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Agent-Based Simulation of Wind Farm Generation at Multiple Time Scales

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1. Introduction

Since the past decade, energy systems are undergoing a deep paradigm shift, caused by the liberalisation of energy markets, the introduction of renewable energies, and the emergence of new, distributed producers that feed into the grid at almost every level of the system.

The general trend towards the introduction of renewable energy sources in the industrialised countries implies one of the greatest changes in the structure of energy systems. These systems are moving away from a centralised and hierarchical energy system, where the production follows a top-down principle under the strict control of the electricity supply companies towards a new system where diverse actors influence the energy supply. The production is no longer limited to large energy providers, as small decentralised producers now exist and inject energy at much lower voltage levels than before. These energy systems are suffering the consequences of such a paradigm change. This change basically consists in new regulations and the introduction of new energy production technologies that transform traditional centralised systems into decentralised ones. This whole process is part of the framework of the fight against the causes of climate change, which is mostly due to CO₂ emissions. This paradigm change encompasses new tools and methods that can deal with decentralised decision-making, planning and self-organisation. The large amount of new actors and technologies in the energy production chain requires a shift from a top-down to a more bottom-up approach.

Multi-scale simulation systems offer several advantages over classical models. The ability to run simulations on different time scales using the same model is an important issue for the upcoming modelling of energy systems. The main advantages are that there are fewer models and no need to port data between platforms. This leads to a more efficient simulation run and decision-making support. The challenges of these kind of simulations are that a multi-scale model for the moment will not be as accurate as a purpose made model. So, the modelling method, the parameters, etc. included must be carefully chosen to ensure both flexibility and accuracy.

The work presented in this chapter concerns the wind generation module of an agent-based model for integral energy systems (developed at the European Institute for Energy Research

(EIFER) in cooperation with the EUI de Vitoria-Gasteiz). It is based on earlier works where the model is already partially presented Kremers et al. (2009).

The proposed model aims to represent the wind power production by modelling wind farms consisting of wind turbine units on different time scales, ranging from short (minutes) to long-term simulations (months), taking into account fluctuating wind speeds and technical reliability. The model is able to compute the aggregated output power of the wind farm influenced by different random factors and can thus recreate a realistic power unit to be used in integral energy system simulations. The simulation of this data is performed in real time, so that the power output at a specific time can be reproduced and injected into the energy system simulation.

2. Agent based modelling for energy system simulation

Agent-based modelling (ABM) is a technique that is gaining more and more importance during the past two decades. An agent-based model combines the use of small, reproducible entities called agents, that interact among themselves and with an environment and lead to complex system behaviour, like emergence. These models possess several characteristic, as they can create a wide solution space and allow the appearance of distributed intelligence. They are commonly used to obtain decentralised solutions where a central controlled solution method is not applicable. These include open or at least very dynamic environments, systems constituted naturally by agents and systems that have to be easily extendible or scalable. A detailed introduction to the subject is given by (Wooldridge, 2009).

Basically, ABM focuses on the modeling of systems at the local level through the definition of their elementary units (called agents) and their interactions. These units are intended to be modeled in a simple way, while the complexity of the system is an emergent property of their interactions. There are three main groups of actions that must be modeled:

1. Sensing the environment: Agents are capable to acquire information of the local environment through sensors.
2. Taking decisions: Each agent can autonomously decide what action should be taken regarding its local information to fulfill his objectives.
3. Reaction to the environment: Through actuators, the decisions made by the agents have a response on the environment. Therefore a feedback loop exists between the environment and the agents.

It has to be noted that the decision making process can be of complex nature, but does not have to. In the case of the wind turbine modelled in this paper, we will see that this process is quite simple. It is basically reduced to checking the status (failure or not) and produce electricity if there is enough wind.

The agent-based modeling approach has been applied successfully to a large number of fields (e.g. biology, sociology) during the last decades. Nevertheless their application in energy systems is nowadays still marginal. There exist some approaches related to management and control of power grids, demand modelling and electricity markets. In the field of production though, few applications can be found (e.g. Chappin & Dijkema (2007), which is though closely related to markets and CO₂ emissions).

Agent-based modelling can be easily combined with other approaches, because of its nature. So, an agent can include a decision algorithm which is based on a completely different approach, as for example, System Dynamics or Discrete Event models. This possibility to use agents in an multi-method environment is an additional benefit.

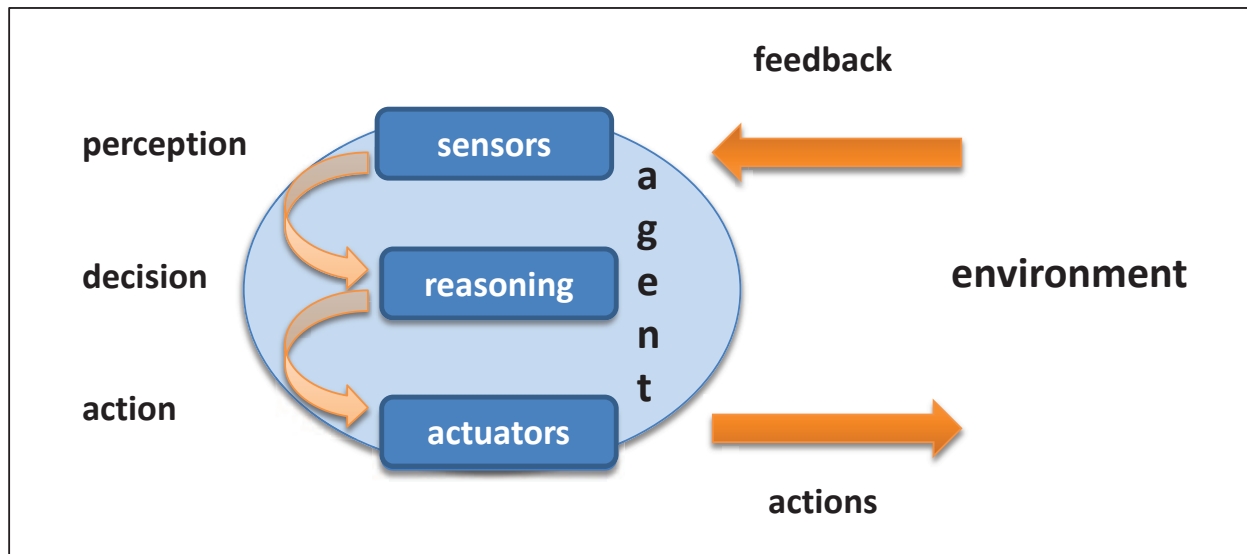


Fig. 1. Structure of a generic agent (adapted from Wooldridge (2009))

In order to integrate the wind power production into an integral energy systems simulator, an simplified but still enough accurate simulator for wind speeds and generation was necessary. The agent based approach was chosen because of several reasons:

- the facility to integrate heterogeneity among the agents
- the possibility to create a modular structure which is interoperable with other platforms (using JAVA)
- the ability to represent different time scales with the same model
- the possibility to use more than one approach and combine them in the model
- the easy scalability of the model (allowing to add and remove agents dynamically, e.g. failures, scenarios of enlargement of the farm, etc.)

