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# MODELLING NON-STATIONARY WIND SPEED FOR RENEWABLWE ENERGY SYSTEMS CONTROL

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Abstract: This paper deals with the modelling of the wind speed, treated as a non-stationary process. In the proposed modelling methods, the wind speed has two components: a long and medium term-component, described by an available spectral characteristic in the low frequency range, and a non-stationary turbulence component, which is “attached” to the medium and long-term component. Two procedures for turbulence component generation, using some shaping filters, are proposed. In both methods turbulence component proprieties are determined depending on current mean value of the medium and long-term component. Numerical results and comment concerning the implementation aspects are also presented

Keywords:. wind speed, turbulence, power spectral density, numerical simulation, non-stationary signals, shaping filters.

## 1. INTRODUCTION

The investigation of wind power conversion systems and – especially – the development of control solutions involve the modelling of the wind speed, as a random process. The wind speed is considered as consisting of two elements:

– a slowly varying mean wind speed of hourly average. Usually, this component is modelled as a Rayleigh distribution (Leithead, De la Salle and Reardon, 1991):

$$p_R = (\bar{v}) = a \cdot v \cdot \mathrm{e}^{-1/2a\bar{v}^2} \qquad (1)$$

where $\bar{v}$ is the hourly wind speed average and $a$ is related to the very long time scale mean speed; Toujours

– a rapidly varying turbulence component, modelled by a normal distribution with mean value equal to zero and standard deviation proportional to the current value of the average wind speed. The dynamic properties of the turbulence component are given by the Von Karman power spectrum:

$$S_{vv}(w) = \frac{0.475 s^2 \, L/\bar{v}}{\left[1+\left(wL/\bar{v}\right)^2\right]^{5/6}} \qquad (2)$$

where $s$ is the turbulence intensity and $L$ is the turbulence length scale.

Generally, the speed modelling offers the support for basic applications in wind engineering, such as: performance estimation of a wind system (i.e., prediction of the energy output) and analysis of the turbulence influence on the energy conversion and on the system dynamics.

However, the most important applications of wind speed modelling concern the development of the control structure of wind systems. For example, the classical approach in optimal control of the wind power system consists in a LQG problem, where the

This paper was recomended for publication by A. Filipescu controlled process includes the wind turbine – electrical generator ensemble model and the model of the turbulence wind speed component (Ekelund, 1997; Novac et al., 1995). Other approaches in the control of wind power systems also require the spectral characteristic $S_{vv}(w)$ ((Leithead, De la Salle and Reardon, 1991).

The development of control strategies for hybrid Wind – Diesel systems (Lipman, 1990) involve modelling of the wind speed in the short, medium and long time scale.
This paper deals with the modelling of the wind speed, treated as a non-stationary process, characterizing the wind properties an short, medium and long time scale.

The paper is organized as follows: in the next section, the Van der Hoven's large band spectral model (Van der Hoven, 1957) is analyzed. Section 3 discusses a Von Karman type model, used in (Welfonder et al., 1997) in order to identify the turbulence component. Section 4 and 5 present two new procedures for large band modelling of a non-stationary wind speed. Section 6 presents the numerical results concerning the generating of the non-stationary wind speed. Some concluding remarks are given in the final section.

## 2. VAN DER HOVEN'S LARGE BAND MODEL OF THE WIND SPEED

In studies concerning the hybrid Wind-Diesel systems, a reference model for the wind speed is considered the Van der Hoven's experimental model (Lipman, 1990), reproduced in Figure 1. The power spectrum of the horizontal wind speed is calculated in the range from 0.0007 to 900 cycles/hour, which is

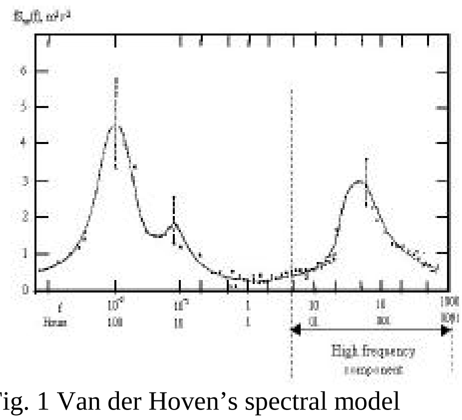



Fig. 1 Van der Hoven's spectral model

more than six decades. The knowledge of the spectral characteristic of the wind speed in such a frequency range would bring solutions to wind simulation research, as it contains the spectral domain that describes the medium and long-term variations, as well as the spectral range of the turbulence component.

