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Generation of Random Wind Speed Profiles for Evaluation of Stress in WT Power Converters

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Abstract—Wind turbines are subjected to wind speed variations that cause a power profile that will stress the overall system. This stress is transferred to the power converter, resulting in temperature variations of the power devices and, hence, causing the reduction of the lifetime. The lifetime expectation changes depending on the real wind speed once the wind turbine is operating. Usually, the real wind speed profiles are employed to evaluate this stress but they do not consider all possible operation conditions and require intensive computations. To solve these issues, this paper proposes the generation of random wind speed profiles, based on the measured ones, in order to evaluate the thermal stress of the power devices based on a simplified statistical approach.

I. INTRODUCTION

Power converters for Wind Turbines (WT) must be reliable in order to reduce maintenance costs, ensure the appropriate operation of the wind farm and give a low cost of energy. The reliability of WT power converters depends on the selected power converter topology and design, the characteristics of the employed components (capacitors, power devices, PCB, ...), the employed manufacturing process and the on-site operation conditions, also called mission profile (electrical, thermal, vibrations, humidity ...).

As it is shown in Fig. 1, the thermal stress of power devices in a certain WT power converter can be assessed in simulations from both the electro-mechanical and the electro-thermal model of the WT [1] [2]. The generated electrical power (v_g , i_g) can be evaluated from the measured wind speed (v_w), the air density (ρ) and the applied pitch angle (β). Depending on the grid voltage and frequency, the selected power converter topology, the employed control strategy and the electro-thermal model of the power devices included voltage drops, currents and junction temperatures (T_j) of semiconductors can be obtained. Then lifetime models can be applied to the amplitude, mean value and cycle period of T_j (ΔT_j , T_{jm} and t_{cycle} respectively) to evaluate the lifetime expectation of the employed power devices under the mission profile. The lifetime of the power semiconductors is usually weighted by the number of temperature cycles [1] [3], which is also called the cycle life. The cycle life is related not only to the amplitude of the temperature cycles, but also the mean value and period of the temperature cycles. The rainflow algorithm is usually employed to statistic the temperature cycles for a certain mission profile due to the fact that ΔT_j ,

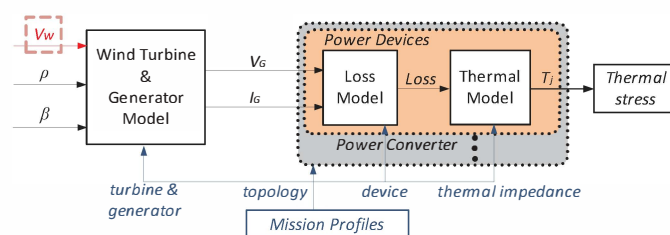


Fig. 1. Procedure for evaluation of the thermal stress in WT power converters.

T_{jm} and t_{cycle} will keep on varying in real loading conditions [4]. However, the rainflow algorithm requires the availability of large wind speed measurements at the selected location in order to analyze all possible operation conditions.

The statistical analysis of the wind speed data can be found in literature for both static design of wind turbine subsystems/farms and also forecasting. The first approach is employed in [5] for evaluation of energy potential at a certain location. Ref. [6] evaluates the impact of a wind farm in the electrical network. At a subsystem level, [7] and [8] employ this analysis for design purposes of a storage subsystem and electrical generators respectively. In case of forecasting, the works in [9] [10] allow also the electrical power to be forecasted.

This paper presents a method for generation of a number of wind profiles, with customized length and retaining the characteristics of the measured one, in order to analyze the effect of wind power variations on the thermal stress of power devices within the WT power converter. The proposed method allows wind speed profile variations to be analyzed, while reducing the computational burden associated to large wind speed profiles. Section II describes the effect of wind speed variations on the WT mechanical power. The generation of random profiles is described in section III and a simulation model and the obtained results are provided in sections IV and V respectively.