3. Stochastic wind speed simulation

Generating realistic wind speeds is an important task when the effects of wind production in an electricity system have to be analysed. The fluctuating wind speed is the origin of the temporal variation of the power injected by this production type and thus has direct effects on the production-demand balance and the grid stability. One of the challenges of wind speed simulators is mainly to reproduce the different scale term fluctuations, as described in (Nichita et al., 2002). To this end, different models have been developed during the past decades. The model chosen here is built up in two steps, comprising two components, a slow and a fast called and is the same as in (Bayem et al., 2008) with some minor modifications. More accurate wind models (that take into consideration e.g. long-term (Billinton et al., 1996) or cross-correlations (Allerton, 2008)) are available, but this one should be sufficient for the purposes of this work. An overview of some more approaches can be found in (Aksoy et al., 2004). It is important to add that to get a realistic simulation of a specific site, records of historical data are needed to obtain the parameters of the model, as even the best model is useless if not accurately fitted.

3.1 The slow component

The first part, which was already used in a previous work of the author (Kremers et al., 2009; Viejo & Kremers, 2009) is a generator of hourly mean wind speeds. This time series model is based on an ARMA (Auto-Regressive Moving-Average) model which is given by

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \dots + \phi_n y_{t-n} + \alpha_t + \theta_1 \alpha_{t-1} + \theta_2 \alpha_{t-2} + \dots + \theta_m \alpha_{t-m} \quad (1)$$

The data series y_t is used to build the model, i.e. to calculate the auto-regressive ϕ_i ; $i = 1, 2, \dots, n$ and the moving average parameters θ_j ; $j = 1, 2, \dots, m$. $\{\alpha_t\}$ is a Gaussian white noise process with zero mean and standard deviation of σ_α which is part of the moving average (MA) part of the model. Considering the orders, the process is referred to as ARMA(n, m). The parameters used in this work were chosen from an ARMA(3,2) approach, but the model was developed up to ARMA(4,3) and can be easily adapted to other orders. For example, a pure AR(2) model (Aksoy et al., 2004) which was also implemented before can be seen as a as an ARMA model with $n = 2$ and $m = 0$. The order of the model depends on the quantity of historical data available, since, if there is only a little data, an accurate model cannot be reached even with higher orders. There is a range of literature available regarding parameter estimation. Fitting models are normally based on the least squares regression methods that try to minimise the error value. For AR parameter estimation, the Yule-Walker equations are widely used.

The simulated hourly mean wind speed (Billinton et al., 1996) can be obtained by

$$\bar{v}_1(t) = \mu + y_t \quad (2)$$

where μ is the mean wind speed of all the observed data. If observed hourly mean speeds μ_h and standard deviations σ_h are available, a more realistic simulated wind speed can be calculated as:

$$\bar{v}_2(t) = \mu_h + \sigma_h \cdot y_t \quad (3)$$

The method is explained in detail in (Billinton et al., 1996).

3.2 The fast component

Being able to compute hourly mean wind speeds might be enough for several applications of the energy systems model, but as temporal scalability was a requirement for the latter, a more detailed model was needed. The ability to reproduce realistic wind speeds in real time can be gained by adding a so called fast component to the previously described slowly varying signal. For this purpose turbulent phenomena are modelled by a highly fluctuating signal given in (Bayem et al., 2008) by the following differential equation:

$$\frac{dw}{dt}(t) = -\frac{w(t)}{T} + \kappa v_h(t) \sqrt{\frac{2}{T}} \zeta(t) \quad (4)$$

where $T = L/\bar{v}$, being L the turbulence length scale, κ a factor that depends on the geographical location of the wind turbine site (Welfonder et al., 1997), $\zeta(t)$ a Gaussian white noise and $v_h(t)$ the hourly mean wind speed. The equation describes a stationary Gaussian process. This component allows us to generate a time continuous signal that represents a real time wind speed.

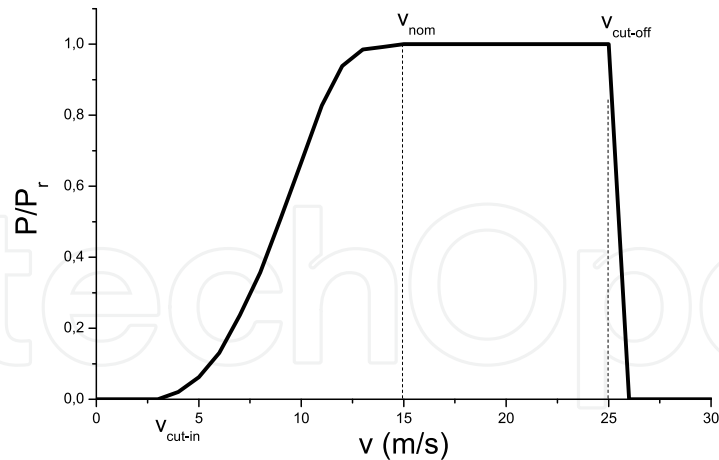


Fig. 2. A sample power curve. P_r is the rated power

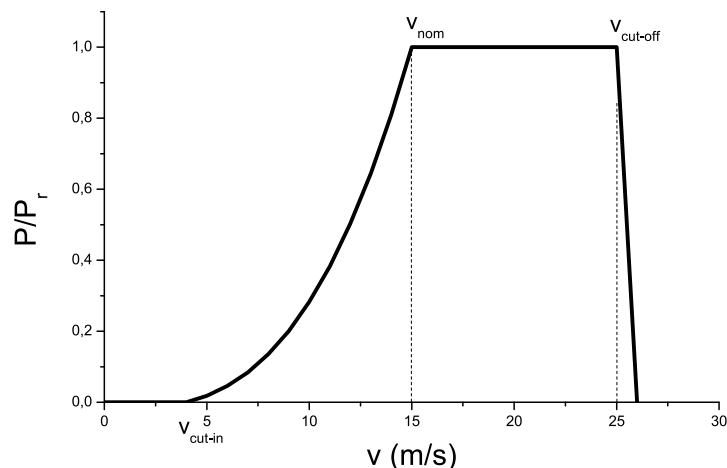


Fig. 3. Polynomial approximated power curve

4. Turbine model

There are plenty of technical models for wind turbines. The model used here is a generic approach, which takes into consideration the agent-based approach of the framework. As the wind turbine has to be able to be replicated (in order to create wind farms with tens or even more turbines), a simple model was chosen to ensure fluid simulations. The basis of this model is the relation between the power output of the turbine, which is a function of the wind speed actuating on its rotor blades. Three different models that are commonly used have been identified in the course of this work. The *real model* is not a mathematical model itself. It just shows the $P(v)$ curve of a specific turbine - based on the manufacturer's data. In general, the curve has a shape similar to the one shown in Figure 2.

