GRID INTEGRATION OF WIND ENERGY CONVERTERS AND WIND FIELD APPLICATIONS

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ABSTRACT

The use of wind power has taken an enormous rise and is on the step to a large-dimensioned technical use. This development was started by the progress in wind power plant technology and is characterised by an increase of output, thus linked with a reduction of costs and remarkable improvement of reliability.

Larger and larger wind power plants (0.5 MW - 2.5 MW) and wind parks in the range from 10 to 100 MW are connected even to weak grid areas in order to exploit the available wind potential. In future, therefore, apart from improvements of grid compatibility also controlling, conducting and regulating methods as well as the introduction of systems for failure prediction will open new aspects. Thus, with increasing rated power of the plant a clear tendency towards technologically innovative systems can be recognised in the MW-Class. By speed-variable operation with active and reactive power control it is possible to reduce stresses in the drive train and to improve the compatibility with the public mains.

Worldwide, wind energy is almost exclusively used for producing electricity. With regard of the energy transmission to electrical supply companies they have to observe differences between systems with limited feed-in facilities which occur in insulated operation or by supply to weak grids, and the connection with rigid public mains with an unlimited capacity for feed-in.

Wind power plants are required to enable a reliable operation in both fields of application. Further the reactive power supply with pulse-controlled inverter reduces the reactive power demand from the grid. Pulse-controlled inverters as power-factor controller also allow an active voltage control of the mains voltage limits.

By plant- and grid-specific dimensioning it is possible to connect more wind power plants, than without voltage control, especially in strong wind areas with weak dead-end feeder. The acceptable voltage fluctuations and flicker can be kept usually at small expenditure. Costs of measures for grid reinforcement can be saved thus to large extent.

1 INTRODUCTION

Due to its very high power capacity (in relation to the nominal values of connected consumers) the interconnected network can be regarded, as a nearly inexhaustible source of active and reactive power, and for small power feed-in supply such as wind power plants it works as an electric acceptor of an unlimited taking-in capacity with constant voltage and frequency rates.

The electrical power supply system is principle structured into five voltage levels (Fig. 1). The power in- and output ability, safety-relevant aspects and connection costs essentially determine the selection of a grid connection. Because of the favourable system costs the low- and medium -voltage system integration is preferred. That is dominated by low voltage machine with a medium voltage connection.

In the offshore-range wind power plants are in development with medium voltage generators connected to the medium- or high-voltage level.

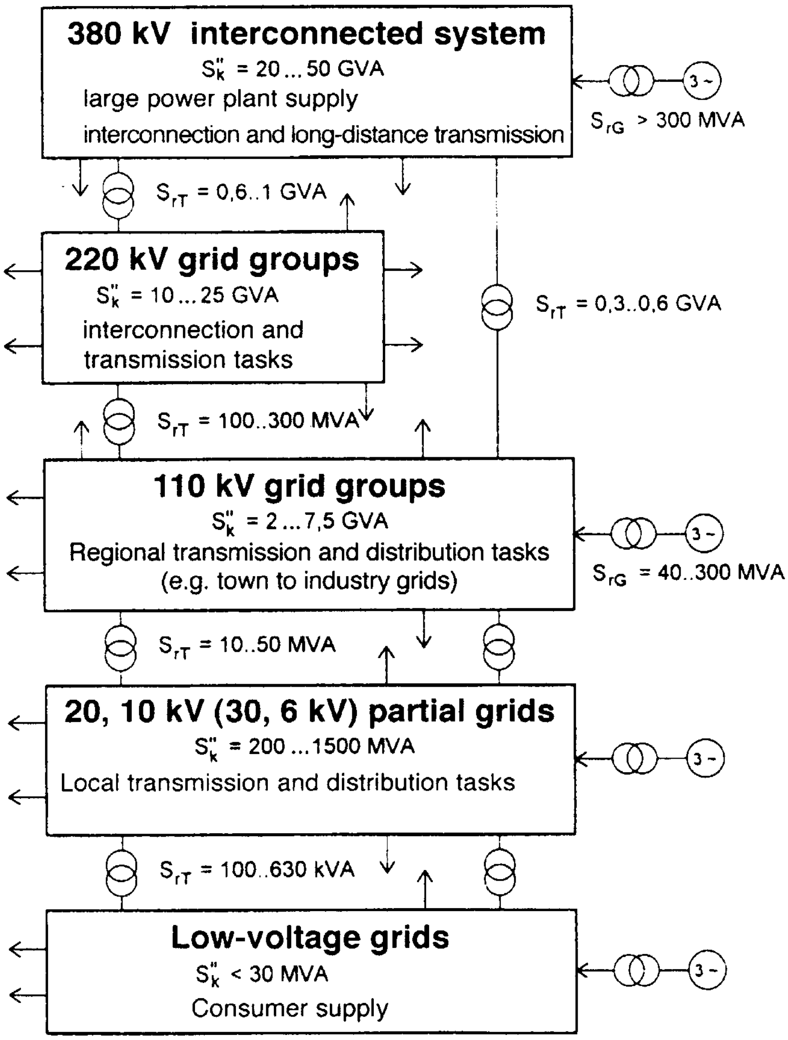

Fig.1: Voltage levels and feed-in possibilities of electrical power supply system.

In contrast to thermal power stations wind turbines are often installed at remote places with limited feed-in facilities. Therefore, frequently a weak grid connection is found with partly long branch lines. The feed-in capacity of large wind power plants and wind parks can thus easily reach the max. limit of the grid transmission capacity or might get to such close proximity to it that interference effects will have to be taken into consideration.

Effects of wind power plants on the grids are determined, on the one hand, either by the way of power generation or the kind of grid connections thus resulting from it; due to the influence of the protection devices and the short circuit power, on the other hand, security aspects and the grid protection may be involved and the proper functioning of the switch devices may be impaired. Furthermore, grid interference's can possibly turn up which may cause changes in harmonics and voltages and may have an influence on the grid control.

