Dispersed Generation Modeling in SCADA Time Scale

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Abstract—**The rapidly increased installation of dispersed – especially wind – generation requires closer consideration of the impact on power system operation. Therefore, simulation models covering the temporal and informational ranges of system operation (SCADA) were developed and integrated into an existing training simulator, thus allowing power system operators to be trained under realistic circumstances. In particular, the wind generation models are described in more detail and their integration and application in the training simulator are reported.**

Index Terms—**Distributed generation, Modeling, Operator Training, SCADA systems, Wind generation.**

I. INTRODUCTION

The ongoing implementation of large scale dispersed and renewables based generation is accompanied by numerous simulative studies. The simulation tools widely used for such purposes are mostly designed for

- estimative studies such as energy harvest investigation or plant/grid design [1];
- detail studies such as the investigation of the impact of wind generation on power system dynamics [2,3] or the performance and interference of particular converters within a wind park,

thus covering either the long term time range and being based on condensed or aggregated plant data, or covering the short term time range and necessarily being based on rather detailed information of the particular components and grids.

In contrast, simulation in the time domain of *power system operation* requires

- representing the performance of the dispersed generation devices in particular with regard to their operational observability and controllability (SCADA),

and at the same time

- confining the input modeling data of the generation plants required to that portion usually available to grid control centers.

Following these principles, a library of various Dispersed Generation (DG) models was developed at the university Duisburg-Essen; all models are especially well suited to perform operational investigations of power systems comprising dispersed generation as for instance

- design of configuration and management of long/short term storage systems in renewables based small island power systems or in particular
- simulation of bulk power system operation under influence of large unpredictable sources such as wind farms.

For the latter purpose most notably the wind generation models have been incorporated into an existing operator training simulator (OTS); this gives the excellent opportunity to provide scenarios and sessions where power system operators can be acquainted to deal under realistic operational circumstances with all wind generation caused insufficiencies and inadequacies occurring in practical system operation.

II. DISTRIBUTED GENERATION MODELS

The realized concept provides a library of individual modular component blocks (Table I), consisting of

- stochastically operated primary sources (photovoltaic and wind),
- primary sources suitable for demand dependent operation (such as fuel cells and Diesel engines), also in combined heat and power operation,
- long and short term storage systems (e.g. hydrogen path, batteries, flywheels),
- electrical machines of different types,
- converters (AC/AC or DC/AC) of diverse characteristics (IGBT / thyristor based),
- reactive power compensation

from which the particular distributed generation plants as well as complete energy systems to be modeled can be individually composed.

All DG component models were originally developed under the Matlab/Simulink® environment. Therefore, some of them considerably exceed the time resolution required purely from the viewpoint of SCADA; on the other hand, this additionally allows

- to also use the models for diverse applications apart from the operator training simulator integration mentioned above;
- to at least have the impact on, and reaction of, local circuits such as protection relays etc. included in the overall simulator functionality.

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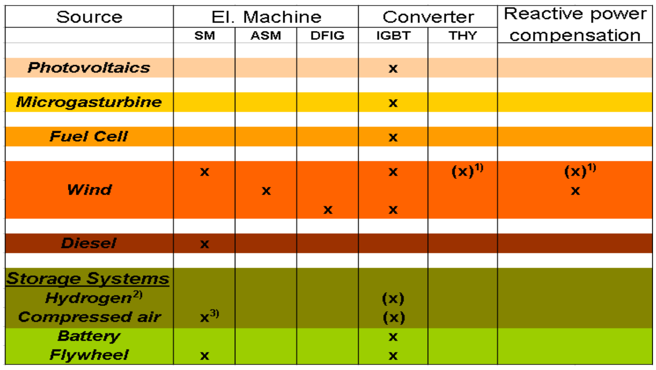
TABLE I
DISTRIBUTED GENERATION COMPONENT MODELS AVAILABLE



Source	El. Machine			Converter		Reactive power compensation
	SM	ASM	DFIG	IGBT	THY	
Photovoltaics				x		
Microgasturbine				x		
Fuel Cell				x		
Wind	x			x	(x)$^{1)}$	(x)$^{1)}$
		x				x
			x	x		
Diesel	x					
Storage Systems						
Hydrogen$^{2)}$				(x)		
Compressed air	x$^{3)}$			(x)		
Battery				x		
Flywheel	x			x		

1) For conventional thyristor converters reactive power compensation is required.
2) An IGBT-bridge may be needed to connect the electrolyzer to AC.
3) Synchronous generator and turbine.

The particular models are characterized briefly in the following. From the viewpoint of *power system operation*, among all types of dispersed generation *wind energy* is presently the dominating and most problematic sector. Thus, modeling of wind converters and complete wind parks is focused later in more detail.