The curve shows the typical profile of a wind turbine. The cut-in speed is the minimum wind speed at which the turbine can start working, the nominal wind speed is the point at which rated power of the turbine is achieved. This power is normally almost constant up until the cut off wind speed is reached, at this point the turbine must be shut down to avoid damage caused by too strong winds. So, four principal working states can be defined as:

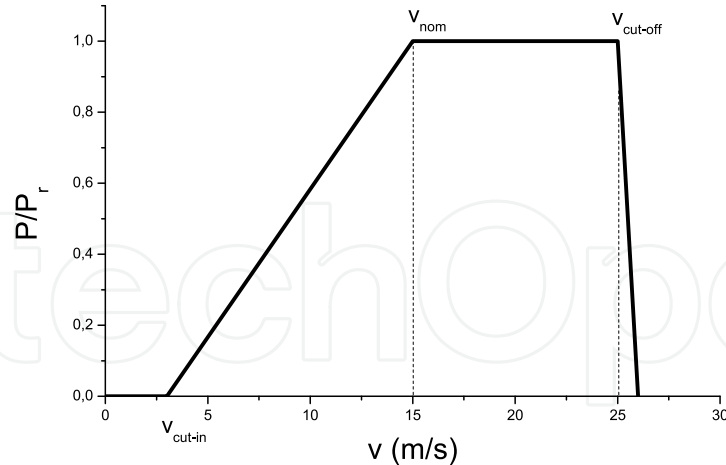


Fig. 4. Linear simplified power curve

- Stopped: for $v < v_{cut-in}$
- Partial load: for $v_{cut-in} < v < v_{nom}$
- Rated load: for $v_{nom} < v < v_{cut-off}$
- Cut-off: for $v > v_{cut-off}$

The transitions between the states are smooth because of the technical characteristics of the rotor and generator in the real curve. The most interesting state to be observed is the partially loaded state, where the turbine shows a non-linear $P(v)$ dependence. Here it can be observed the start dynamics of the turbine as well as the adaptation to the fully loaded capacity at rated speed. This phase can be approximated by a polynomial term as shown in Figure 3. The polynomial model assures the curved shape of the curve, but the trace just before achieving the nominal wind speed is idealised. The linear approximation of the curve, which is used in more simplified models, can be defined by linearly interpolating the values for v_{cut-in} and v_{nom} . It can be seen in Figure 4. The last model might have use when only the characteristic wind speeds of the turbine (and no power curve) are available. Though, the polynomial approach can be also be used as approximation by using a polynomial of degree three as described in (Chedid et al., 1998).

The cut-off state is reached when the turbine gets shut-down because of exceeding $v_{cut-off}$. Further, a $v_{cut-back-in}$ parameter can be defined for the model. Its value denotes the wind speed, at which the turbine gets back to work after having entered the cut-off state. This value adds the restart behaviour of the machines after strong wind periods.

Being MTBF the Mean Time Between Failures of a unit defined by

$$MTBF = \frac{1}{\lambda} = \frac{\text{operational time}}{\text{number of failures}} \quad (5)$$

where λ is the failure rate. Using MTBF allows modelling the availability of a wind turbine over time. The equation describing the Mean Time To Recover

$$MTTR = \frac{\text{down time}}{\text{number of failures}} \quad (6)$$

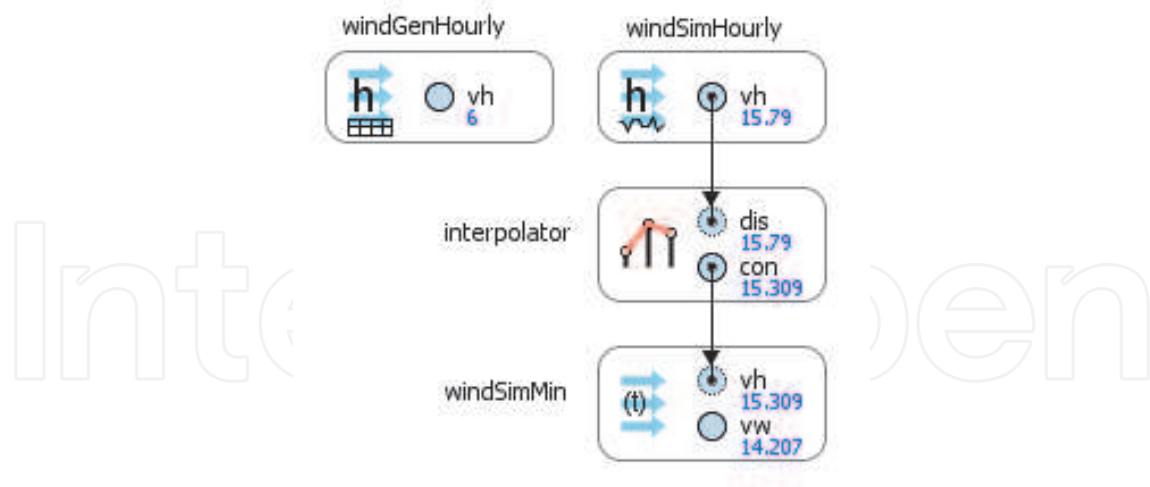


Fig. 5. Modules of the wind simulator

is also included, where *down time* is the time when the turbine is inactive because of a failure, maintenance or reparations. The MTTR is so an indicator for the average time until the unit gets started up again after an incident. Considering these two parameters, a failure model is integrated into the turbine model. The rates (inverse values of them) are used to determine failure probability used in the transition among states.

5. Implementation

5.1 Wind simulator implementation

To build the wind simulator, different modules were developed in Anylogic, a software package from XJ Technologies (XJ Technologies, 2010). Each module was encapsulated to work independently and has well defined interfaces. This allows for different releases for the same module which can be easily replaced.

The wind simulator modules are the following:

- **Hourly speed module:** The hourly speed module has to provide the hourly wind speeds. In the current model, there are two possible implementations:
 1. The hourly wind speed generator is a module that allows using a given dataset for the speed generation. Normally it uses historical as input, which gives hourly mean wind speeds. It can also be used to test extreme situations by simulating extreme conditions. Further, it allows for replicable simulation runs, by using the same time series as input for multiple simulations.
 2. The hourly simulator implements the slow component ARMA model described in section 3.1. The parameters of the model are the hourly mean wind speed μ_h , the hourly standard deviation σ_h , the standard deviation σ_α of the $\{\alpha_t\}$ process and the AR and MA coefficients $\phi_1 \dots \phi_4$ and $\theta_1 \dots \theta_4$, respectively. The output generated is the hourly mean wind speed $v_h(t) = \bar{v}_2(t)$ by implementing the method described in Equation (3).
- **Detailed module:** The detailed module is needed for short time-scale wind simulations. The present release is a simulator. It is the implementation of the fast component using an average hourly wind speed as input. The input signal $v_h(t)$ is superposed with some