Figure 2 shows the grid connection of a wind energy plant. Its Connection Point (CP) is chosen on the lower-voltage side. By means of a transformer and a medium-voltage line, which contains ohmic, inductive and capacitive elements, the feed-in connection to the Point of Common Coupling (PCC) is brought about. The feed-in capacity or the power output of the connection point and thus also its short circuit power are dependent on the transformer, the transmission line, and the superordinate grid (Fig.3 a, b).

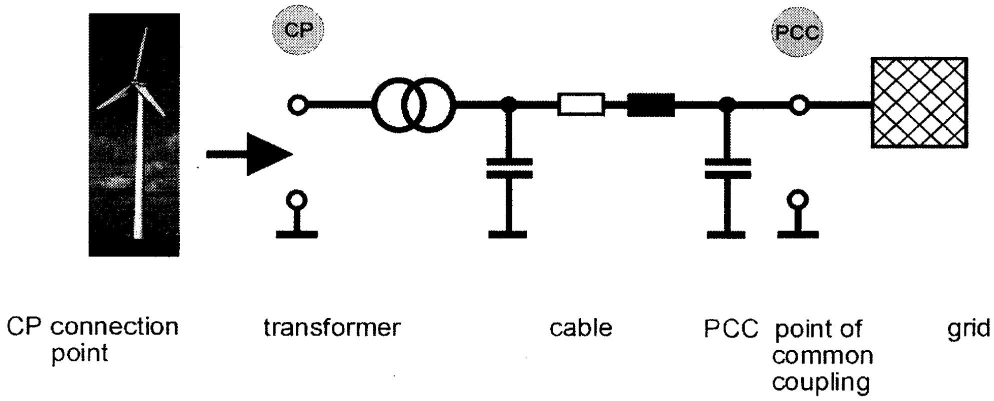

Fig.2: Low voltage grid connection of a wind power plant

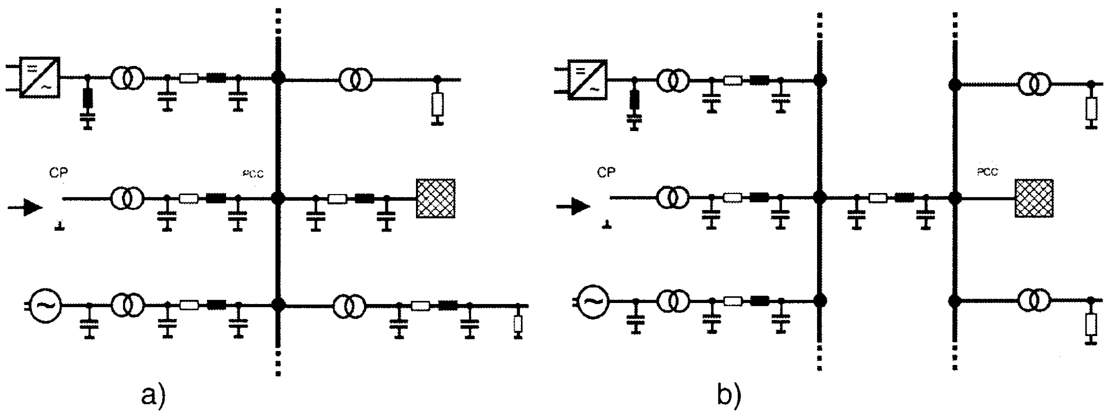

Fig.3: Grid connection of power plants and load
a) common bus bar
b) separate bus bar.

2 PRESENT SITUATION OF WIND POWER PLANT TECHNOLOGY

The development of wind power plants of the modern type led from the plants of the 10 to 50-kW class in the early eighties to converters ready for series production with a rated power of 500 to 2,500 kW quite 15 years later.

So far, in plants up to 1000-kW systems with three-blade rotor, power limitation by stall effect, and asynchronous generator with fixed grid coupling have become clearly predominant. The prices for those plants well-approved and long established in the market vary from 1,500 DM/kW to 1,800 DM/kW rated power or 550 DM/m 2 to 750 DM/m 2 rotor circle area. Energy yields of 600 to 800 kW/m 2 and year can be attained in inland areas and mountainous regions of medium height, and 900 to 1,200 kWh/m 2 can be achieved on the coast in Germany.

For the time being, the corresponding costs are still higher for those plants that are being presently introduced to the market and belong to the 2,000 kW nominal rate type. Pitch control and variable speed plant operation are dominant especially in these systems. Strong tendencies towards gearless drive train conceptions and double fed asynchronous generator can be recognized currently. All in all a definite trend to technologically more subtle and innovative configurations is to be noticed. Differences in price are determined among other things by varying conceptions, rotor diameter and hub heights (e.g. coast or inland type).

3 GENERATORS AND GRID CONNECTION

For the mechanico-electric energy conversion in wind power plants only polyphase machines are used because of their robust construction. These generators can basically be divided into asynchronous and synchronous machines with direct grid connection as well as with static converter coupling. Figure 4 gives a survey of the converter systems that have already been approved of and will be used in the near future.