II. EFFECT OF WIND SPEED VARIATIONS ON THE MECHANICAL POWER

According to [11], the mechanical power (P_{mech}) in a wind turbine can be obtained by applying

$$P_{mech} = \frac{1}{2} \rho C_p(\lambda, \beta) A_R v_w^3 \quad (1)$$

where

$$\lambda = \frac{R\omega_m}{v_w} \quad (2)$$

$$C_p = 0.5 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}} \quad (3)$$

$$\frac{1}{\lambda_i} = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right) \quad (4)$$

where A_R is the area covered by the blades during rotation [m^2], $C_p(\lambda, \beta)$ is the power coefficient of the turbine, ρ is the air density [kg/m^3], λ is the tip speed ratio of the rotor blades, β is the blades pitch angle [$^\circ$] and R is the radius of the blades [m].

For analysis purposes of the on-site wind characteristics, (1) can be divided into two terms corresponding to the wind turbine conversion capability and the wind conditions

$$P_{mech} = C_p(\lambda, \beta) \cdot P_{wind} \quad (5)$$

where

$$P_{wind} = \frac{1}{2} \rho \cdot v_w^3 A_R \quad (6)$$

which depends on the weather conditions at the selected location. In the case of P_{WT} , temperature variations and icing can change the values of C_p , it will result in variations of the extracted wind power [12]. In case of P_{wind} , the weather and altitude must be also considered to have realistic data. Focusing on the second term, P_{wind} , measurements of the wind speed, humidity, temperature and atmospheric pressure is used to be available and they are required for analysis of the resource availability.

A one year registration of the wind speed at the roof of the Renewable Energy Laboratory, Dept. of Energy Technology, Aalborg University, has been considered for analysis purposes. These values have been corrected considering wind shear according to the Prandtl logarithmic law [13], resulting in the measurements shown in Fig. 2. The measurements shown in Fig. 2a correspond to average wind speed values in 5-min intervals. The corresponding probability distribution function (pdf) is shown in Fig. 2b, where the average wind speed is $\mu = 6.673 \text{ m/s}$ and the pdf follows nicely a normal distribution with $\sigma = 4.658 \text{ m/s}$. The variance of the measurements is $var = 22 \text{ m/s}$.

The pdfs corresponding to instantaneous wind speed measurements, at diverse world locations and sample rates, are available through local meteorological services but time-domain measurements of the wind speed, not only the frequencies, are required for analysis of the thermal stress in WT power converters.

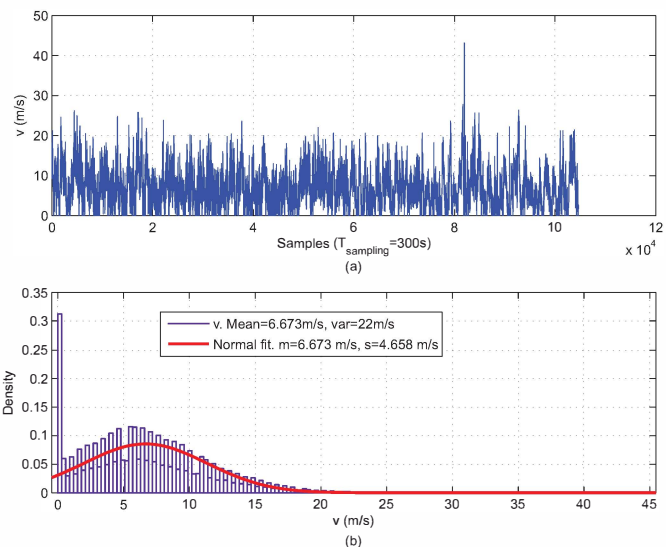


Fig. 2. Wind speed in one year at Aalborg University, Denmark, from 13-march-2012 to 13-march-2013. a) instantaneous values with 300s sample rate and b) probability distribution.

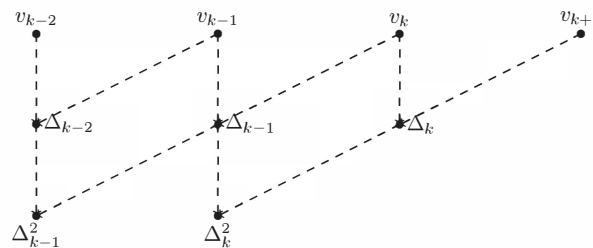


Fig. 3. Time evolution of values of v , Δ and Δ^2 .