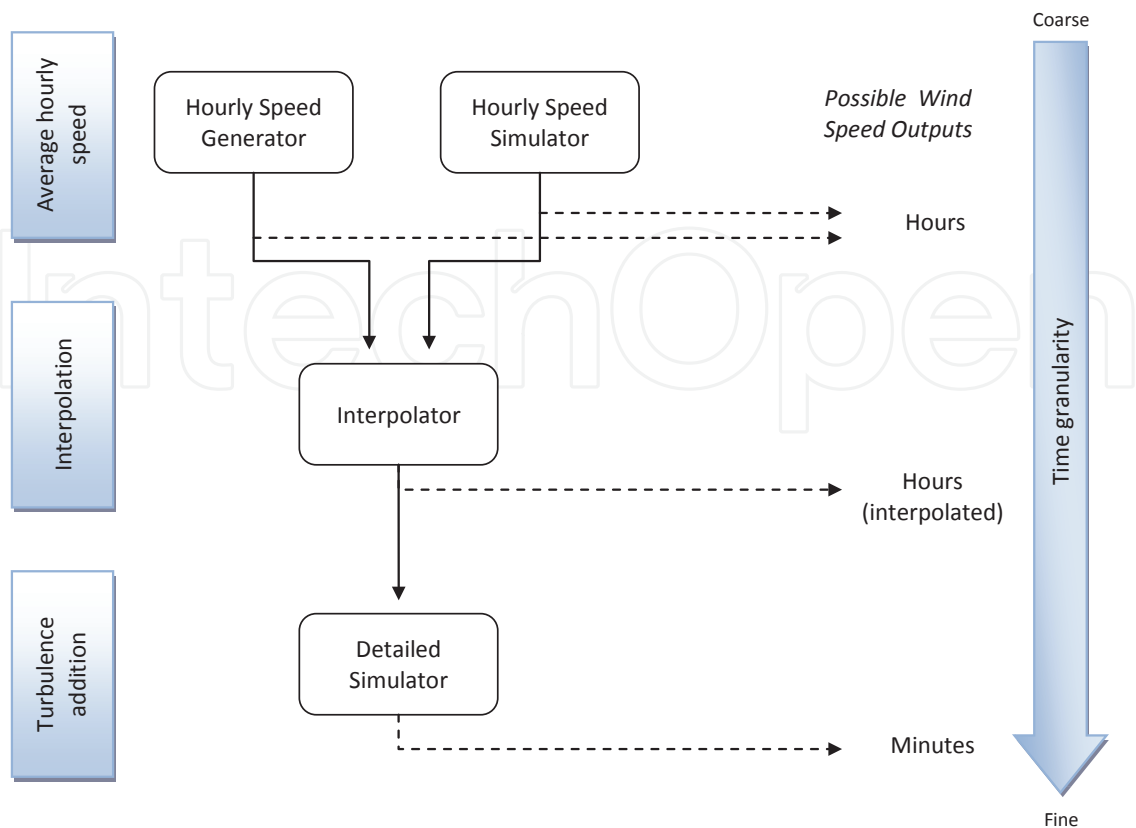


Fig. 6. Time granularity of the model

turbulences. This can be fitted to real turbulence data by the parameters κ and L described in Section 3.2. The solution to the differential equation is computed by Anylogic's engine using the Euler method.

- **Interpolator module:** The interpolator is necessary to generate smoothed final wind speeds. As the hourly mean wind speed is calculated or given in discrete values for each step, the change of the mean would cause a non continuous piecewise function with abrupt jumps in the final wind speed signal. Thus, a linear interpolation for the hourly wind speed was implemented. The module owns a parameter to determine the interpolation interval t_i measured in time steps of the current model time. It is interconnected between the hourly simulator and the detailed simulator, as shown in Figure 5.

The interoperability of the modules allows several combinations. For example, when historical data of hourly mean wind speeds are available, and continuous values are needed, the wind speed generator and the detailed module can be used. However, if only statistical data on the site are given, the hourly wind speeds can be simulated through the hourly simulator based upon that data.

5.2 Turbine implementation

The wind turbine is the core of wind power production. The requirements of the turbine were to convert the wind speed to a suitable magnitude for the power system, i.e. the injected power. This reflects the process of the wind turbine converting the kinetic energy of the wind into electric energy by means of the generator. The wind turbine is modelled as an agent,

because it will be replicated several times to create wind farms and each entity has similar but not exactly identical characteristics. The agent can be customised through its parameters, which are shown in Table 1.

Making use of Anylogic's features to create hybrid models (Borshchev et al., 2002; Denault, n.d.; Helal, 2008), the turbine was modelled using the power curve model of the $P(v)$ relation described in Section 4 in combination with UML state charts. The power curve model was chosen to ensure flexibility in the application of the model. It is assumed that when modelling a wind farm, detailed information about the used turbines is available. This way, it is possible to customise each turbine with its correspondent power curve. The model of the wind turbine agent remains the same in any case.

The state chart elaborated here is classified in states dependent on the output power and failure state. The three working states of the turbine are as follows:

- **Off:** this state is active when the turbine is not producing any output power, regardless of the cause (no wind, too strong wind speeds, etc.) except in the case of a failure
- **Failure:** this state is achieved when there is a failure or a shutdown of the turbine due to maintenance.
- **On:** the turbine is in this state when producing output power, regardless if the rated power is gained or the turbine is only partial loaded.

The transition conditions between the states are defined by the wind speed for the transitions between the *On* and *Off* states, and by the corresponding rates of the MTBF and MTTR in the case of transitions to and from the *Failure* state, respectively. The MTBF is used for both transitions from the *On* and *Off* states. The rates are always adapted to the current timescale by a factor that is proportional to it and set automatically by the model in function of the scale chosen.

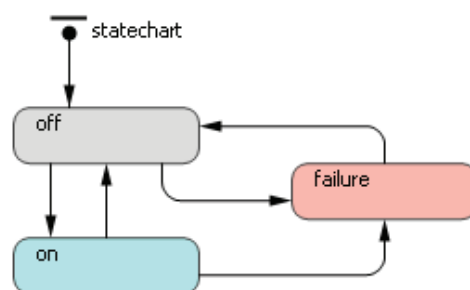


Fig. 7. State chart of the wind turbine including failure behaviour

Parameter	Description	Value
P_{nom}	Nominal power	275 kW
v_{cut-in}	Cut-in wind speed	3 m/s
$v_{cut-off}$	Cut-off wind speed	20 m/s
$v_{cut-back-in}$	Cut-back-in wind speed	18 m/s
$MTBF$	Mean Time Between Failures	1900 h
$MTTR$	Mean Time To Recover	80 h

Table 1. Wind turbine parameters

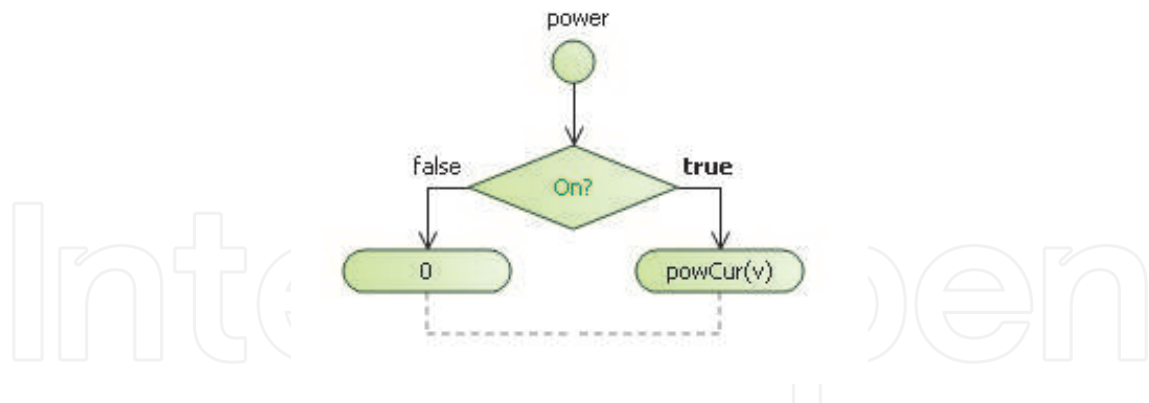


Fig. 8. Action chart of the wind turbine

For the computation of the output power, the so-called action chart of Anylogic is used to link both the discrete state chart approach with the continuous power curve. The output power is only taken from the power curve, if the current state is set to *On*. The state chart and the action chart are shown in Figure 7 and 8.

6. Integral multi-scale wind power simulation

After implementing the basic elements of our simulation, the wind turbine agents are grouped into an environment that defines common values for all agents within it and creates a framework among them that allows us to extract common statistical data. For instance, the aggregated output power of the wind farm, or the mean power by turbine is computed.

A wind farm with 25 wind turbines is generated in the current sample, being this is a typical number for medium size onshore wind farms. The power curve of the generators is the same for all, since it is assumed that the same type of turbines are installed. The power curve used here is inspired by the turbine type GEV MP 275 from the manufacturer Vergnet Eolien. It has a 32m diameter rotor and a rated power of 275kW and is specially designed to be used in remote locations and can sustain hurricane winds when secured to the ground.