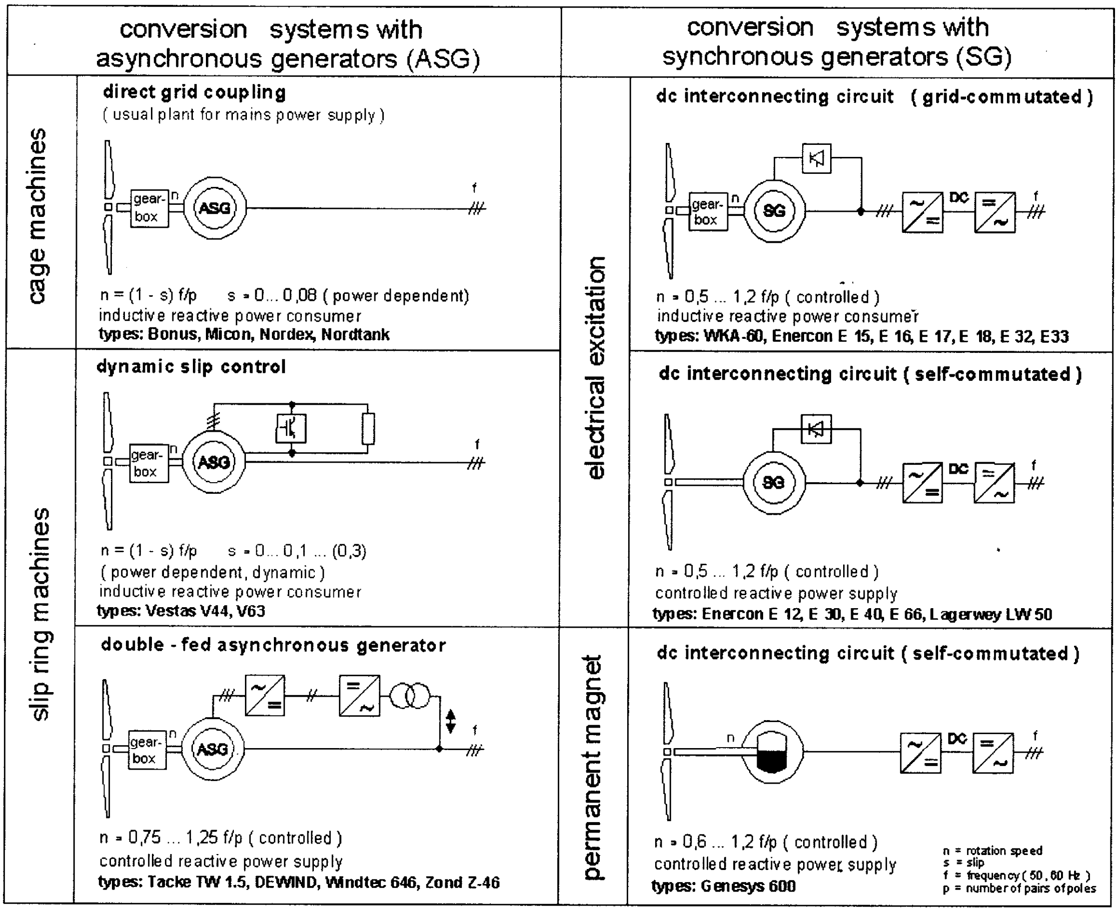

Fig. 4: Systems for converting mechanical into electrical energy

More than 90 % of the world-wide operated wind power plants are equipped with direct-grid-coupled asynchronous generators. In Germany, however, to a large extent both gearless synchronous machines with rectifier, dc link and pulse inverter, and doubly-fed asynchronous generators are applied.

In fixed speed units power and voltage fluctuations as well as the mechanical stresses on the drive train rise up to particularly high values. Speed-variable systems are affected by these stresses only in a considerably lowered kind, but require a higher technical equipment. Already relatively small speed ranges (e.g. 5 %) are enough to diminish power fluctuations and mechanical stresses essentially. Due to a large speed variation range (e.g. 50 % to 100 %), especially in part-load, the wind turbines can be operated close to their power optimum. In this way higher energy yields can be achieved. Thus, by the choice of the energy converter conception, the plant behaviour as well as the influences to the grid can also be strongly influenced.

3.1 Plants with Asynchronous Generators

Normally, asynchronous generators are directly connected to the grid on their stator side. Couplings via static converter systems are the exception. Cage rotor machines have got a largely rigid coupling with the grid. Variations are normally only possible within the nominal slip range. Nowadays, standard frame sizes between 50 and.2,000 kW generally have slip values around 1 %, and with increasing machine size smaller slip rates and thus higher efficiency are reached. Yet, the speed variation range is reduced accordingly. Mechanically induced power fluctuations may therefore cause voltage fluctuations in the grid. Specifically designed generators with increased slip rate result in smaller power fluctuations and lower stresses on the drive train and in the grid. A doubling of the nominal slip effects roughly a halving of the power fluctuations. Due to slip-proportional losses, however, larger machine sizes and a lower efficiency rate are the consequence.

Slip ring machines can be operated speed-variable in their slip range. Doubly-fed asynchronous generators offer the possibility of using the slip in over- and subsynchonus band. The further development of the necessary power electronics and converter technology increasingly provides the possibility to use technologically more subtle power converter systems at reasonable costs. A certain trend to such converter systems is to be recognised in plants of the 600 to 2,500 kW class. A direct grid connected stator winding of a doubly-fed asynchronous generator have the advantage that only 3 1 of the power have to be converted by the inverter-system, in contrast to the synchronous generators with frequency converter, mentioned in the following section.

3.2 Plants with Synchronous Generators and Static Converter

For the generation of electricity in conventional thermal power plants almost exclusively electrically excited synchronous generators are used. By this system active and reactive power can be adjusted to grid requirements. As wind turbines in their power behaviour are subject to the wind velocities or their gradients, synchronous generators are not operated directly connected to the grid because of their rigid speed coupling to the grid frequency. Their grid connection via static frequency converters enables a decoupling of the turbine speed from the grid frequency and consequently a speed-variable operation.

Up to 1993 synchronous generators were used only in combination with gearboxes. In the multi-pole generators introduced in the market, however, there is no gear necessary. So far both high-speed and slow-running synchronous generators with electric excitation have been produced.

Progress in material technology in general and in consequence a decrease of costs for highly qualified magnet material, though, allow to expect an economical employment of permanent excited synchronous generators in near future. Disadvantage of a smaller type of construction are enormous material costs and a higher expenditure of the inverter.