III. GENERATION OF RANDOM WIND PROFILES FOR THERMAL STRESS EVALUATION

Time-domain representation of wind speed measurements is required to carry on simulations and evaluate the thermal stress in WT power converters. In order to reduce the computational burden an statistical approach can be employed to reduce the length of the measured wind profile while maintaining its relevant statistical parameters and time related info. Two operators are defined for this purpose:

$$\Delta_k(s) = s_{k+1} - s_k \quad (7)$$

$$\Delta_k^2(s) = \Delta_k(s) - \Delta_{k-1}(s) \quad (8)$$

where s_k is the value of the wind speed at sampling instant k . Considering that the sampling rate is maintained constant in the initial measured wind profile, these operators correspond to the first and the second derivative of the wind speed. The relation among wind speed samples and the operators is shown in Fig. 3.

The correlation, at a certain location, of the wind speed and the defined operators can be obtained. Fig. 4 shows the obtained probability distribution functions corresponding to Fig. 2. From Fig. 4a, given a certain speed v_k , there is a certain probability of having a wind speed variation at time $k + 1$,

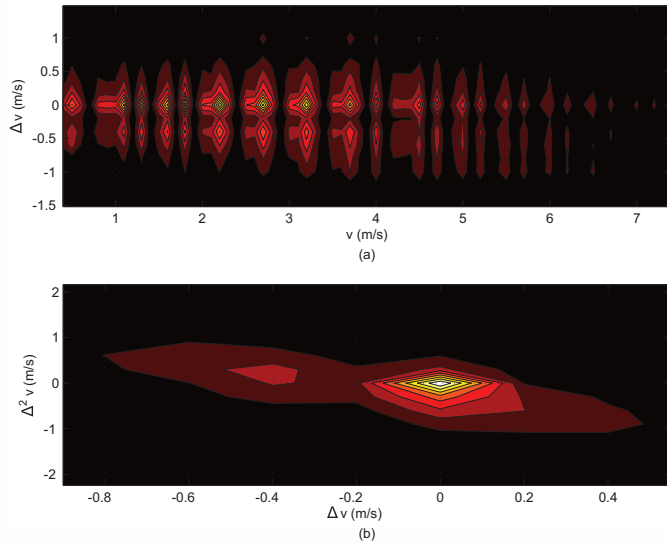


Fig. 4. Probability of having a) v with a certain Δv and b) Δv with a certain $\Delta^2 v$. Darker=lower probability.

which depends on v_k . High speed winds are less probable and, then, the variations of the wind speed are lower. From Fig. 4b, it can be seen that, despite of being low, if the wind speed increases at instant k then there is a high probability of decreasing in $k + 1$. The most probable values are obtained around $\Delta_k v = \Delta_k^2 v = 0$.

From (7)-(8) and Fig. 3, the following relationship can be obtained for the wind speed:

$$v_{k+1} = v_k + \Delta_k(v) = v_k + \Delta_{k-1}(v) + \Delta_k^2(v) \quad (9)$$

where, selecting random values of Δ_{k-1} and $\Delta_k^2(v)$ according to the obtained pdfs (depicted in Fig. 4), random wind profiles with customized lengths can be generated.