Starting from Van der Hoven's experimental characteristic, we have used a numerical procedure, based on the sampling of the spectrum, in view of wind speed simulation

Let us consider $w_i, i=\overline{1,N+1}$, the discrete angular frequency and $S_{vv}(w_i)$ the corresponding values of the power spectral density. The harmonic at the frequency $w_i$ has the amplitude

$$A_i = \frac{2}{p}\sqrt{\frac{1}{2}\left[S_{vv}(?_i)+S_{vv}(?_{i+1})\right]\cdot\left[?_{i+1}-?_i\right]} \qquad (3)$$

and the phase, $j_i$, randomly generated. The wind speed, $v(t)$, is simulated by the relation

$$v(t)=\sum_{i=0}^{N} A_i \cos(?_i t + j_i) \qquad (4)$$

where $w_0 = 0, j_0 = 0$ and $A_0 = \bar{v}$ is the mean wind speed, calculated on a time horizon greater than the largest period in Van der Hoven's characteristic (i.e., $T = 2p/w_1$ ).
Fig. 2 presents a five hours wind speed fluctuation, simulated with the relations (3) and (4).

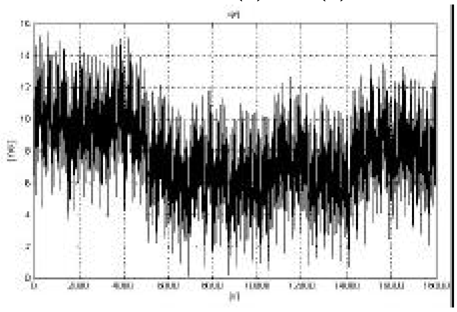


Fig. 2 Van der Hoven's model based simulation of the wind speed for time horizon of five hours

One can notice:
– important variations of the mean wind speed, which proves the capability of the Van de Hoven's model to characterize the wind behaviour on long and medium term;
– the turbulence in the Van der Hoven's model has the same parameters, regardless of the mean wind speed.

Thus, the Van der Hoven's model cannot be used for a complete description of the wind speed on a time range of seconds, minutes, hours, etc., because this model has a main deficiency: the turbulence component is treated as a stationary random process. This component has always the same properties, concerning the fact that its properties don't depend on the "mean" values variations, having the time range of hours, days, etc.

## 3. VON KARMAN'S MODEL OF THE TURBULENCE COMPONENT

Experimental data show that the turbulence component characteristic depends on the value of the mean speed. (Welfonder, *et al.*, 1997) deals with a simulation scheme, where the non-stationary turbulence component is modelled using a shaping filter, which colours a synthetically produced white noise. The transfer function of the shaping filter, according to the von Karman's turbulence spectrum (Welfonder, *et al.*, 1997; Ekelund, *et al.*, Leithead, *et al.*, 1991) is:

$$H_F(j?) = \frac{K_F}{(1 + jwT_F)^{5/6}} \tag{5}$$

where the static gain $K_F$ is obtained from the condition that the coloured noise, delivered from the filter , $w_c(t)$, has unitary value of the variance. This condition is obtained with the following relation between the parameters $K_F$ and $T_F$ (Welfonder *et al.*, 1991)

$$K_F \approx \sqrt{\frac{2p}{B\left(\frac{1}{2},\frac{1}{3}\right)} \cdot \frac{T_F}{T_s}} \tag{6}$$

where $T_s$ is the sampling period and $B$ designates the beta function.