4 GRID COMPATIBILITY AND GRID INFLUENCES

The integration of wind power plants in the public grid may cause undesirable influences in these grids and may rouse disturbances in consumer units. In order to secure a disturbance-free public power supply system the utilities are obliged to require the compliance with the fixed limiting values for grid influences and grid interferences from the side of the feed-in producers and the consumers. Thus, the feed-in capacity of wind power, the so-called grid capacity, is essentially effected by.the grid compatibility of the supplying wind power plants. Under these circumstances grid influences matter a great deal due to voltage changes, voltage fluctuations, flicker and harmonics. Other influences such as voltage asymmetries, inter-harmonics, changes of the ripple-control signals, decreases of the power factor, as well as other disturbance emissions, yet play a subordinate role. Furthermore, changes of the grid impedance and thus the short circuit power are the result. In addition to that possible grid resonances and electromagnetic disturbances will have to be paid particular attention to.

4.1 Voltage Variations

The electric power of a wind power plant is subject to periodic and stochastic fluctuations which – due to converter conception – are transmitted directly, or after a short-term interim storage smoothened, to the grid. These power changes bring about corresponding voltage variations in the mains, which can be noticed e.g. as flickers.

Periodic power fluctuations, which are induced especially by high wind gradients, tower-created-turbulence effects, play a subordinate part particularly in speed-variable plants as to voltage influences. In contrast to that the power and voltage fluctuations caused by short-term and long-term wind velocity changes reach dominating values. The switch-in of the generators also produces accordingly high switched currents and so in consequence voltage fluctuations.

4.2 Harmonics

Various converter systems imply big differences of harmonics according to their grid connection. In general, even with an increasing number of different plants asynchronous generators directly connected to the grid do not result in a higher rate of harmonics, but in most cases harmonics and interharmonics already existing in the grid will be even reduced. In contrast to that the rate of harmonics will rise according to the number and the power of the grid-connected wind power plants with static converter.

6-pulse grid-commutated inverters cause considerably stronger grid disturbances than 12-pulse inverters, because the 5 th and 7 th harmonic do not occur with these. Self-commutated pulse inverters with a high pulse frequency in the kHz range have in contrast even remarkably lower harmonics. Those inverters are nowadays mostly used in wind power plants. Moreover, they provide a facility to give a backing effect to the grid.

4.3 Electromagnetic Compatibility

Also via magnetic and electric fields as well as by electromagnetic waves disturbances may be fed in the public mains. These wireless emitted disturbances will have to be particularly taken into account because of their electromagnetic compatibility (EMC). Especially in wind power plants with pulse inverters of high pulse frequency (10 kHz range) disturbance emissions will occur, unless adequate filters are used.

5 WIND PARKS

For wind parks which exclusively exist of plants with asynchronous generators static or rotating phase shifters provide the facility of an optimal use of the grid capacities brought about by dynamic reactive power or voltage controlling.

Owing to the common operation of directly grid-coupled asynchronous generators and speed-variable controlled plants with grid coupling via static converters technical and economical advantages for wind parks can be expected. Pulse inverter plants with a corresponding design are capable to take over the voltage regulation of similarly dimensioned asynchronous generators or to provide the required reactive power. Due to the increased short circuit power and the filtering effect of generator- and compensation-reactance there will appear distinctly reduced grid influences.

By means of resonance investigations critical states through current or voltage resonances can already by determined in advance e. g. during the phase of planning and design. Thus, by the choice of the grid coupling or by remedial measures a safe operation of wind power plants can be guaranteed even at high grid capacity utilization without the grid being influenced in a disturbing way. In combination with a different number of grid-connected plants impedance changes and resonance shifts will have to be considered. A further noticeable factor is that resonance points with a decreasing short circuit power will shift to lower frequencies and will result in higher impedances and – in case, of excitation – in larger voltage drops at the point in question. Thus, with decreasing short circuit power the operation of harmonic-loaded suppliers will increasingly get more critical.

In addition, for a grid-compatible operation of wind parks it is necessary to supervise the permitted values by an ingenious unit for park management both in the individual plants and at the grid's common coupling point. There ought to be a possibility to regulate both the grid voltage and the output power as well as to influence the connecting minute of the single plants via control. Moreover, for a grid-compatible and demand-oriented supply of high wind power it is useful to develop and integrate innovative, decentralised supply-oriented control and instrumentation technology, supervisory and failure prediction systems.

6 WIND PARK DESIGN

From the coastal regions it is well-known, that at location with good wind-power conditions rarely good grid connection conditions are to be found. This is connected strongly with the small population density in rural areas. However also in the inland regions one meets ideal grid connection conditions rarely. In many cases even the situation is more unfavourable then at the coast. High costs for grid reinforcement or even to build new transformer stations make the use of the available potential of wind-power more difficult. In addition the substantial length of time comes with the implementation of grid reinforcement measures. Therefore it is from large interest to have technical solutions those which make it possible to connect large amants of.wind power to the available medium-voltage system. In addition belong the appropriate technical proofs of the grid compatibility belong.

6.1 Wind park

In a existing wind-park 4 wind power plants were in operation. Further 8 wind-power plants are to be erected (Table. 1).

Table 1: plants in the wind-park

Number, Type	nominal power, kW	yield MWh/a	
1 Micron M750	$1 \cdot 250$	$1 \cdot 250$	*
3 Vestas V39	$3 \cdot 500$	$3 \cdot 850$	*
3 Micron M1500	$3 \cdot 600$	$3 \cdot 1{,}125$	#
5 Enercon E40	$5 \cdot 500$	$5 \cdot 950$	#
12 WPP	$\sum 6{,}050$	$\sum 11{,}200$	

* - in use # - in planing

An overhead transmission line, which is the connection to 4 km removed transformer station, crosses the location. The short circuit power in the connecting point is S" = 68.5 MVA.