The *photovoltaics* simulation model is based on location specific parameters such as

- geographical location of plant
- UTC time and date of simulation
- daily minimal / maximal temperature per month,

atmospheric effects such as

- absorption and scattering
- grade of cloudiness
- wind speed

and modules characteristics such as

- elevation / azimuth angles
- PV module surface
- cell type and module efficiency
- temperature coefficient of module efficiency
- tracking facilities if applicable.

The insolation variations are procured randomly.

Usual IGBT based *inverters* are considered with their loading dependent efficiency curves and – if necessary – the impact of DC voltage amplitude on the efficiency. The ranges of active and reactive power available are determined by design and rated power of the inverter, Fig.1. For inverters based on thyristors the *Q=f(P)* characteristic is applied. Transients below seconds are neglected.

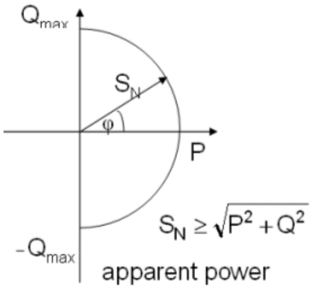


Fig.1. Active and reactive power ranges of IGBT inverter.

Generators (synchronous, induction and doubly fed types) are represented by their well known 1st order equations.

The *microgasturbine* and *Diesel* models are rather simple and regard

- nominal power
- upper and lower power limits
- efficiency as function of the electrical power output
- the engine's time constants.

Since the net calorific value of the used fuel is entered as parameter, the model is not limited to gas oil as fuel; rather, it can be utilized for petrol, hydrogen and propane gas as well.

The electrical part of the *fuel cell* model is based on

- nominal power
- upper and lower power limits
- electrical efficiency as a function of the electrical power output and
- time constant.

For possible combined heat and power applications of Diesel, microgasturbine or fuel cell the interrelation between actual electrical and thermal power output is considered by using mass flow and temperature of the exhaust gas as functions of the electrical power output, as well as its specific heat capacity and thermal time constant.

Energy storage can be a crucial component of DG supply systems in order to comply with power peaks, to reduce installed generation capacity and to balance missing long and short term coincidence between power generation and demand. Generally, storage systems can be divided into long term (weeks up to months) and short term (seconds up to days) applications. Various types of storage systems (see Table I) are modeled considering

- capacity
- maximum charging and discharging power
- time constant of the charging/ discharging process
- efficiency of the charging and discharging process and
- a fill level dependent loss factor.

All DG models developed can either be run separately – e.g., under their original Matlab-Simulink® environment for detail studies – or they can arbitrarily be transferred as components of superior structures such as complete power system simulation.

III. WIND GENERATION MODELING

Wind generation – currently the dominating DG sector in many countries – will be focused on in the following by describing functionality, aggregation and implementation of the developed simulation model.

A. Model of wind converter

The *input wind speed and direction* can either be taken from existing measurement files or computed from a given average wind speed and direction, an additive ramping function of adjustable slope, and a random component constituting gusts and turbulences [3]; thus, on demand the appearance of characteristic events such as passage of storms with rapid increase of wind speed and gusts – possibly demanding shutdown of wind converters by manual control or self-protection – can be realistically modeled. The mechanical power of the *turbine* is calculated according to the well known equation

$$P_{mech}(t)=\frac{1}{2}\cdot\delta\cdot c_p(\lambda,\beta)\cdot A\cdot v_{wind}^3(t) \qquad (1)$$

from the air density δ, the given rotor expanse A, the wind speed v_{wind} and the power coefficient c_p which in its turn depends on the angle of rotor blades β and the tip speed ratio λ. For any given turbine c_p can be determined either by measured characteristic curves if available or by use of equation (2) the coefficients of which were fitted from a given turbine as default:

$$c_p=c_1\cdot\left(\frac{c_2}{\lambda}-c_3\cdot\beta-c_4\cdot\beta^{c_5}-c_6\right)\cdot e^{\frac{-c_7}{\lambda}} \qquad (2)$$

As an example for the potential c_p range Fig.2 shows a three-dimensional diagram resulting from (2) for a 2.3 MW turbine.

Both stall and pitch control can be modeled. In case of an induction machine as generator, power can be pitch controlled only, whereas for synchronous and doubly fed generators both pitch and speed control (influence on λ, too) make an impact on active power.