In order to obtain the turbulence component, $v_t(t)$, the coloured noise $w_c(t)$ is multiplied by the estimated value of the standard deviation, $\hat{s}_v$:

$$v_t(t) = \hat{s}_v \cdot w_c(t) \tag{7}$$

The two parameters: $\hat{s}_v$ et $T_F$ are calculated according to the mean value of the wind speed, $\bar{v}_m$:

$$\hat{s}_v = k_{s,v} \cdot \bar{v}_m \tag{8}$$

$$T_F = \frac{L}{\bar{v}_m} \tag{9}$$

where:

– $k_{s,v}$ is determined experimentally as the slope of the regression curve that describes statistically the relation between $\bar{v}_m$ and $\hat{s}_v$;

– $L$ is the turbulence length scale (a parameter of the analysed site).

This *wind* speed generating model can be adapted to the particularities of a given site, by the use of parameters $L$ and $k_{s,v}$ which characterize it. However, it doesn't allow the simulation of low frequency fluctuations, on the range of minutes, hours, etc.

## 4. LARGE BAND MODELLING OF THE WIND SPEED – METHOD 1

The solutions proposed hereafter are based on the following remarks, issued from the previous sections:

– the method based exclusively on the Van der Hoven model leads to incorrect results, as the turbulence component is not modeled as a non-stationary process;

– the procedure used in (Welfonder, *et al*., 1991), based on the von Karman spectrum, can model the turbulence component as a non-stationary process, but doesn't reproduce the slow fluctuations, that correspond to the low frequency domain in the spectral characteristic of the wind speed.

Consequently, we combine the low frequency model of Van de Hoven's characteristic with a non-stationary turbulence model. We made the assumption that the discrete frequency values $f_0=0$, $f_1=0.001$ cycles/h,..., $f_{30}=4$ cycles/h correspond to the spectral range that describes medium and long term wind speed evolution and the turbulence component (i.e. the short-term component) is given by the spectral range between 5 cycles/hour and 1000 cycles/hour, that corresponds to frequencies $f_{31}$ ,… ,$f_N$, with $N=55$. In this case, $v(t)$ becomes,

$$v(t)=v_{ml}(t)+v_t(t) \tag{10}$$

where

$$v_{ml}(t) = \sum_{i=0}^{30} A_i \cos(?_i t + f_i) \tag{11}$$

is the medium and long term component and $v_t(t)$ is the turbulence component. We have considered that Van de Hoven's model describes correctly only the wind variation on a large time scale, so $v_{ml}(t)$ will be used in the final wind model. This solution is imposed by the fact that the experimental identification of the spectral characteristic of the wind speed in the very low frequency range is difficult, as it needs long term recordings. For the temperate area, the Van der Hoven's model is the only experimental result available, which offers a spectral description of the wind speed in the low frequency domain (0.0007cycles/h…5cycles/h), therefore, it was adopted.

The first modelling method considers that, in Van der Hoven's model, the shape of the turbulence component spectral characteristic is the real one, because it was determined experimentally. We correct the Van der Hoven's model in the high frequency area, such as the turbulence component weight modifies with the long and medium term component, $v_{ml}$.

From the spectra model $f \cdot S_{vv}(f)$, presented in Fig. 1, we deduced the Bode characteristic, $G_{dB}(w)$, of the shaping filter which colours a white noise, in order to generate the wind speed $v(t)$. This Bode characteristic is parameterized by an asymptotic characteristic (Fig. 3), to which corresponds the transfer function of the filter:

$$H_f(s) = \frac{K}{Ts+1}(T_0 s + 1) \cdot H_t(s) \tag{12}$$

where

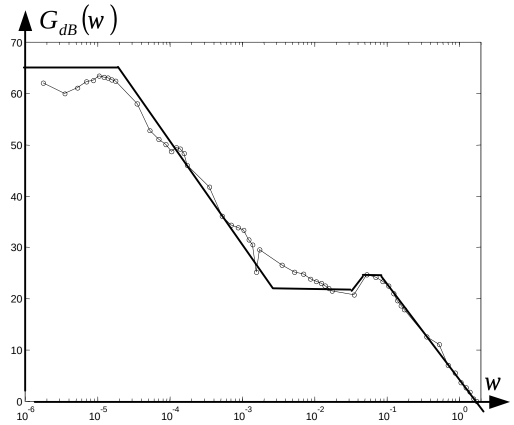



Fig. 3 Van der Hoven's characteristic parameterization

$$H_t(s) = \frac{T' s + 1}{(T_1 s + 1)(T_2 s + 1)} \tag{13}$$

gives the shape of the Bode characteristic in the turbulence component area, and the time constant, *T*, describes the model of the long and medium time scale component. We consider the time constant $T_0$ as a parameter depending by the slowly varying mean wind speed $v_{ml}$:

$$T_0 = F(\bar{v}_{ml}) \tag{14}$$

with $F(\cdot)$ a bounded, monotonically increased function. The variation effects of parameter $T_0$ are illustrated in Fig. 4. For reference value $T_0$, corresponding to speed $\bar{v}_{ml}$, we obtain asymptotic characteristic 1 (Fig. 4). If $\bar{v}_{ml}$ increases to $\bar{v}'_{ml}$, we obtain $T'_0 = F(\bar{v}'_{ml})$, to which corresponds

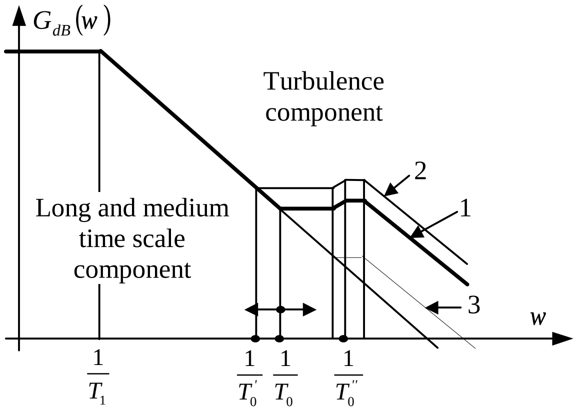



Fig. 4 Turbulence component adjustment principles

characteristic 2. in this case, the shaping filter will generate a turbulence component with increased variance. Characteristic 3 is obtained for a reduced value, $\bar{v}''_{ml}$, of mean speed value, to which we obtain $T''_0(\bar{v}''_{ml}) < T_0$.

We adopted a linear function $F(\bar{v}_{ml})$. It's parameters are adjusted such as turbulent component, $s_{vt}$, satisfies the relation:

$$s_{vt} = k_s \bar{v}_{ml} \tag{15}$$

where $k_s$ must approximate the value of the experimentally determined $k_{s,v}$ (see Eq. (8)).

SIMULINK simulation scheme of the large band wind speed model is presented in Fig. 5. The filter with time constant $T = 50.000s$ and the fourth order Butterworth filter extract the slowly varying component $\bar{v}_{ml} - v_0$, needed for calculating time constant $T_0(\bar{v}_{ml})$.

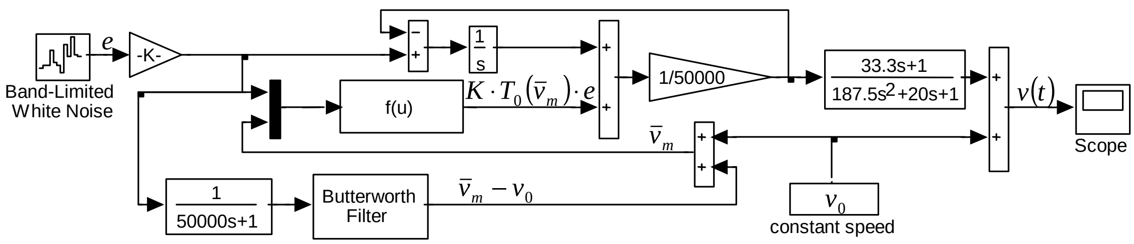



Fig. 5 SIMULINK implementation of the large band wind speed model

## 5. LARGE BAND MODELLING OF THE WIND SPEED – METHOD 2

The model presented in previous section is simple, but it has tow disadvantages:

– requires a special adjustment operation of $F(\bar{v}_{ml})$ parameters;

– the dependence between dynamic proprieties of turbulence component and mean wind speed $\bar{v}_{ml}$ is not explicit treated.

In order to eliminate these disadvantages, we use the Von Karman's turbulence component model, in a model illustrated in the scheme presented in Fig. 6.