After first calculations of the power supply company the grid capacity with the four systems in operation was exhausted. It must be examined thus whether and in which way further plants can be connected.

6.2 Wind-park design with consideration of grid influences

Locations of individual plants within a wind park are usually fixed by local wind conditions, geographical conditions and the existing infrastructure (starting ways, possession rights, grid connection possibilities etc). Beyond that, with increasing spreading of the wind energy and rising wind park power, configurations at meaning, which use the existing grid capacity optimally and so increase the energy which can be supply from the wind-power plants. By the example of a wind park is to be demonstrated on the basis calculated data, which advantages by the common operation of WPP with direct grid connected asynchronous generators and inverter-coupled synchronous generators are possible.

6.3 Optimisation of the power factor

Wind power plants with directly grid coupled asynchronous generators need inductive reactive power, which must be supplied by the grid or the reactive-power compensation equipment. The reactive-power compensation equipment of the asynchronous generators which are used in wind parks, as with WPP usually, are designed for the no-load operation point. This means that the plants both in partial load and in full load operation have a demand on inductive reactive power. Further also the transformers, which are used in the wind park, need inductive reactive power. The cable connections in the wind park work compensating, because these have a capacity. Fig. 5 shows the demand on inductive reactive power of the wind park in dependency of mean active power.

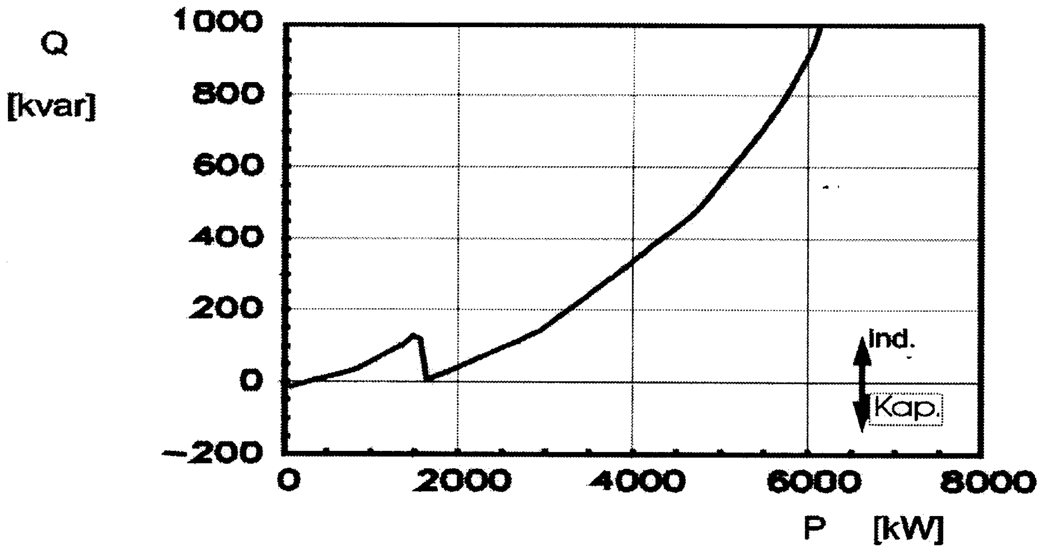

Fig. 5: The demand at inductive reactive power of the wind park in dependency of a mean supplied active power

As it is described in the next section, the feed-in of reactive power from the E40- plants is necessary only up to an active power of the 3.4 MW. Over 3.4 MW (Corresponing to a wind velocity of approx. 9 m/s) a voltage regulation is necessary. Nevertheless the grid can be relieved by a large proportion of the reactive power within the area to 3.4 MW. The wind park operates approx. 75% of its period of operation within the area to 3.4 MW.

6.4 Voltage changes and flicker

Voltage changes and flicker are generated by the fluctuating feed-in of the wind park in the power supply system. There reasons are connecting and disconnecting of plants, switching between generator levels, changes of wind velocity or the tower rope effect. The voltage changes caused by the entire wind field depends on the short-circuit power of the superordinate power supply system, the feed-in power and the power factor. While the supplied power is given by the wind velocity to a large extent, the power factor can be influenced by the Enercon E40, as it is described in 6.3. Fig. 6 shows the relative voltage change in dependency of the power factor with the feed-in of the nominal power of the wind park. From Fig. 6 is to be taken that the power factor must be between 0.77 ind. and 0.98 ind. not to exceed the permitted voltage changes in the medium voltage level of 2 %.

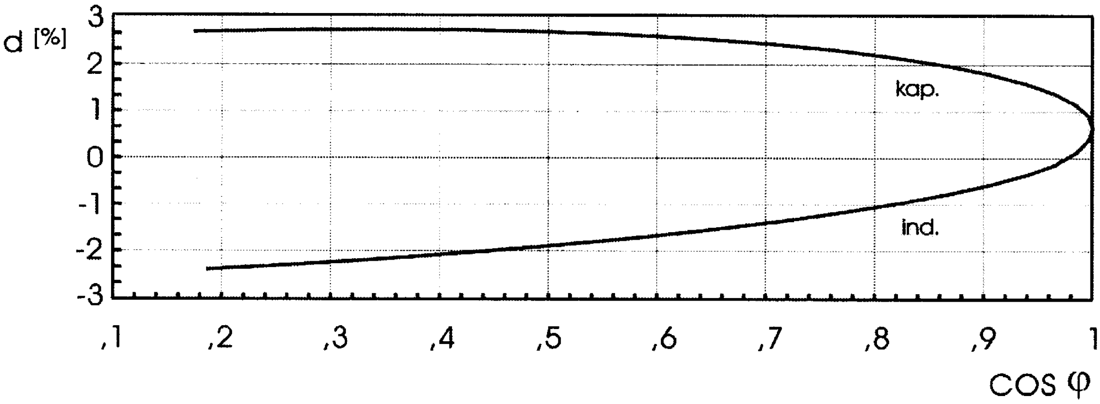

Fig. 6: The relative voltage change in dependency of the power factor.