The algorithm of the proposed method is depicted in Fig. 5. During the initialization stage of this recursive algorithm, the distribution probability functions must be generated for the measured wind speeds: $P_1(\Delta, v)$ and $P_2(\Delta^2, \Delta)$. From this statistical analysis and the number of required random profiles (N), the number of bins and their range for the analyzed variables is established, which is required to define the range of validity of each generated value during the whole process. For each random profile a random seed (x_0), within a certain bin, is selected to apply the recursive algorithm ($x_i = x_0$). The first step, at time instant i , of the recursive algorithm is obtaining the intersection of plane $v = x_i$ with P_1 , which results on $P_1(\Delta_i) |_{x_i}$. The obtained pdf is divided into N equal probability intervals where a point Δ_i is selected randomly. This point must be employed in P_2 in order to generate Δ_i^2 following an equivalent procedure (intersection and random generation of a point in equal probability intervals of $P_2(\Delta_i^2) |_{\Delta_i}$). Having the values of x_i (generated from the previous iteration or due to the seed), Δ_i and Δ_i^2 , the new value of the wind speed is obtained by applying 9. This value must be checked in order to ensure that it is within the ranges of the wind speed profile. In the case of a wrong value, the random values of $P_1(\Delta_i) |_{x_i}$ and $P_2(\Delta_i^2) |_{\Delta_i}$ must be generated again.

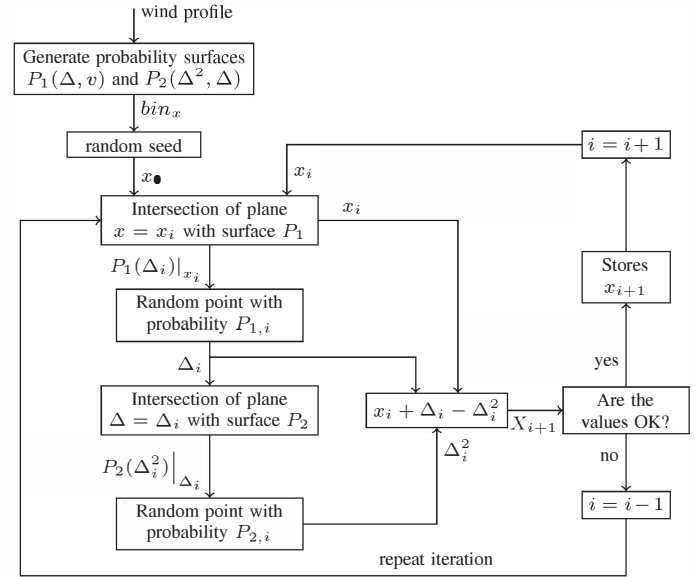


Fig. 5. Algorithm for generation of a random wind profile.

If the obtained value is correct, it is stored in memory and a new iteration is applied. The procedure must be carried up to obtain a wind profile of length L (the procedure finishes if $i = L$). For a new random profile, a different bin of the wind speeds is selected for generation of a new seed x_0 .

IV. SIMULATION MODEL

In order to evaluate the performance of the proposed wind profile generation algorithm, simulations have been carried out using MatLab and PLECS. A 3 MW wind turbine system model is established as shown in Fig. 6. A single stage gearbox is applied in the permanent magnet synchronous generator (PMSG) based wind turbine system to improve the reliability and also to avoid a large rotor diameter. The aerodynamic and generator parameters of the WT are listed in Table I. The dc bus voltage (V_{dc}) is 1100 V while the ac distribution line-to-line voltage is 690 V. The switching frequency is fixed at 2 kHz for both generator side and grid side converters. A speed controller is applied to the generator side converter to implement the maximum power point tracking (MPPT) of the wind turbine. The electrical power reference P_e^* is obtained by the MPPT algorithm based on the rotating speed ω_e . The main purpose of control method for the grid side converter is to stabilize the DC bus voltage V_{dc} , which is implemented by the d-axis current control of the grid-side converter. The current on q-axis can be regulated to control the reactive power injected to the grid, and it is set to be zero here.

The control scheme of the wind turbine system is illustrated in Fig. 6. Speed mode control is applied to the generator side converter to implement the maximum power point tracking (MPPT) of the wind turbine. The rotational speed reference ω_e^* is obtained by the MPPT algorithm based on the wind speed. The main purpose of control method for the grid side converter is to stabilize the DC bus voltage V_{dc} , which is implemented by d-axis current control. The current on q-axis can be regulated to control the reactive power injected into the grid.