The wind parameters for the wind simulator were taken from models developed previously. The ARMA coefficients used for the hourly simulations were taken from (Karki et al., 2006) for the "North Battleford" site. The parameters L and κ were taken from (Welfonder et al., 1997).

6.1 Simulating wind speeds at different time scales

In the following, three case studies were performed in order to show the abilities of the model, to analyse the results and assess the performance of the simulations. The first two studies were both simulated for a period of 24h. The difference between them is that in the first case, a day with low wind speeds is simulated, whereas in the second case high wind speeds are recreated. The third case is a simulation for a whole week, where (due to the duration) both high and lower speeds can be observed. The first two simulations allow us to analyse the reactions of the turbine park to low speed effects such as the cut-in process when the wind is starting to blow. They also allow for analysing the effects on high speeds where cut-off phenomena can be observed. In the third simulation over a week, effects over a longer simulation period can be observed. In all cases, hourly and continuous simulations were run to compare the accuracy and performance of the models.

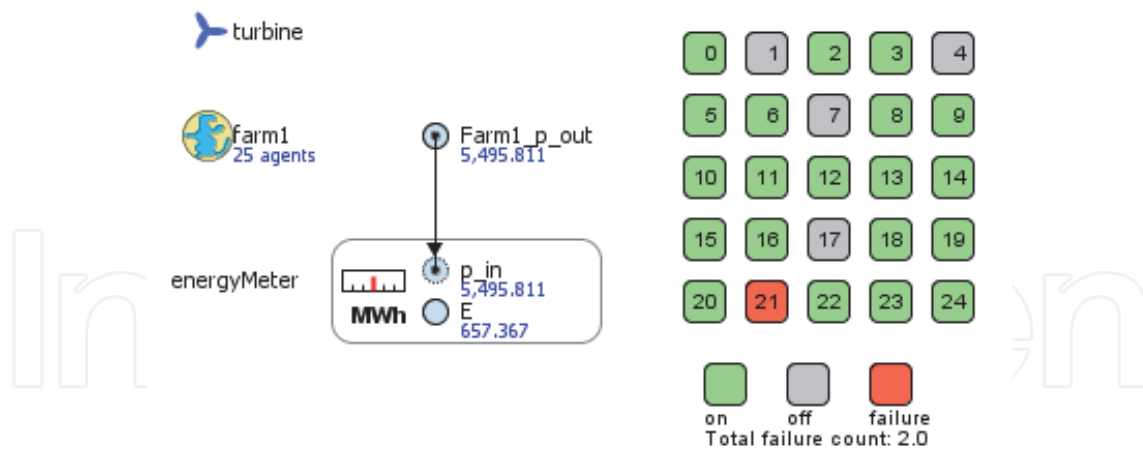


Fig. 9. Representation of the states of the turbines composing a wind farm

It has to be noted in both cases, that the hourly values are computed from a simulation taking as input for the wind turbine directly the hourly output of the wind speed generator, and they are not averaged values from the continuous wind speed time series. For the hourly simulations, the interpolated hourly wind speed is taken as input for the wind farm (turbines) model.

6.1.1 Low wind speed day

In Figure 10 two plots are shown. In the upper plot, the wind speed as a comparison between hourly mean and continuous simulation is represented. The hourly mean wind speed, the interpolated hourly values and the simulated real-time speed (fast term) are shown in the first plot. The piecewise function of the not interpolated hourly wind speed is the output of the slow term module. The interpolated hourly mean values are taken from the linear interpolator. These are again used as input for the fast term module. The outputs of the wind farms is plotted below. Two outputs are shown, one using the interpolated hourly mean speeds as inputs, and the second using the real-time, continuous wind speed output.

This first simulation shows a period of 24h where the wind speeds are relatively low, not exceeding 18 m/s. In particular there are periods with low speeds below 10 m/s where a significant decrease of the output power of the turbines can be observed. Falling under the cut-in speed, they even can stop completely. The simulated wind farms are identical. The difference between them is the wind speed input data. The first farm takes the interpolated hourly mean wind speeds, the second one the real time speeds.

In Figure 10 we can see that the hourly computed power output of the farm follows more or less what could be a hourly mean of the continuous values. There are no great deviations, except a small one around 21h, due to a drop of the continuous wind speed caused by a turbulence in the fast term.

Due to the random failure behavior, some differences caused by turbines in failure status can be observed (e.g. less total power at the last 2 hours of the day in the continuous simulation). It can be seen that the hourly power output follows approximately the continuous simulation, and only short term peaks are neglected (e.g. drop down of the wind speed at 21h that leads to a power drop is not visible in the case of the hourly simulation).