To clarify the dependency of supplied power, power factor and voltage changes fig. 7 shows the characteristics of the wind park which is regulated by the E40.

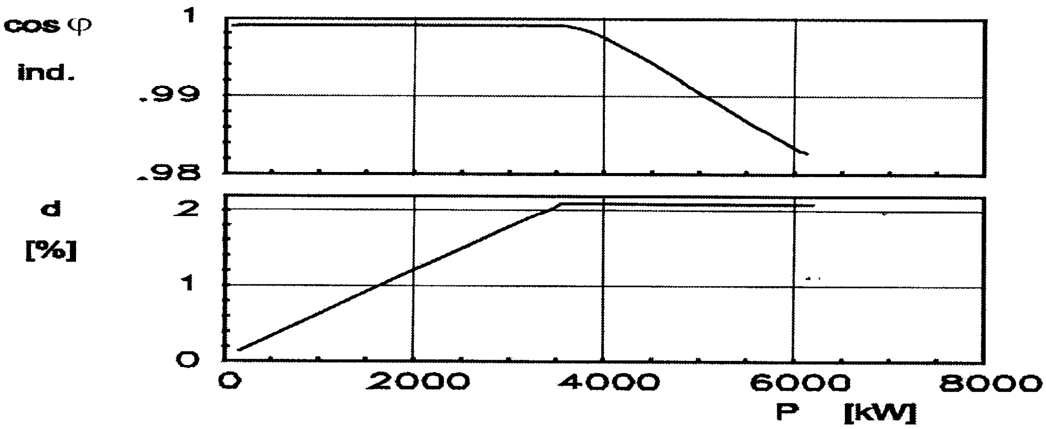

Fig. 7: Power factor and relative voltage changes in dependency of the mean supplied power of a controlled wind park

The regulation is so adjusted that the power factor is held as long as possible to a value close 1. Only if the voltage changes amounts bigger then 2 %, the power factor is regulated, in order to keep the voltage constant.

7 GRID CONTROL APPLICATIONS

Synchronous generators (Enercon, Lagerwey, Genesys, Frisia) or doubly-fed asynchronous generators (TW 1.5, Nordex N80, Vestas V80, Südwind, Dewind, Windtec), with grid connection through self-commutated pulse inverters, are increasingly coming into operation as mechano-electrical converter in wind energy plants and other small power plants. Such electronic power conditioning systems have also become standard in PV plants. They offer diverse control possibilities, like conventional power plants, in view of the energy output to the grid, for example, the adjustability of voltage and reactive power and also the control of active power feed-in.These technical possibilities were previously only used in rare cases.

The newly developed Grid Control Unit (GCU) has the task of adjusting the operational behaviour of renewable, decentralised generating plants, particularly of wind energy plants, to conventional power plants and ensuring their active participation in grid support (mains voltage, power factor, active and reactive power).

7.1 Test Site

The test site for the demonstration of the Grid Control Unit was selected because of the meteorological conditions and also the particularly favourable plant and grid configuration. Several renewable energy generating plants can be found near this test site.

It was imperative that different theoretical investigations and simulations were carried out in developing the Grid Control Unit, before the practical realisation. In the framework of these preliminary tasks, the structure of the relevant grid segment in the area of Friedland-Deiderode, as well as the data of the grid components.(transformers, switch station, cables and overhead lines) used there and the renewable power plants (WTGs, CPP), were recorded. This data formed the basis for the following simulation calculations (short circuit power, load flow etc.), with which the characteristic grid values were established. These grid values, established through calculations, were verified afterwards through measurements in the relevant grid segment.

Four wind turbines, which are situated on a wind-favourable mountain range near a central waste deposit, as well as a co-generation power plant (CPP) which is operated by the utility for the county government. These plants possess the following data:

Table 2: Renewable Power Plants

Plant Type	Quan-tity	Rated Power	Operator
WTG ENERCON E40	1	500 kW	EAM
WTG ENERCON E30	1	200 kW	Private
WTG AN Bonus 600	2	600 kW	Private
CPP Deutz-MWM	2	440 kW	EAM

Fig. 8 provides an overview of the 20 kV grid in the area of the test field.