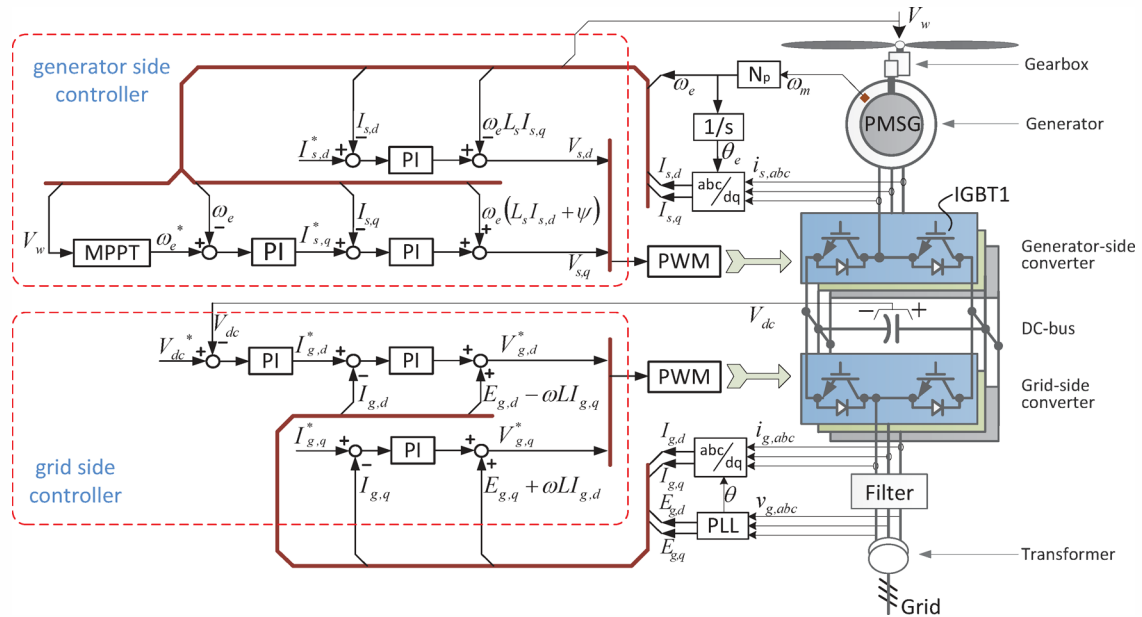


Fig. 6. 3 MW wind turbine model with all control loops.

TABLE I. WIND POWER SYSTEM PARAMETERS FOR 3 MW POWER LEVEL

Symbol	Name	Value
Aerodynamic parameters		
R	Blade radius	46.9m
$V_{w,in}$	Cut-in wind speed	3 m/s
$V_{w,r}$	Rated wind speed	12.5 m/s
$V_{w,off}$	Cut-off wind speed	25 m/s
$C_{p,max}$	Maximum power coefficient	0.48
λ_{opt}	Optimal tip speed ratio	8.1
PMSG parameters		
n_r	Rated rotor speed	15 rpm
N_g	Gear ratio	6.36
N_p	Number of pole pairs	20
ψ_m	Magnetic induced flux	2.8 Wb
L_s	Stator inductance	0.18 mH

In order to evaluate the thermal stress of the power converters, the power loss is calculated first [14]. Then based on the thermal model composed of the power loss source and thermal impedance [15], as shown in Fig. 7, the temperature of the power devices at different points can be estimated. The thermal impedance of the switch from junction to case is defined as a four-layer foster RC network, and the value of the thermal parameters of the power device can be obtained in the datasheets from the manufacturer. In this application a HiPak IGBT Module 5SNA 2400E170300 is employed as a simulation study. The thermal impedances from the case to heat sink are simplified as thermal resistances, which are 0.003 K/W and 0.006 K/W respectively for the IGBT and the diode. The thermal capacitance of the heat sink is much larger than that of the power devices, thus the temperature of the heat sink is much more stable compared with the power devices and thereby it is assumed to be constant as 50 °C [16].