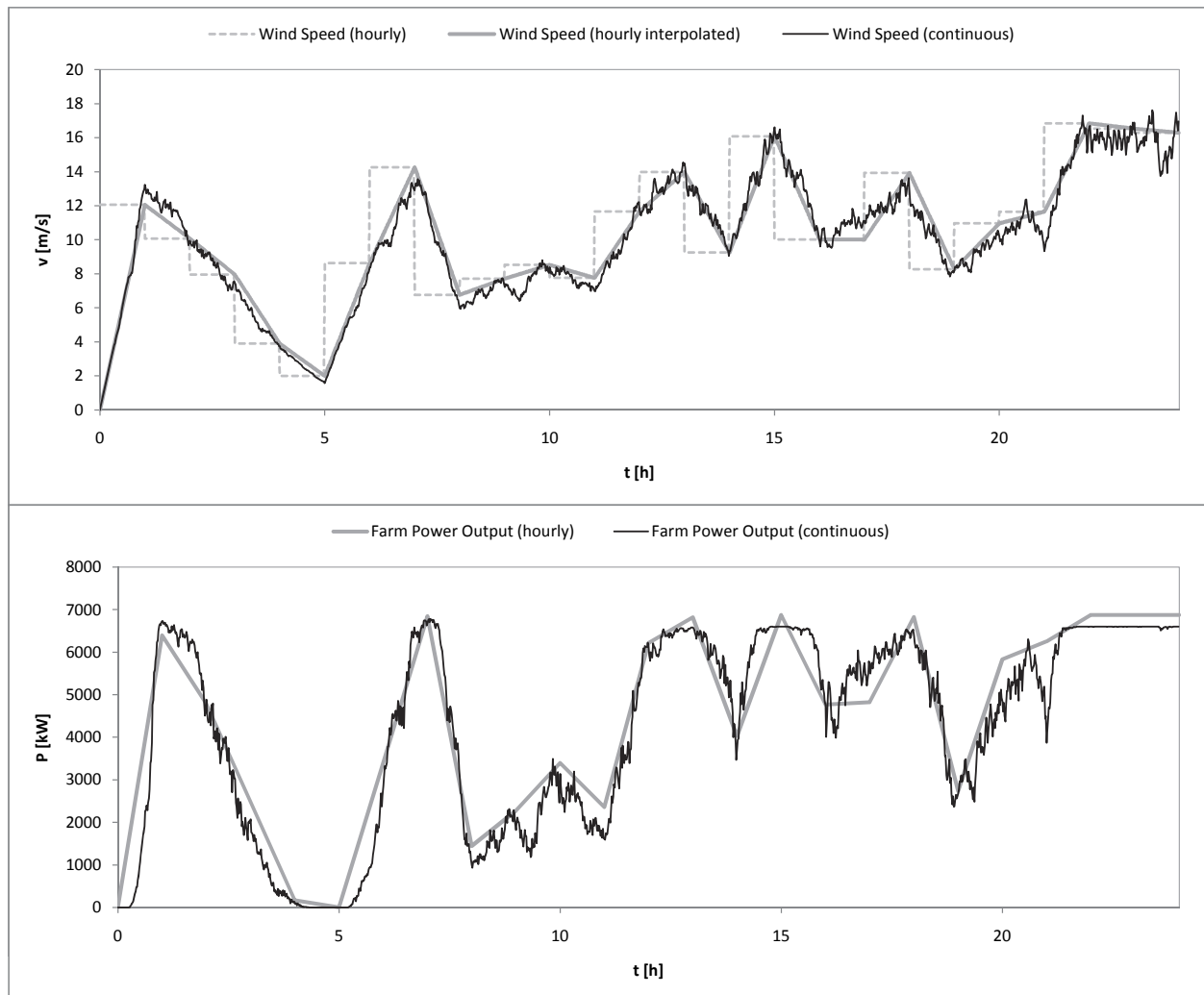


Fig. 10. Comparison hourly and continuous power outputs (bottom) and corresponding wind speeds (top) for a day with low wind speeds.

6.1.2 High wind speed day

In Figure 11 there can be again two plots seen. On top, the hourly and continuous wind speeds are represented, below the aggregated electrical power outputs of the farm can be seen. In this case, a day with high wind speeds was chosen. The speeds (once stabilised) are in the range of 12-25 m/s, being $v_{cut-off} = 20$ m/s, so inside that range. Where the continuous wind speed is $v_w(t) > v_{cut-off}$, a cut-off for some or all (see Section 6.3) is achieved and they shut down, which leads in a complete power drop at individual turbine scale, and important drops at the aggregated farm output. When $v_w(t) < v_{cut-back-in}$, the turbine starts again which causes a power increase. These effects explain the strong fluctuations that can be observed for the continuous power output in the lower plot of Figure 11. It is interesting to observe the hourly output, too. There, such strong fluctuations are not present, which can be clearly seen in the period between 8-20h. Furthermore, in the continuous output cut-offs can occur (due to a surpass of the cut-off speed by some turbulences caused in the fast term module) which are not considered in the hourly output, as the hourly mean remains $v_{h(t)} < v_{cut-off}$. This can be seen in the power drop between 4-5h, while the hourly output stays at the nominal

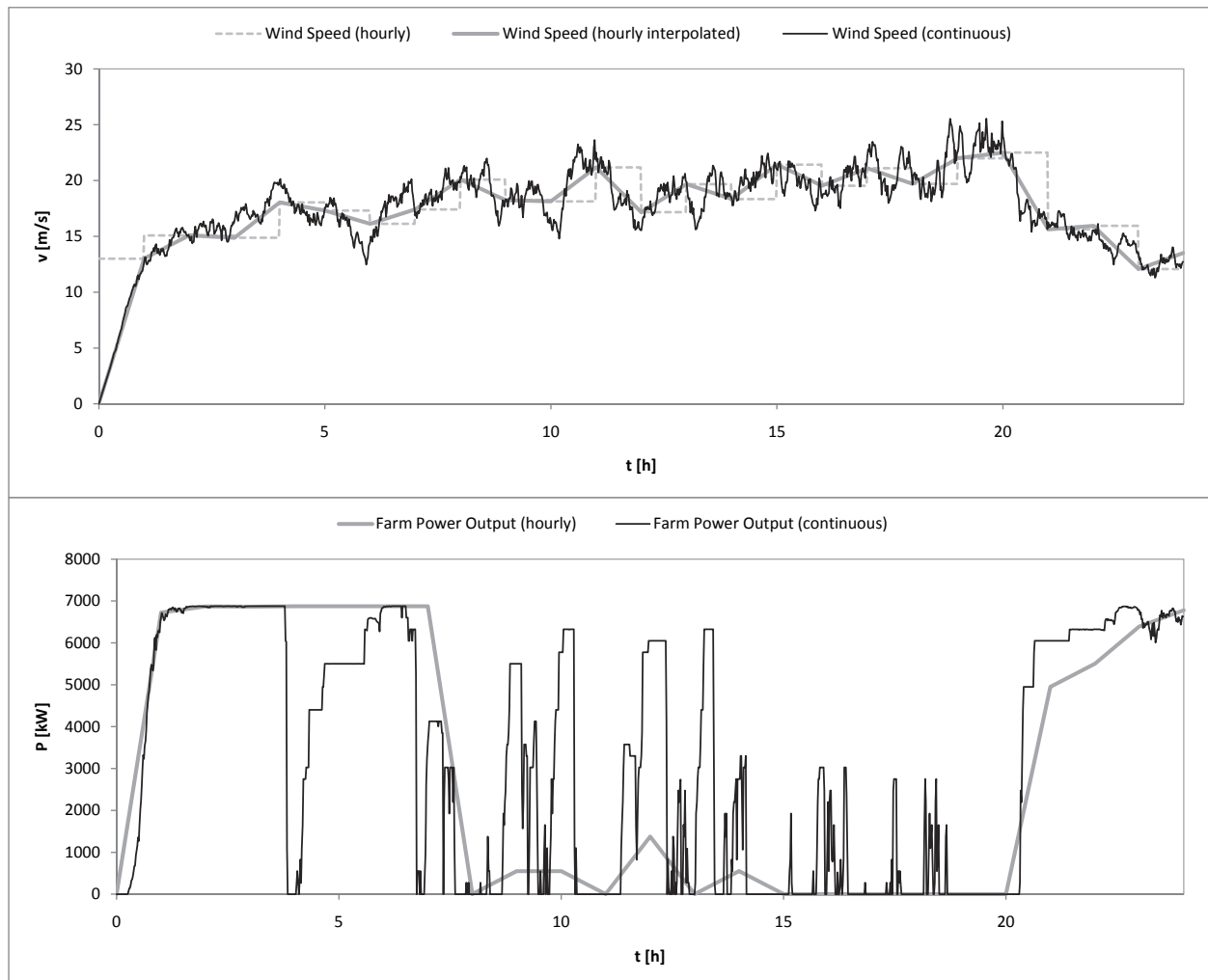


Fig. 11. Comparison hourly and continuous power outputs (bottom) and corresponding wind speeds (top) for a day with high wind speeds. The cut-offs of the turbines can be clearly observed, especially for the continuous simulation.

farm output. Thus, when dealing with fast speeds, the continuous model reflects much better strong fluctuations, which are neglected in the hourly simulation.