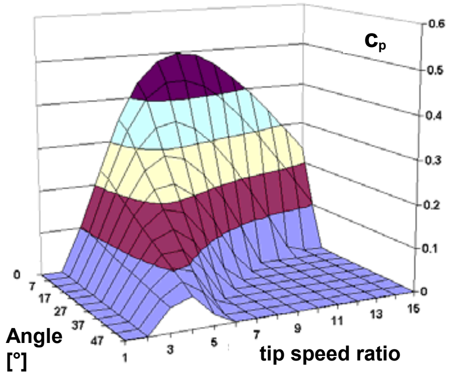


Fig.2. Range of $c_p = f(\beta,\lambda)$.

Under regard of a potentially existing *gear box* – considered by its efficiency and gear transmission ratio – the wind turbine model is coupled with the associated 1st order *generator* representation of induction, synchronous or doubly fed type; all inertias of the system are assigned to the generator. *Inverters* – if existing as for instance in the case of doubly fed generator type – are represented by their characteristics and limitations as described above and shown in Fig.1; these can be included in the generator's stator or rotor circuit equations, thus significantly affecting the wind converter's operating performance by separate control of active and reactive power; under consideration of the inverter type (IGBT or thyristor bridge) the complete wind converter's active and reactive terminal output power as well as their actual limits are calculated under consideration of nominal power and maximal current. Accordant to the particular wind converter under regard, control circuits for speed, pitch and reactive power are assigned to the model.

Fig.3 gives an overview of the realized structure and control loops of wind generation modeling. Auxiliary power demand – of special interest in the start up and shut down phases of the converter – is also considered in the simulation. Simulation time steps can be chosen flexibly, whereas reasonable values for the SCADA application regarded here are in the range of seconds.

B. *Wind park aggregation and effects*

Large *wind parks* consisting of numerous wind converters are simulated efficiently by a condensed and comprehensively parameterized single terminal *aggregated model*.