The impact of the wind speed variation on the thermal stress of the power device is shown in Fig. 8. In the upper part, the two red curves express the different junction temperatures of the power devices in the wind turbine system under different wind speed conditions. The wind speed for

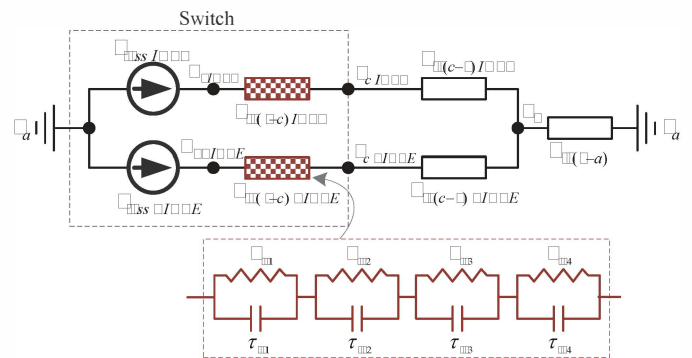


Fig. 7. Thermal model of the power devices. T_a : ambient temperature, T_j : junction temperature, T_c : case temperature, T_h : heat sink temperature. $Z_{th(j-c)}$: thermal impedance from junction to case, $Z_{th(c-h)}$: thermal impedance from case to heat sink, $Z_{th(h-a)}$: thermal impedance from heat sink to ambient.

the higher temperature is 12.5 m/s, while the wind speed for the lower temperature is 10 m/s. In the lower part, the junction temperatures under different wind speed variations are compared. The mean value and the cycle period of the wind speeds between these two cases are the same, which are 9 m/s and 60 s. But the amplitudes of the wind speed cycles are different, which is 2 m/s in wind profile #1 and 3 m/s in wind profile #2 respectively. As a consequence, the variation in junction temperature under wind profile #2 is larger than that under wind profile #1. According to the results, the junction temperature of the power device of the wind power converter is not only related to the mean wind speed value but also to the variation of the wind speed.

V. SIMULATION RESULTS

The proposed algorithm for generation of random wind profiles for evaluation of the thermal stress in WT power converters has been applied to a 10 hour wind speed register, with

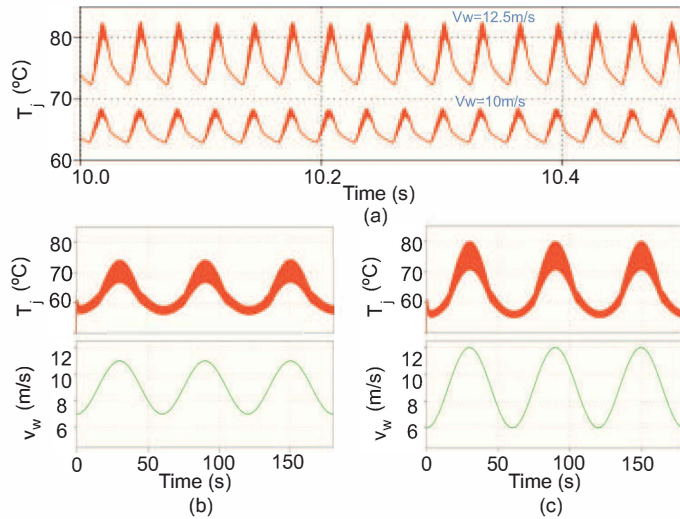


Fig. 8. Impact of the wind speed variation on thermal stress of the power device. a) Two wind speed profiles with different average values, b) Effect of 2 m/s amplitude variations and c) Effect of 3 m/s amplitude variations.