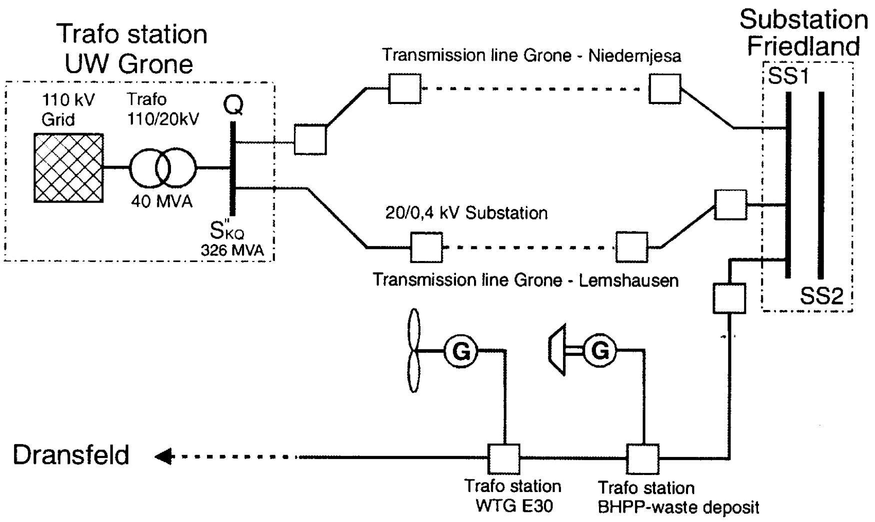

Fig. 8: Structure of the Grid Area

Because of its central location and function for the relevant grid area, bus bar 1 of the Friedland substation was selected as the grid point on which the Grid Control Unit should act. The relevant 20 kV grid segment is supplied over a 40 MVA transformer from the 110 kV grid, installed in the transformer station. At this grid point, the short-circuit apparent power Sk amounts to 326 MVA on the 20 kV level at an operating voltage of 20.8 kV. Bus bar 1 of the substation is decisive for the project, it is connected to the transformer station over two separately running 22.6 and 23 km long transmission routes. A large number of the 20 kV trans-former stations (23 and 27 pieces), for the supply of secondary low-voltage systems, are connected to both cables. All of the generating plants described above feed in together, over a 20 kV branch line on bus bar 1 substation. Thereby, the circuit length from the Friedland substation to the next generating plant (CPP) is 3.7 km long. The distance from the substation to the most far removed generating plant.amounts to approx. 5.5 km. Two further 20 kV cables also depart from this bus bar and supply a number of small low-voltage systems over branch lines.

7.2 Hardware development

Firstly, a hardware concept for the grid control system was to be established. The selected concept intends the grid control system to consist of a central GCU computer and decentralised data acquisition units, which are each stationed at the power generating plants. The data exchange, between the GCU central unit and the de-centrally located data acquisition units, takes place over a RS485 bus.

The hardware configuration of the grid control system is depicted in Fig. 9. The system consists of a central GCU computer and six data acquisition units.

Three of these units are connected to the RS485 bus directly over the data cable. Three further measuring points, on wind turbines, which do not have a connection to the data line, are coupled to the serial bus over radio modems.

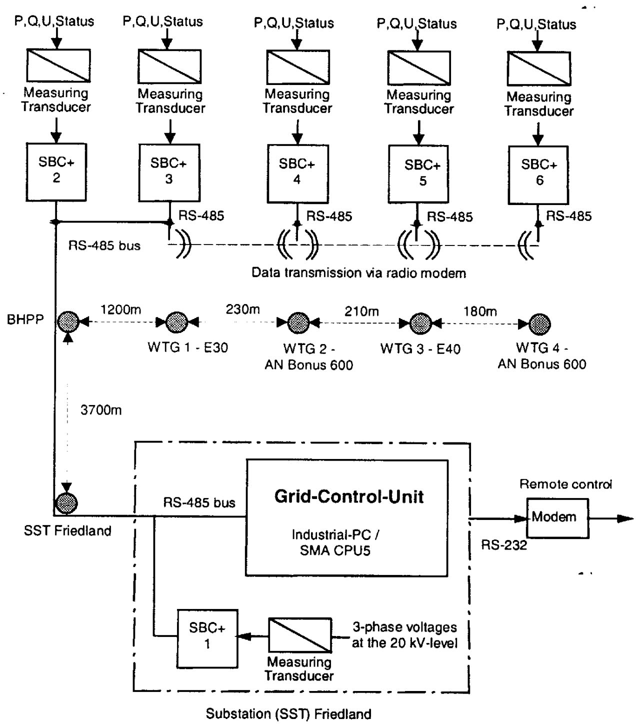

Fig. 9: Structure of the Grid Control System at the test site

Essentially, the three following devices are employed:

- the *Sunny Boy Control Plus* functions as data logger for immediate data storage and A-D conversion,
- the measuring transducer *SIMEAS T,* with current and voltage inputs, is utilised for power measurement and signal generation
- the *ELPRO 405U* radio modem is used for serial data transmission over great distances.

The data acquisition units, required for every measuring point, are installed in the unused cabinets or in the compact transformer stations of the wind turbines

7.5 Software development

In view of the diverse tasks and demands which are placed on the grid control system, and thereby especially on the GCU central unit, the development of software gains particular importance.

The software of the grid control system was programmed with *BridgeView 2.1* from National Instruments. BridgeView is based on the more well known software LabView and is a very efficient development environment for software application in the fields of data acquisition, automation and process control.

The newly developed application software for the GCU central unit possesses the following main functions: it is responsible for data acquisition, data processing and archiving and for the visualisation of the measurement values. As well as this, different functions are implemented in the GCU software for the averaging of selected measurement values and also the control algorithm for grid control.

Unlike LabView, BridgeView is equipped with an OPC interface. This is a standardised software interface which enables communication with different software applications over a so-called OPC server.

Figure 3 depicts the data exchange, described above, between the SBC+ data loggers and the GCU central unit.

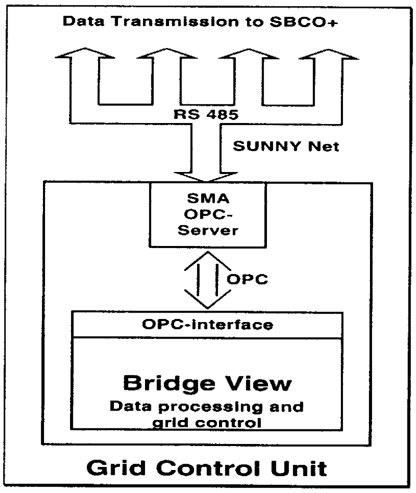

Fig. 10: Data Exchange between GCU and SBC+

8 RESULTS AND OUTLOOK

Fig 11 shows the influence of the grid voltage by the reactive power variation of the feeding system. Fig. 12 shows beyond the mode of operation of the controlling system with the intervened by regulation of the reactive power because of the voltage.changes. Altogether in peak and low load periods with high or low wind power supply the grid control leads to good grid conditions and high utilisation of the grid capacity.