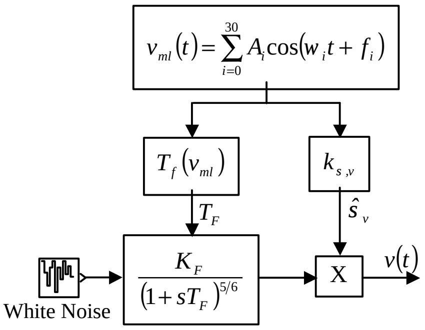



Fig. 6 Large band model for non-stationary wind speed

The generating of short-term wind-speed fluctuations is achieved by using the following data (measured or estimated), regarding the analysed site:

– the turbulence length scale *(L)*;

– the slope of the regression line, $k_{s,v}$ , which describes the dependency between the standard deviation and mean value of the wind speed.

For the preliminary studies concerning the wind systems control, it is often enough to make use of general information concerning the site, that determine the turbulence length scale $L$ and the slope $k_{s,v}$ of the regression equation (8). The parameters $L$ and $k_{s,v}$ are correlated : for the coast and offshore sites, the turbulence length scale is small (e.g.. 100-200 m), as well as the slope $k_{s,v}$ (e.g.. 0.1…0.15). In the cases where the influence of the site's relief is more important, the values of $L$ and $k_{s,v}$ are higher (i.e. 200…500m and 0.15…0.25, respectively) (Welfonder, *et al.*, 1991).

Let us now consider that parameters $L$ and $k_{s,v}$ are known, either by experimental identification, or by adopting them according to the *a priori* site's characteristics. The procedure for the large range wind simulation consists of the following steps, in the recursive version:

1. Generate with (11) the current value of the long and medium term component, $v_{ml}(t)$, using the sampling period $T_{s1}$. Let us consider $i$ the current step of the procedure and $v_{ml}(iT_{s1})$ the generated value of this component.

2. Actualise the parameters of the turbulence component's model, at the beginning of the current interval $[iT_{s1}, (i+1)T_{s1}]$ . We suppose that at the time scale of the variable $v_t(t)$, the long and medium term component is considered as the mean value of the wind speed. The current values of the turbulence component's model are:

$$T_F^{(i)} = L / v_{ml}(iT_{s1}) \tag{13}$$

$$\hat{s}_v^{(i)} = k_{s,v} v_{ml}(iT_{s1}) \tag{14}$$

$$K_F^{(i)} \approx \sqrt{\frac{2p}{B\left(\frac{1}{2},\frac{1}{3}\right)} \cdot \frac{T_F^{(i)}}{T_s}} \tag{15}$$

At the generation of the turbulence component, the sampling period is $T_s$ , so that $T_s << T_{s1}$.

3. Calculate the impulse response of the filter (5) with actualised parameters $K_F^{(i)}$ and $T_F^{(i)}$, using the equation :

$$h^{(i)}(t) = \frac{2}{p}\int_0^{\infty} P^{(i)}(w)\cos(wt)\mathrm{d}w \tag{16}$$

where

$$P^{(i)}(w) = \mathrm{Re}\left[\frac{K_F^{(i)}}{\left(1 + jwT_F^{(i)}\right)^{5/6}}\right] \tag{17}$$

The discrete impulse response is calculated using the sampling period $T_s$ and a finite limit in the integral (16). Generate the turbulence component in the interval $[iT_{s1}, (i+1)T_{s1}]$, using the convolution model

$$v_t^{(i)}(t) = \int_0^t h^{(i)}(t)w(t-t)\mathrm{d}t \tag{18}$$

described in the discrete time domain, with sampling period $T_s$ .

5. Calculate the current value of the wind speed

$$v(t) = v_{ml}(iT_{s1}) + s_v^{(i)} \cdot v_t^{(i)}(t) \tag{19}$$

with sampling period $T_s$.