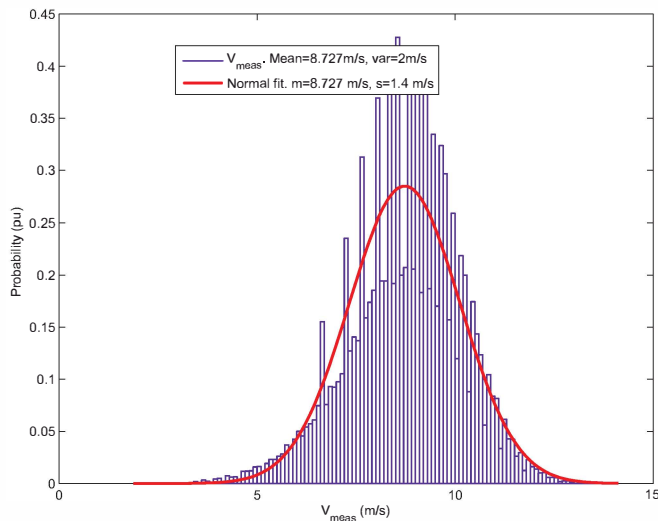


Fig. 9. Probability of having a certain wind speed within the measured wind profile.

a 5 Hz sampling rate. The probability distribution function of the initial wind profile is shown in Fig. 9, which can be fitted by means of a normal distribution with $\mu = 8.727 \text{ m/s}$ and $\sigma = 1.4 \text{ m/s}$. This wind speed profile has been processed with the proposed algorithm (see Fig. 5) in order to obtain a set of 20 random wind profiles, with 10 minutes length each one (with the same sampling rate). The pdfs of the obtained wind profiles are shown in Fig. 10, where mean and standard deviations are provided for each generated profile. In all the cases, the measured mean and standard deviations values are $\mu = 8.73 \text{ m/s}$ and $\sigma = 1.4 \text{ m/s}$, which match the values of the measured wind speed profile. Comparing the probability distribution functions of both the measured and the generated wind speed profiles it can be noted that the number of bins decreases once the proposed algorithm is applied, which is due to the fact that a lower number of samples is available and the Freedman-Diaconis rule has been applied for representation

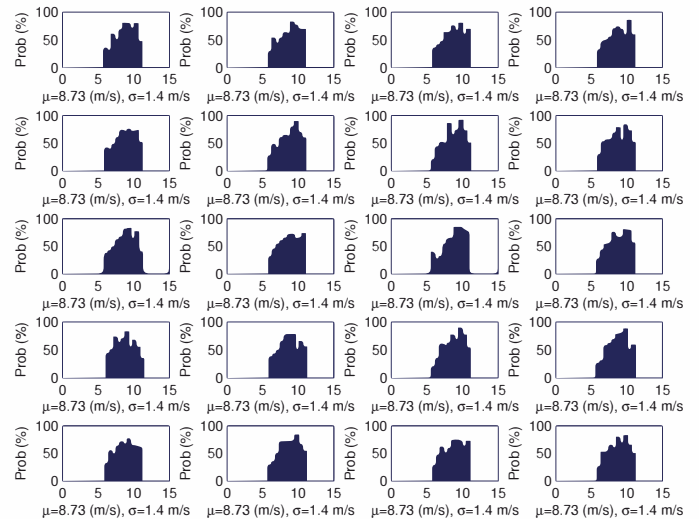


Fig. 10. Probability distribution functions corresponding to the generated 10 minute wind speed profiles.

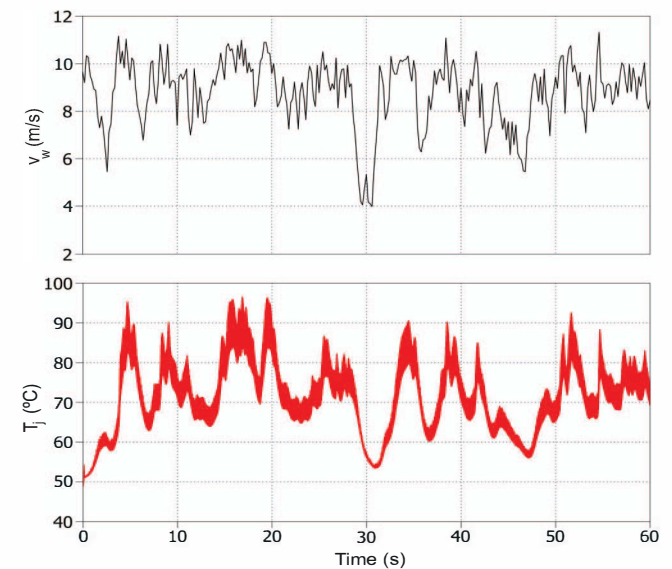


Fig. 11. One of the generated 10 minute random wind profiles. a) Wind speed (60 seconds) and b) the evaluated IGBT junction temperature.