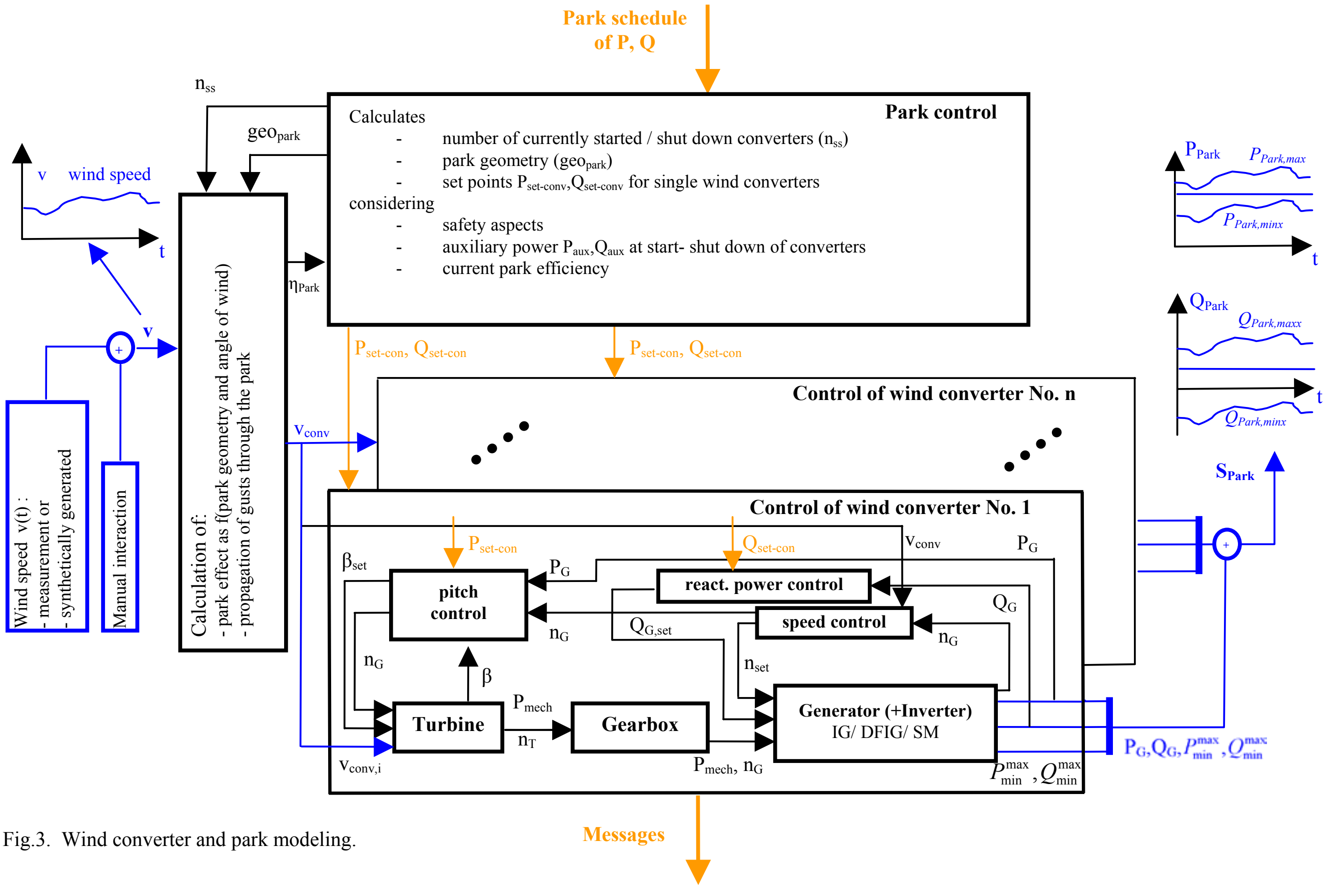


Fig.3. Wind converter and park modeling.

The actual operating points of the set of wind converters being aggregated to one condensed substitute model are calculated by a superior park control (see Fig.3), taking into account

- the actual schedule for active and reactive park power;
- the resulting number of converters currently running / out of gear;
- current park efficiency under regard of shadowing effects as well as the wind gust propagation through the park;
- park specific time constraints (start / shutdown procedure duration, minimal time between two switching actions);
- auxiliary power (P/Q) at start / shut down of converters
- safety aspects.

Furthermore, actual *short term* (pitch and speed control) as well as *long term* (start up / shut down) *active and reactive power limits* ("available power bands", see Fig.3) are calculated and thus available for superior power grid control.

Both wind dispersion in the park as well as shadowing effects – the latter impacting the global park efficiency – significantly influence the actual overall output active power and are in their turn specified by the park geometry and the related wind direction. Fig.4 shows the geometrical context of wind angle and distances in a rectangular park with *m* lines and *n* rows of converters.

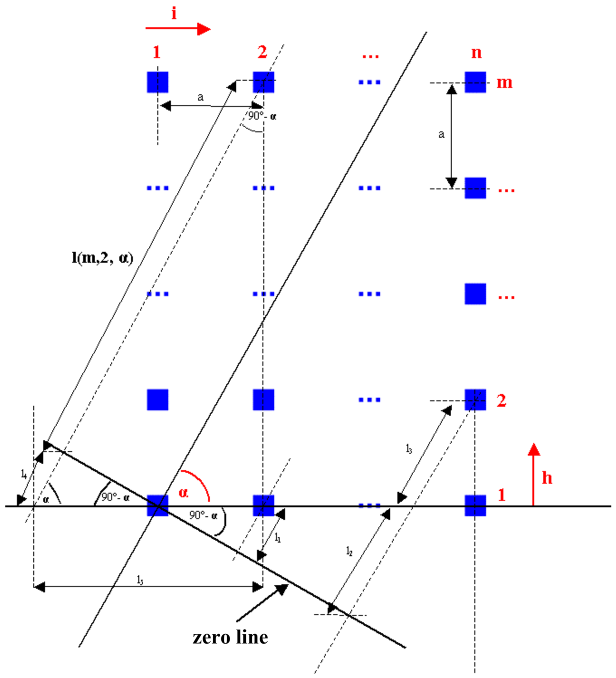


Fig.3. Geometrical context of wind park.

The angle dependent distance *l* of converters from the zero line is calculated by application of trigonometric equations according to Fig.3:

$$l(h,i,\alpha)=\frac{(h-1)\cdot a}{\sin\alpha}+\left[(i-1)\cdot a-\frac{(h-1)\cdot a}{\tan\alpha}\right]\cdot\sin(90-\alpha) \qquad (3)$$

The also calculated "average distance between converters in actual wind direction" and eq. (3) were combined to an approximation well fitting with real park efficiency measurement curves [4].

As an example, in Fig.5 the tremendous variation of the global park efficiency in consequence of wind direction angles of 0…90° (distance of 4 rotor diameters between converters in both "h" and "i" direction) can be clearly seen.

The effect of wind (gusts) propagation in the park area is treated globally, too: According to (3) the maximal distance of a converter from the zero line is calculated. Division by the actual wind speed delivers the time T_{park} for, e.g., a gust to permeate the complete park under given circumstances (wind angle and speed). Park output power changes whensoever the gust front impinges on a particular converter; this happens stepwise in the reality according to the given wind angle and speed (Fig.6, solid line) and can, as experiments proved, well be approximated for the substitute aggregated model of the complete park by a 2nd order time delay element with critical damping, Fig.6, dotted line: the natural frequency ω_{pT2} is determined by T_{park} (see above) and a park geometry dependent factor κ which was gained by fitting for various park sizes and geometries:

