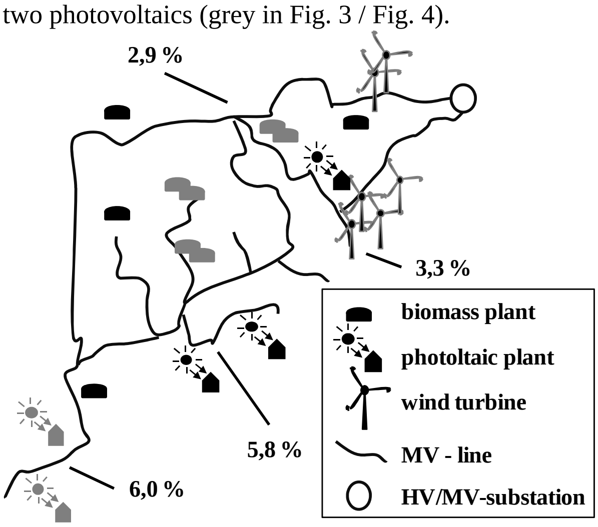

Fig. 3: Voltage change of the example grid in 2030 without additional measures

Up to 2030 six additional photovoltaics and biomass plants are expected (black in Fig. 3 / Fig. 4); meanwhile the total load of the wind turbines will increase up to 18 MW by the factor 1.7. In the scenario 2030 a total injection of renewable energies of 22.5 MW will be integrated.
The distributed generation units will cause voltage increases up to 6.0%, due to the massive generation and a high proportion of overhead lines. The violation of the given borders (2.0%) can neither be prevented by local measures like restructuration (change the setting of local switches) nor by substitution of overhead-lines by MV-cables.
The admissible voltage range in MV and the maximum transmission load of the MV-lines will not be violated in the scenario 2030, so that the focus of the recommended measures is on the voltage increase.

Recommended grid structure

To ensure the capability of the presented grid to integrate renewable energy converters as foreseen in the scenario 2030 in line with the guidelines, significant changes of the grid structure are necessary:

- The wind turbines located southerly are directly connected to the MV-busbar of the HV/MV-transformer substation via a six km cable with a cross-section of 800 mm². So the circuit feedback of the wind turbines will be minimized and the rest of the MV-grid is relieved sustainably.
- In the second extension stage, the cable will be used to establish a satellite grid. Via additional four km of cable, a point of common coupling with high short circuit power is provided in the centre of the local accumulation of biomass and photovoltaic plants. Due to this the circuit feedback of the generation units on the rest of the MV-grid can be minimized.

Fig. 4 shows the example grid including the recommended measures. The listed voltage increases show, that an operation of the grid in 2030 in line with the technical guidelines is possible. Furthermore additional capacities for integration of renewable energy converters in MV- and LV-grids are created.

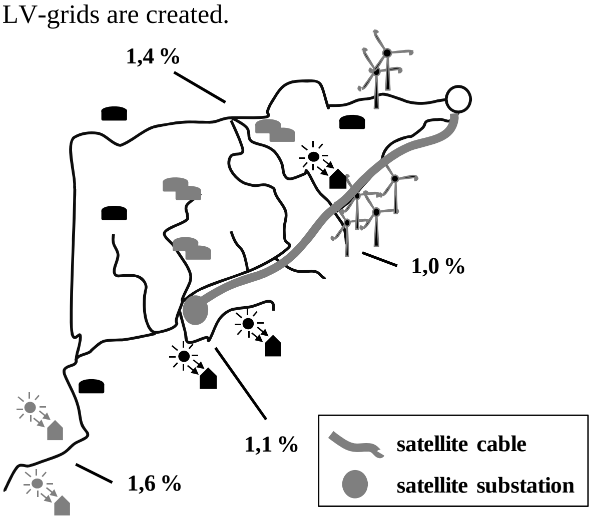

Fig. 4: Voltage change of the example grid in 2030 after realization of recommended measures

KEY-RESULTS

Concrete measures

As the example shows, the operation of rural MV-grids in line with today's technical guidelines is only possible in the future, if the grid is massively restructured and enhanced.

To increase the capacity of the considered MV-grid for renewable generation units till 2030 and to create additional reserves for renewable injection in the subordinated LV-grids approximately 30 Mio € have to be invested in the whole region (Fig. 2) at all. Four main types of concrete measures to increase the grid capacity have been found:

- Substitution of several overhead-lines (~15 km) by standard cables with 300 mm² cross-section.
- Local adjustment of the MV-grid-structure for enhancing renewable injection
- Additional high capacity cables (approximately 81 km) for eight satellite substations (20 kV) to provide local points with high short-circuit power
- Construction and integration of two additional 110-kV transformer substations (40 MW rated power each)

Recommendations for new planning guidelines

The concrete results of the study can be generalized and transferred to most rural MV-grids in Germany. Certain expansion options are suitable to restructure given grids and sustainably enhance the capacity for renewable energy converters. They can be used like a tool-box of grid extension measures:

1. In exceptional cases the **local restructuring** like insulation of high-power wind turbines from the rest of the grid can increase the capacity of MV-grids. In case of cabling of overhead-lines, 300 mm² should be the preferred cross-section.
2. High-power wind turbines have to be separated from the existing grid by establishing a **direct connection** between the MV-busbar of HV/MV-transformer substations and wind turbines.
3. **MV satellite grids** should be established by a direct MV-cable (800 mm² cross section) from the HV/MV-transformer substation to a decentralized satellite-substation to provide a point of common coupling with high short circuit power in a large distance to the HV-overhead lines (7-15 km). The satellite grids behave like an extension of the MV-busbars of the transformer substations. The satellite-substations are recommended to be located near or on the sites of existing MV/LV-substations with telecontrol and circuit breakers if possible.
4. As a last option **HV/MV-transformer substations** should be erected directly under existing HV-overhead-lines without causing a long-winded authorizing procedure. Standard HV/MV-Transformers with a capacity of 40 MVA are foreseen to integrate wind turbines with high power, but as well to establish additional connection points to the overlay grid.

CONCLUSION

The rural medium-voltage grids are the basis for today's fundamental changes in energy business in Germany. Their structure has to be adapted and enhanced significantly, since the major task of those grids is not only distributing energy from the transmission-grid to the customers anymore, but collecting a massive amount of renewably produced energy, too. Even today significant problems like local overloads and inadmissible voltage are daily business in those grids. They can be overcome by massive investments and restructuring of the MV-grids only. As demonstrated, the grids can be operated in line with the technical guidelines in Germany, if new enhancement guidelines presented in this paper are established.

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