purposes. As a consequence, first and fourth quartiles of the pdfs in Fig. 10 end roughly. In order to obtain smoother pdfs, the length of the generated wind speed profiles must be increased.

The generated random wind speed profiles have been applied to the simulation model, according to Fig. 6. A 60 second extract of one of these generated wind speed profiles is shown in Fig. 11a, which results in the IGBT junction temperature plotted in Fig. 11b. As it can be seen, variations associated to the amplitudes of the temperature cycles follow the amplitude variations of the wind speed.

The obtained temperatures have been analyzed by applying a rainflow analysis. The obtained results are shown in Fig. 12 and compared to the obtained ones in the case of the initial wind speed profiles. The density of cycles corresponding to the

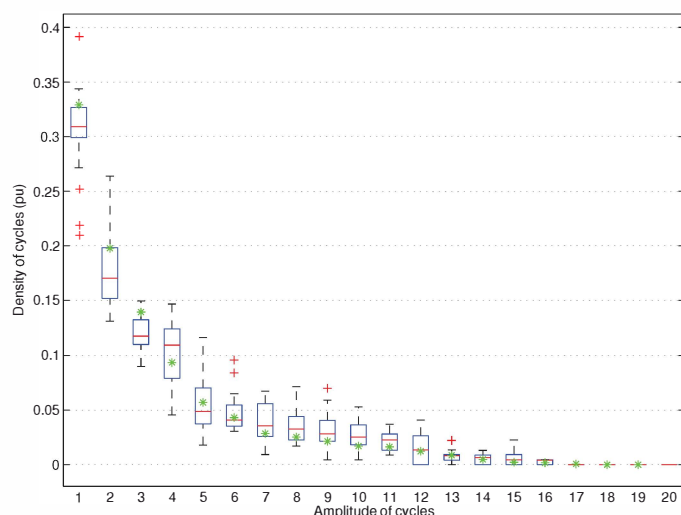


Fig. 12. Density of temperature cycles of a certain amplitude for both the measured (asterisks) and the generated (box plots) wind speed profiles.

10 hour measured profile are depicted by means of asterisks while the amplitudes of the temperatures cycles, in the case of the set of random profiles, are depicted by means of boxes. The bottom line of the box is limiting the first and the second quartiles of the distribution of densities while the upper one limits the third and fourth quartiles. The whole distribution is delimited by means of short black lines. As it can be seen, all the temperature cycles corresponding to the measured wind speed are within these limits and, as a consequence, the proposed wind speed random generator can replicate the thermal stress of the power devices obtained by means of the measured wind profile but reducing the computational burden and allowing a wider stress range to be considered.

VI. CONCLUSION

Wind speed variations increase the thermal stress of the power devices in power converters for WT. In order to evaluate the stress of the power devices random wind profiles, matching the measured wind speeds at a certain location, can be generated. By applying the proposed random wind profile generator in the thermal stress analysis for WT power converters the required simulation time can be reduced, while the whole pdf of the wind speeds, at a certain location, is considered and not only the part corresponding to the measured wind profile. The obtained results show that in the case of a measured 10 hour wind speed profile and 10 minutes generated ones the simulation time can be reduced in a 1/60 ratio.

The execution time can still be improved due to the fact that all the generated random wind speed profiles are independent and, using these profiles, the simulations can be carried out in parallel, which cannot be done in the case of the measured wind speed profile. Moreover, due to the employed statistical approach, the impact of a wider set of wind speed conditions can be analyzed by applying the proposed method, which will result in a probability of having a certain thermal stress of the WT power converter.

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