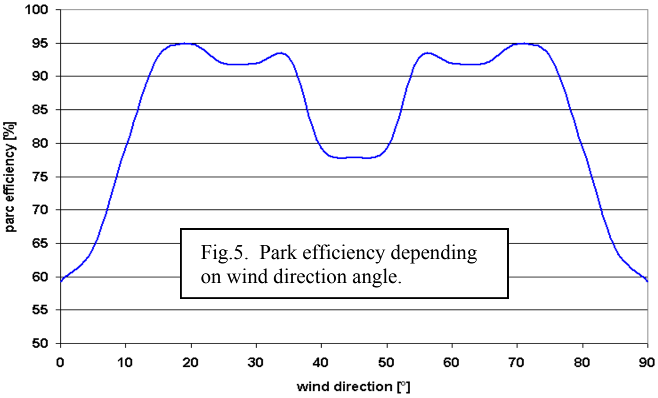


Fig.5. Park efficiency depending on wind direction angle.

$$\omega_{pT2}=\frac{\kappa}{T_{park}} \qquad (4)$$

with $\kappa \approx 4.1$ for larger parks (> 15 converters).

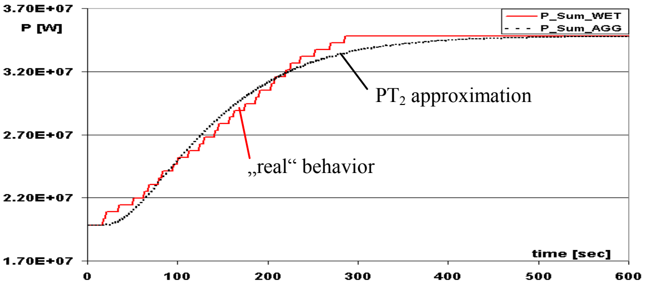


Fig.6. Approximation of global wind park output power resulting from wind propagation within park area after arrival of a gust.

C. *Wind generation modeling performance*

With the following scenarios the performance of wind generation modeling is intended to be shown. The scenarios are based on an assumed rectangular wind park equipped with *9*8 = 72* wind converters having the following technical data:

- Doubly fed induction generator type
- Pairs of poles: 3
- Generator speed: 700 … 1300 rpm
- Rated power: 2.3 MW
- Nominal wind speed: 14 m/s
- Diameter of rotor: 90 m
- Distance between converters: 4 rotor diameters
- Height of hub: 80 m
- c_p-characteristic as given in Fig.2

Scenario 1:

In the assumed wind park 39 converters are actually running, Fig.7a; previously given active and reactive power set points for the complete park are $P_{Park} = 58.7\ MW$ and $Q_{Park} = 1\ Mvar$ respectively, Fig.7b. With a wind direction of *20.2°* and average wind speed (see section III,A) of *10.5 m/s* (at hub height) *39* converters are running at approx. $P_{Conv} = 1.5\ MW$, $Q_{Conv} = 26\ kvar$ each; the generator speed is set at *1300 rpm* by speed control (in order to maximize yield).