6.1.3 Simulation over a week

In this case, a complete week was simulated. Figure 12 shows two plots of the power output for a 25 turbine wind farm (the same as in the examples before), for the hourly and continuous outputs, at top and bottom, respectively. As can be seen on the plots, over 7 days the output of each method differs strongly only in some cases. There are some points where $v_w(t) > v_{cut-off}$. The turbines shut down because of over speed reasons in this case, but looking at the same point in the hourly mean simulation, there is not such a power drop. This is because $v_w(t)$ surpasses the hourly mean $v_h(t)$ punctually. To reach a power drop in the hourly simulation, $v_h(t) > v_{cut-off}$ is needed. These drops are a problem for the grid stability, as they are very significant and occur in a short time. Indeed, control mechanisms of the wind farms that shut down turbines proactively depending on wind speed forecasts or similar to prevent such abrupt drops have not been considered yet. Furthermore, the rapidly fluctuating

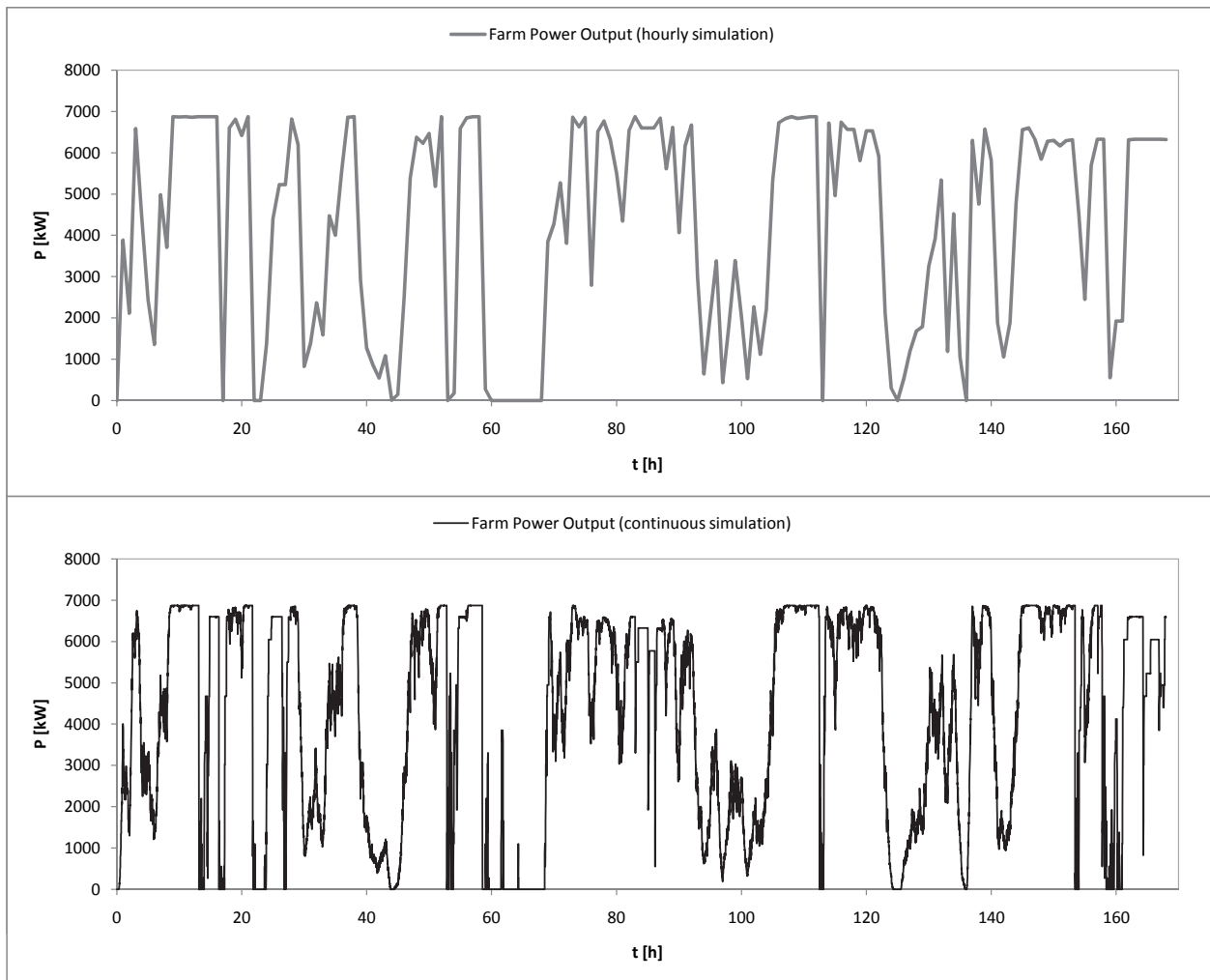


Fig. 12. Comparison hourly (top) and continuous (bottom) simulation for one week

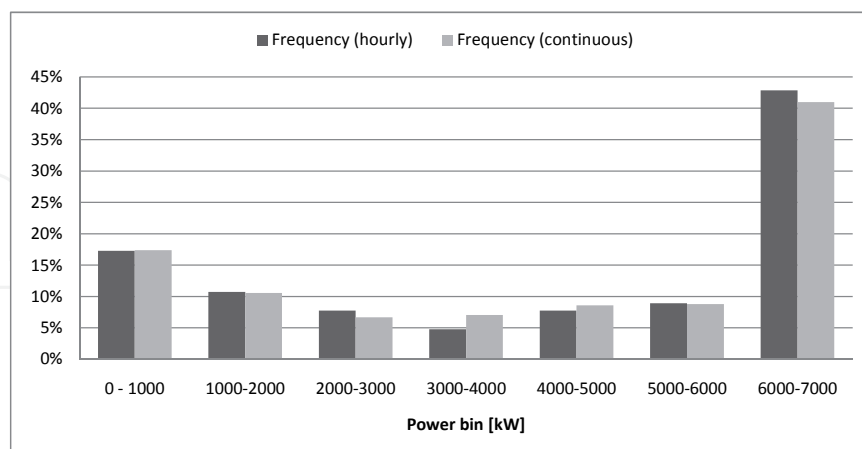


Fig. 13. Histogram for the hourly and continuous simulations of the output power for one week

wind speed component is transmitted to the power output of the plot below, while the curve of the hourly one is much smoother.

In Figure 13, the histogram of both the continuous simulation (10.080 points) and the hourly average simulation (168 points) are compared. It can be seen that no large differences exist and the distribution is only slightly affected by one method or the other. For example, the high power values (6-7 MW) are more frequent in the hourly simulation, as some cut-offs are not considered in this model.

This is an example of how the model can be adapted to different of energy system simulation requirements. If short term data is needed, a real-time simulation can be run in order to get data that is continuous in time. If the simulation takes place over the medium term, i.e. some weeks or months, hourly mean speeds are used and the fast term component module is deactivated, giving a more efficient computation. For long-term simulations, the statistical data provided for the simulation can be used to compute monthly energy output of wind farms.

6.1.4 Comparison of the simulations

The simulations run above can be also compared regarding computational performance. In Table 2 a comparison of different features is shown. The use of only hourly mean value allows for avoiding the use of the fast term component. This component is computationally slower, as it is based on a differential equation solver. By waiving this component, simulation performance can be importantly increased, (around factor 50). However, it has to be taken into account that this increase is only affordable when accuracy and short term fluctuation do not have to be considered (e.g. for longer term simulation). For simulating at higher temporary resolutions though, the model including the fast term can be very interesting. Memory use is not considerably affected by the choice of the time resolution of the model.

Simulation period	24h		168h (1 week)	
Resolution	Continuous	Hourly	Continuous	Hourly
Number of turbines	25		25	
Execution time	122,0s	2,3s	753,8s	14,5s
Memory used	16MB	16MB	21MB	15MB

Table 2. Simulation run comparison

6.2 Failure behaviour of the turbine units

As explained previously, the turbine model is provided with a failure function that allows us to simulate technical failures using specific parameters that can be obtained empirically. In this way, failures of individual units are randomly simulated over time. The average time to restart the turbines after such a failure is also considered.

Randomly driven timeouts are used to represent the transition to the failure state, which is triggered according to a rate. This rate is the inverse value of the MTBF. In order to get back to the working state, the rate corresponding to the MTTR is used. To trigger the transitions, exponentially distributed random numbers are used. The distribution is parametrised by the rate.