6. Make $i=i+1$ and return to step 1.

The variables $h^{(i)} \equiv h^{(i)}(kT_s)$ and $v_t^{(i)}(m) \equiv v_t^{(i)}(mT_s)$ are calculated with:

$$h^{(i)}(k) = \frac{2}{p} T_s Dw \sum_{r=0}^{M} P^{(i)}(r)\cos(krT_s Dw) \quad k = \overline{0,N} \tag{20}$$

$$v_t^{(i)}(m) = T_S \cdot \sum_{p=0}^{N} h^{(i)}(p) w_C(m-p) \tag{21}$$

where

$$P^{(i)}(r) = \mathrm{Re}\left[\frac{K_F^{(i)}}{\left(1 + jr\Delta w . T_F^{(i)}\right)^{5/6}}\right], \quad r = \overline{0,M} \tag{22}$$

and the parameters M and N are adopted so that

$$P(w)\big|_{w>M\cdot Dw} \cong 0; \quad h(t)\big|_{t>N\cdot Ts} \cong 0 \qquad (23)$$

In order to limit the numerical errors, the parameters $Dw$, $T_s$ ,$M$ and $N$ are chosen so that the static gain of the non-parametric filter, $\hat{K}_F$ , established according to impulse response (20), *i.e.*

$$\hat{K}_F = T_s \cdot \sum_{k=0}^{N} h(k) \qquad (24)$$

should correspond, with a certain imposed error, to the $K_F$ parameter of the transfer function (5).

## 6. NUMERICAL RESULTS

Fig. 7 shows the evolution of the wind speed, generated using the first method.

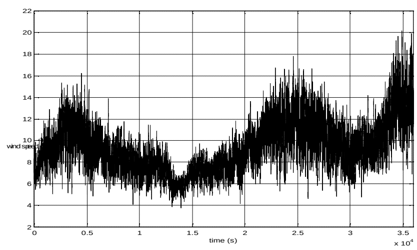


Fig. 7 Profile of the generated non-stationary wind speed, using the first method

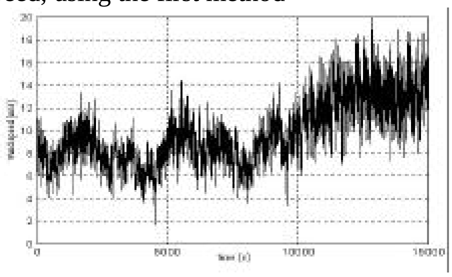
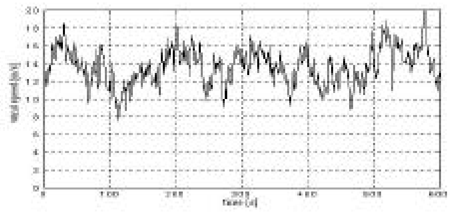


Fig. 8 Profile of the generated non-stationary wind speed, using the adjustable shaping filter (5)

Fig. 8 presents a profile of non-stationary wind speed, generated using the adjusting shaping filter (5), for time horizon of 15.000 s. the chosen parameters in the algorithm have been: $L = 180\,\text{m}$ , $k_{s,v} = 0.16$ , $T_i = 180\,\text{sec}$ , $T_s = 1\,\text{sec}$ , $Dw = 0.002\,\text{rad/sec}$ , $N = 500$ and $M = 100$ .

In order to achieve a more detailed view of the turbulence component, Fig. 9 shows the evolution of the wind speed, in two time intervals of 10 minutes. These intervals have been chosen so that the long and medium component, $v_{ml}$ , has different values: 13 m/s and 3.5 m/s.

a) $v_{ml} = 3.5\,\text{m/sec}$



b) $v_{ml} = 13\,\text{m/sec}$

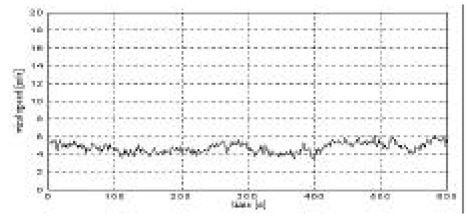


Fig. 9 Wind speed in 2 time intervals of 10 min.

## 7. CONCLUDING REMARKS

The purposed wind speed models consider the wind speed as a non-stationary process, having two components: the long and medium-term component and the turbulence component. Two procedures for non-stationary turbulence component generation, using some adjustable shaping filters, are proposed in the paper. First procedure, based on the Van der Hoven's turbulence component model, is simple but less precise. It can be used only in qualitative analysis of the wind systems control strategies. The second procedure, which uses a non-rational filter (), is more precise but requires an important computational effort.

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