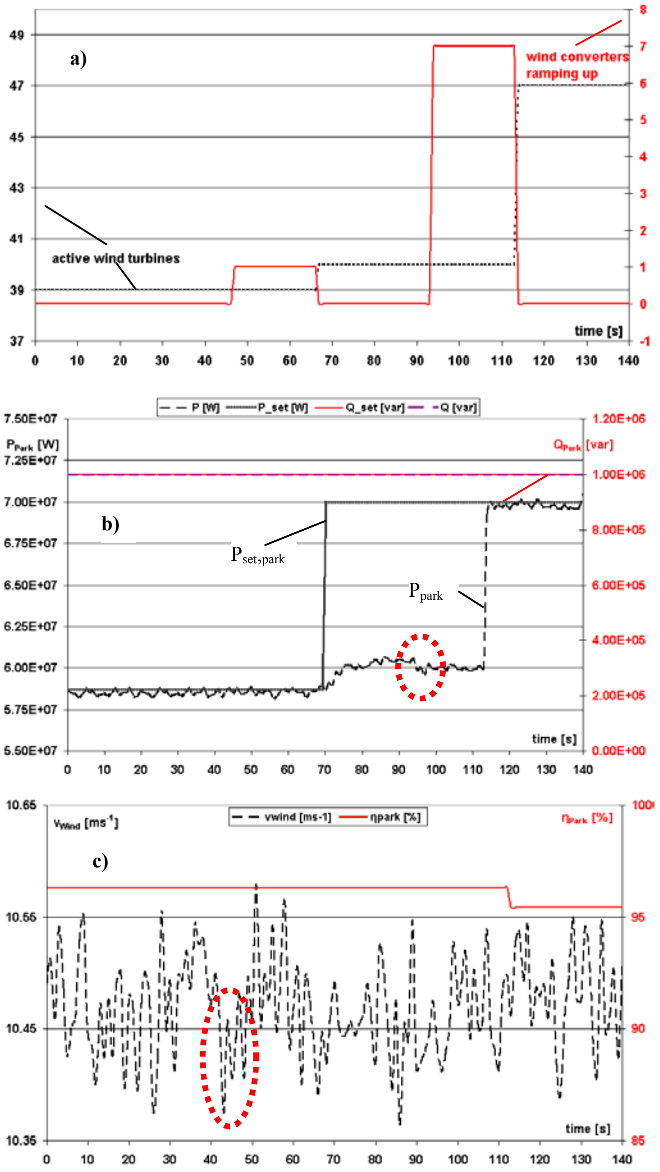


Fig.7. Simulation results for *scenario 1* (see text).

Due to relatively low average wind speed in the time interval *40…50 s* (marked in Fig.7c) the park control activates one additional converter at *t = 47 s* which is synchronized after the ramping time (set to *19 s*), Fig.7a. Short time later – at *t = 70 s* – a new active power set point of *70 MW* is given to the park control by operator's interaction, Fig.7b. Instantly pitch control tries to increase the output power which – due to the large control stroke – does not suffice and leads to activation of 7 more converters at *t = 94 s* under consideration of the minimal time span between switching actions (set to *47 s*); in Fig.7c the slight decrease of global output power in consequence of the auxiliary demand during ramping up (*50 kW* per converter) is marked, whereas the reactive ramping power demand (*50 kvar* per converter assumed) is instantly compensated by the IGBT inverters. After synchronization of the 7 additional units at *t = 113 s* – Fig.7a – the new power set point is met within few seconds, Fig.7b. Fig.7c also shows the reduction of the global park efficiency due to the shadowed position of the additionally activated converters. By the start up of 8 additional converters during this *scenario 1* the available short term active power band has increased from *61.5 MW* to *73 MW* approximately; with the given average wind speed of *10.5 m/s* the long term active park power available (all units operated) would be *113 MW* approximately according to the calculated power bands available for superior grid operation.

Scenario 2:

Starting from the operating point obtained from *scenario 1* running 47 converters at *70 MW* global power set point, in the *second scenario* – based on a new calculation of times – the angle of wind direction at *t = 25 s* begins changing linearly from *20.2°* to *10°* within 10 seconds, Fig.8a. This air stream change propagates through the entire park with wind speed – which is approximated according to Fig.6 –, thus progressively lowering the park efficiency from *95.4%* to finally *76.1%*, Figs.5 and 8a. Correspondingly the active park output power is reduced which is tried to be corrected by pitch control – see Fig.8b –, but this measure is not sufficient which leads to the requirement of consecutive automatic start up of 13 additional wind converters, Fig.8c. Due to time interlock between switching actions (see above), the release of auxiliaries supply and consecutive run up of groups of additional converters happens after a delay of 47 seconds. By pitch control the power of finally 60 units in operation is tried to be regulated to the still valid set point of 70 MW despite of the stochastic wind speed fluctuations. The long term upper active power limit is reduced from *113 MW* to 90 MW by the wind direction change.

Scenario 3:

In the third scenario it is assumed that – based on the final situation according to *scenario 2* – the average wind speed linearly decreases from *10.5 m/s* to *6 m/s* within 15 minutes. Fig.9 shows that consecutively by pitch control first, but because this does not suffice by start up of groups of converters the park control tries to keep the global park power at the given set point of *70 MW*. After appr. *300 s* all 72 converters are operated, and the further wind decrease cannot be compensated any more which leads to tremendous mismatch between given power set point and actual park power output.