In Figure 9 the representation of the turbines and their current state is shown. The model can easily show the state of each turbine and the aggregated current output and energy production. Also the state of an individual generator and its production values can be observed. The inclusion of the failure behaviour in real-time allows us to consider its direct influence on the power output of the farm within the same model.

6.3 Distributed parameters

All turbine manufacturers provide technical specifications that document their characteristics in detail. The values shown in these documentation normally are not specified for each unit individually, as they are obtained using average values for all units of the same type. Although the units are supposed to be identical in construction, small differences cannot be avoided.

To model this heterogeneity among the same units, the parameters of the turbines were slightly varied among themselves, by distributing them normally with a mean $\mu_{[value]}$ corresponding to the indicated value and a small standard deviation of $\sigma_{[value]} = 0.1\mu_{[value]}$. Further studies could get exact values for the variation of parameters among different units. This leads to small variations in the behaviour of each unit, that can result in aggregated effects on the wind farm output, and which are usually not considered in classical models. One of the strengths of the model is that it relies on the heterogeneous modelling of the individual agents.

Figure 14 shows the breakdown of the power production of the wind farm by individual turbines. Their heterogenous behaviour can be observed in the Figure. Having different characteristics as well as a slight variation of the local wind speed lead to unsynchronised operation of the turbines. This makes the model more realistic.

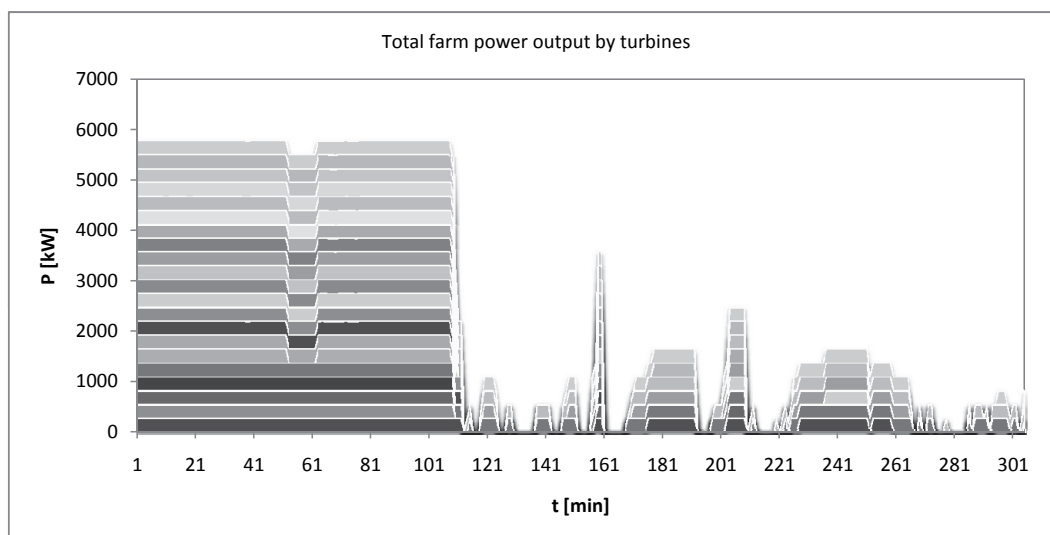


Fig. 14. Total power output for a wind farm (continuous simulation) broken down by individual turbines

7. Conclusion

Modelling the power output of wind farms at different time scales can be a quite complex activity. In this chapter, a model for simulating wind power system on multiple time scales was presented. The multi-method approach was chosen in order to satisfy the various needs of the model, where not only the pure generator but also failure related and the consideration of a wind farm as a whole is integrated. Furthermore, the model was conceived to allow for the simulation at different time scales, looking for the best computational efficiency in each case. The scalability included in this model allows to integrate different time scale simulations into the same module and reduce the number of total modules.

The model allows us to simulate wind power generation at different scales using the same model, only switching between the different modules. The characteristics of the model are

maintained at the different scales. So, for example, failure behaviour is modelled and can affect also short term simulations, if needed. The following scope was made:

- The primary aim of the model is not to estimate the accumulated energy productions over a period (used for example for the dimensioning of wind farms) but rather to simulate real time power outputs for energy system simulations.
- At high speeds, cut-off effects are better reflected in a high resolution (continuous simulation) model.
- The hourly model though seems to approximate the hourly mean well in low speed periods.
- The model is flexible enough to cover different needs arising from different time scales in integrated energy systems simulation.

This model brings together different modelling approaches, unifying continuous models, (differential equations, e.g. Equation 4) with discrete events (hourly changing mean speeds, state chart modelling within the turbines) and agent-based modelling (e.g. of the failure behaviour and for the integration of the turbines into the wind farm). The use of different paradigms allows us to create more realistic models that can take advantage of the different strengths of each approach. Due to the agent based approach, it is possible to set distributed parameters to the individual turbines, creating a heterogeneous park which recreates a more realistic behavior not only at individual, but also at aggregated scale. Further, each turbine can be customised with real data (e.g. power curves, etc.). In this way it is possible to simulate realistic behaviour of wind farms in contrast to static, homogeneous multiplication of identical objects.

A compromise between accuracy of the output powers and performance of the model can be found in dependance of the application scope of the model. In large scale energy systems simulations (over several months or years), the estimation of the low term is enough, profiting from the performance and this lightweight model. For medium term, interpolated values can be used. For short term simulations (up to some days), the fast term providing a model which simulates high resolution turbulences can give better results.

Even though, some drawbacks of the model were identified, among them wind direction, which is not taken into account for the moment, so the turbines are supposed to follow it fairly well. The model is also only valid for active power injections, as reactive effects are not considered yet. In order to optimise the continuous simulation it could be replaced by a minute by minute one, as the power output is not as directly coupled to wind speed as represented in the model, because of inertia of the rotor and modern automatic turbine regulation of the output.

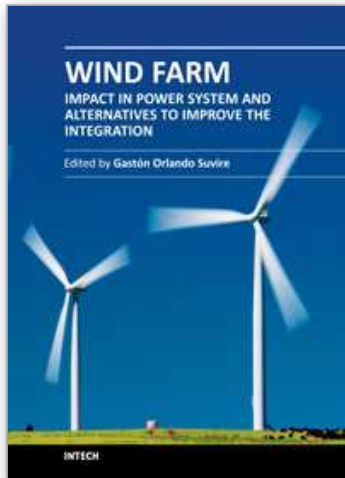
Even taking into consideration these limitations (or especially because of them), a simplified model that does not need large number of parameters was created, allowing for integration to energy systems simulation as a light weighted and optimised model for different time scales.

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Wind Farm - Impact in Power System and Alternatives to Improve the Integration

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During the last two decades, increase in electricity demand and environmental concern resulted in fast growth of power production from renewable sources. Wind power is one of the most efficient alternatives. Due to rapid development of wind turbine technology and increasing size of wind farms, wind power plays a significant part in the power production in some countries. However, fundamental differences exist between conventional thermal, hydro, and nuclear generation and wind power, such as different generation systems and the difficulty in controlling the primary movement of a wind turbine, due to the wind and its random fluctuations. These differences are reflected in the specific interaction of wind turbines with the power system. This book addresses a wide variety of issues regarding the integration of wind farms in power systems. The book contains 14 chapters divided into three parts. The first part outlines aspects related to the impact of the wind power generation on the electric system. In the second part, alternatives to mitigate problems of the wind farm integration are presented. Finally, the third part covers issues of modeling and simulation of wind power system.

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