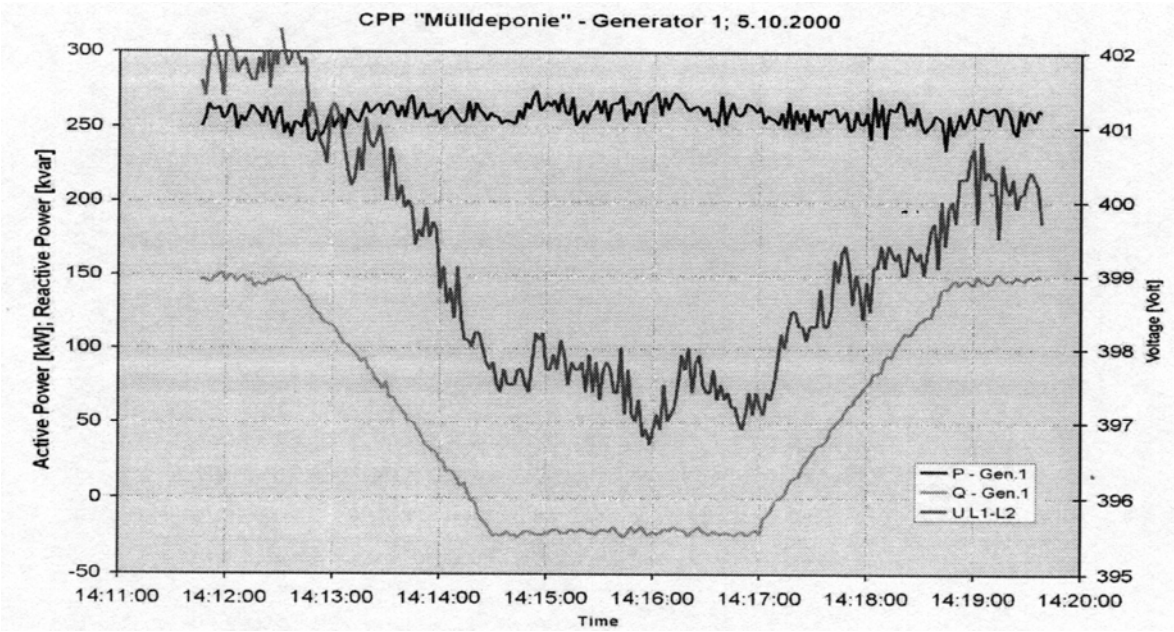

Fig 11: Voltage change by reactive power regulation

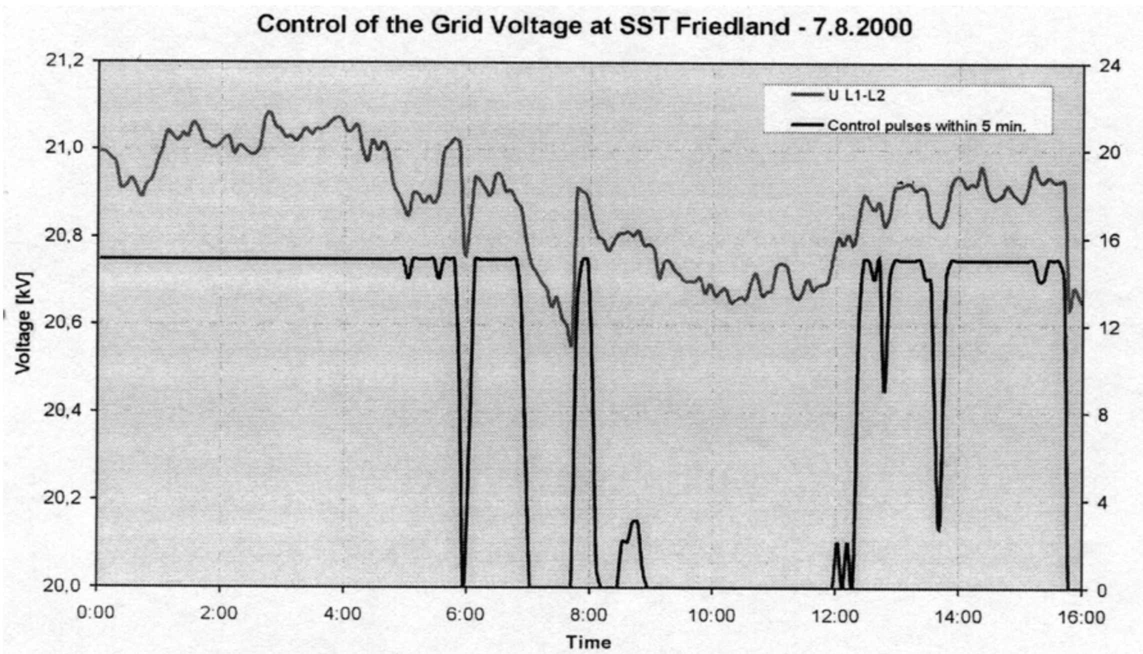

Fig 12: Mode of operation of the grid control

The market potential for the grid control system with renewable energy plants is considerable. The imple-mentation of this type of grid control system particularly offers advantages for large wind farms, at inland, off-shore or coastal sites with installed power of e.g. from 10 MW, and in highly loaded grid areas. Technical improvements can be achieved through grid support, higher grid compatibility, etc. This type of grid control system also offers excellent economical perspectives, through the elimination of grid extension costs and a possible compensation of the reactive power control in comparison to the small additional costs.

ABOUT THE WRITER

Siegfried Heier was born in 1948 in Stuttgart, Germany. He received his graduate degree from Stuggart University in electrial engineering in 1973 and his Doctor’s degree from Kassel University in 1993. Specialized in electrical power supply systems, electrical machines, automatic control engineering, grid integration of renewable energy systems and wind power plants. He worked as Scientist at Institute for Electrical Machines - Stuttgard University, as scientist of the art of teaching at Kassel University and as scentist with proffesorship. He has been Deputy Head of Institute Electrical Energy Supply Systems and Coordinator of Wind Energy Projects.