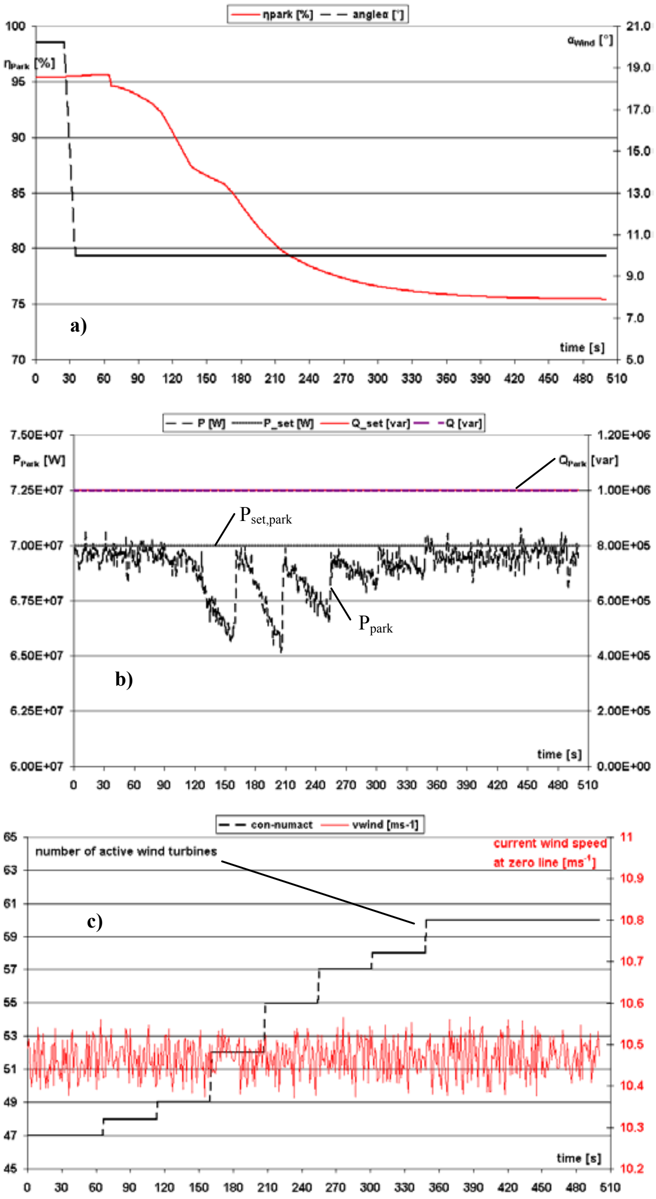


Fig.8. Simulation results for *scenario 2* (see text).

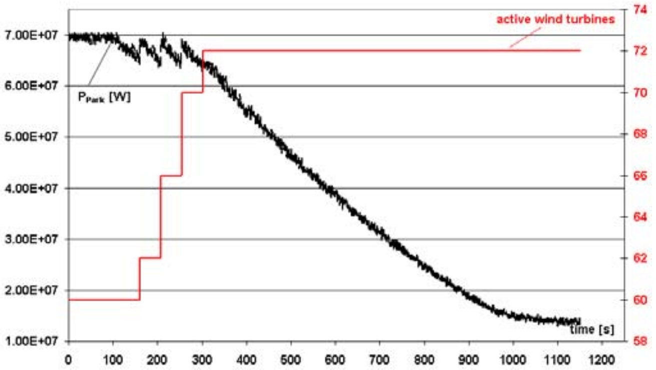


Fig.9. Simulation results for *scenario 3* (see text).

Smoothing of power fluctuations by short term storage

As completion of the wind generation modeling scenarios the effect of potential short term energy storage on active power output of a single 2*.3 MW* wind converter in case of strong wind fluctuations is briefly sketched. A *300 kW / 6 kWh* flywheel storage is assumed to be connected at the wind converter terminals; charge and discharge as well as storage time dependent losses are considered in the model with plausible values taken from literature [5].

Fig.10a shows the comparison of the active power output with (solid line) and without (dotted line) flywheel storage operated at a converter's power set point of *1.56 MW*. The assumed wind variations are in the range of *9…13.7 m/s* corresponding to low 5 up to high 6 Beaufort, Fig.10b, solid line. It can clearly be seen that even moderately sized short term storage is able to largely compensate the impact of wind fluctuations; only in cases of heavy gusts the rated charge / discharge power of the storage assumed does not suffice. Increasing average wind speed (as to be seen at $t > 60$ *s*) leads to approach of the storage charge limit – Fig.10b, dotted line – thus making the storage effectless (merger of solid and dotted lines in Fig.10a). This would have to be counteracted by raising the power set point.

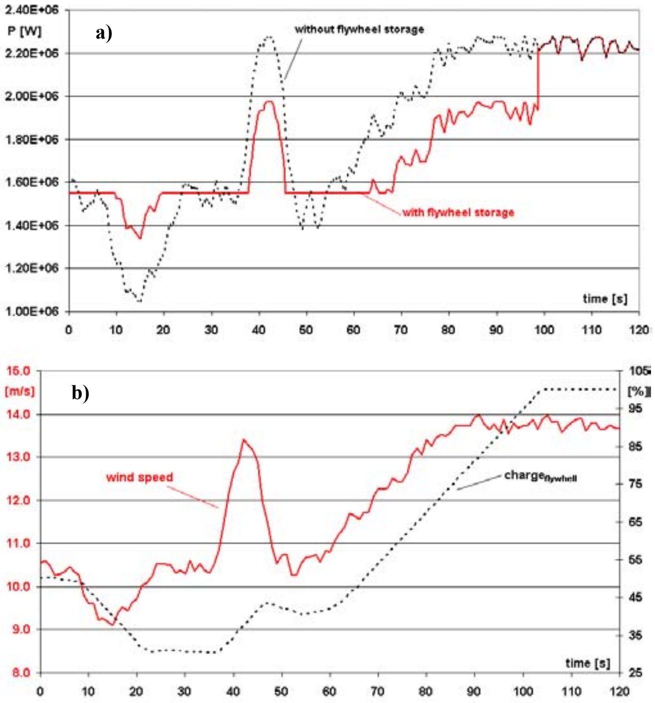


Fig.10. a) Output power with/without flywheel storage.
b) Wind speed and charge level of flywheel storage.

IV. TRAINING SIMULATOR INTEGRATION

An example of practical application especially benefiting from the SCADA capabilities of the DG models developed is their firm integration into an existing operator training simulator (OTS). An OTS consists of three principal components [6]: The *SCADA system* includes the operational user interfaces and the process data handling. The *event processing* (telemetric line interface) is used for the connection of, and the data exchange with, the models of the technical equipment such as switching and protection devices, automatic tap changers, generation units, load performance, etc.. The *power system calculation engine* simulates the physical performance of the entire power system represented by the actual grid topology retrieved from the SCADA system and the physical parameters of all equipment (el. grid, generation plants, load trajectories etc.) [6]. The calculation results are sent back to the SCADA system as "measurement values".

Additional features of the OTS used here are representation of hierarchical power system control organization comprising several control centers in parallel – also capable of splitting grid control and generation control –, powerful scenario management as well as flexible setup by use of an efficient data system [7]. The training simulator is especially designed to provide operational realism within SCADA time frame representing mid- and long-term performance of the entire physical system including grid, generation and load situation under 'normal' as well as 'abnormal' up to total blackout operational conditions [6].

For OTS integration the DG models developed under the Matlab/Simulink® environment, in particular the specified wind generation model, were converted into C code using the Real Time Workshop©. The automatically generated C code was then adapted to fit into the structure of the OTS calculation engine coded in Fortran; clear interfaces were defined to handle the wind model as a "plug-in" which can arbitrarily be extended or replaced. Instances of all wind converters and parks regarded are compiled into the simulation engine as a monolithic block during simulator setup to achieve rapid calculation which is required for on-line operational capability. The interfaces for data exchange comprise

- *Parameterization:* structural data (types, sizes and limits of wind turbines, configuration of parks etc.) is entered and assigned to the particular models in the frame of simulator setup for the actual power system under regard.
- *Wind profile:* time series of wind speed values can be created automatically (by specifying an average wind speed which is randomly varied) or given as measurement files; propagation and shadowing effects are considered globally as described above. These profiles can be impacted by the trainer by, e.g., critical ramps or sudden gusts during simulator operation.
- *Control:* operational data at runtime (control commands, alarms and status messages, active and reactive power output as well as bands of power available, terminal voltage, frequency) is processed as SCADA information corresponding to that of conventional equipment. Via an additional DG operational surface the operators / trainees can interactively control dispersed generation units during training sessions (set points, start / shutdown commands etc.) [8]. Additionally full automatic operation is possible as well.

The interfaces provided also include models to represent the DG operational control behavior: auxiliary demand, synchronization, automatic operation, protection, as well as wind speed distribution within different geographic zones of the power system area under regard.

V. APPLICATION FOR TRAINING COURSES

For training sessions the OTS is set up with the given power system comprising all entities involved, i.e. control centers of the power system(s) under regard, neighboring control centers of interconnected systems, power production control centers including dispersed generation if applicable, and others. Thus, operational realism of high fidelity is achieved in the training sessions including the interactions and communications between operators of the particular entities [8]. Training is supervised from the trainer's desk allowing the trainer to invoke accidental events (e.g. system failures, sudden gusts or wind speed change). The training sessions combine theoretical lectures and practical exercises to get operators acquainted with the newly arising operational tasks and to give them hands-on knowledge and experience in operating power systems highly penetrated with distributed generation, especially wind generation.

VI. CONCLUSION

Dispersed generation plays a more and more significant role in the operation of both small local as well as large interconnected power systems. Complementary to available simulation approaches, a library of dispersed generation models especially covering the SCADA time scale was developed which combine concise parameterization and potential aggregation with the capability to be integrated into superior power system simulation structures and external operability. The practical application was proven in particular with the implementation of the developed wind generation model into an existing operator training simulator, thus procuring a facility to get the operators acquainted with the imponderability of large scale regenerative generation.

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