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Synthesis of a compact wind profile using evolutionary algorithms for wind turbine system with storage

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***Abstract*— In this paper, the authors investigate two methodologies for synthesizing compact wind speed profiles by means of evolutionary algorithms. Such profile can be considered as input parameter in a prospective design process by optimization of a passive wind system with storage. Compact profiles are obtained by aggregating elementary patterns in order to fulfil some target indicators. The main difference between both methods presented in the paper is related to the choice of these indicators. In the first method, they are related to the storage system features while they only depend on wind features in the second.**

I. INTRODUCTION

Small renewable energy systems as wind turbine are actually very useful especially for remote areas for electricity production, pumping and water desalination. The design of these systems requires taking account of the wind potential and the load demand. In a prior study [1], a battery sizing methodology has been presented for a 8 kW stand alone passive wind turbine system (see Fig. 1). This method consists in determining the constraints (in terms of power and energy needs) associated with the storage system from temporal Monte-Carlo-based simulations including wind and load profile variations. In this work, the evolution of the wind speed was considered as stochastic while the load profile was deterministically day to day repeated. In order to take account of the wind potential features, multiple dynamics have been integrated in the wind profile, i.e. fast dynamics related to turbulence phenomena as well as slow dynamics related to seasonality represented with a Weibull statistic distribution. Consequently finding the most critical constraints on the storage system requires the system simulation on large time duration in order to include all dynamics (i.e. wind and load profiles dynamics) and all correlations of those variables (e.g. time windows with small wind powers and high load powers and inversely).

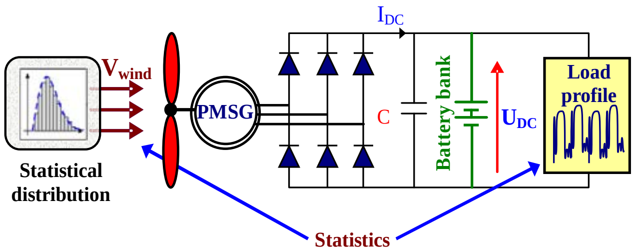
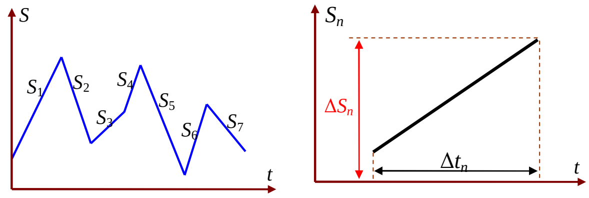


Figure 1. Passive wind system subjected to a wind profile and a load profile

It is shown in [1] that 70 days of system simulation are necessary to obtain an accurate sizing of the battery, allowing the correlation of the load profile with the wind conditions. If this approach can be locally used to optimize the battery sizing when the other components of the passive wind turbine are known, it cannot be applied in a global optimization context [2] requiring a wide number of system simulations. In this case, the computational time would be drastically increased by the repetition of simulations on large time windows. In order to face this issue, we investigate in this paper a methodology for reducing typical wind profile while keeping the wind features in terms of intensity, variability and statistics.

II. SYNTHESIS PROCESS OF COMPACT PROFILES FOR ENVIRONEMENTAL VARIABLES

The synthesis process of compact wind profiles is based on the approach developed in [3] for railway driving missions. It consists in generating a fictitious profile of any environmental variable (e.g. temperature, wind speed, solar irradiation…) by fulfilling some constraints related to the variable (typically minimum, maximum and average value, probability distribution function…). These constraints are expressed in terms of target indicators that can be evaluated from a set of real cycles or from a single real cycle of large duration. The fictitious profile is obtained by aggregating elementary segments as shown in Fig. 2. Each segment is characterized by its amplitude ΔS_n ($\Delta S_{minref} \leq \Delta S_n \leq \Delta S_{maxref}$) and its duration Δt_n ($0 \leq \Delta t_n \leq \Delta t_{compact}$).



(a) : Profile generated by segments *(b) Pattern parameters*: ΔS_n *et* Δt_n

Figure 2. .Principle of the profile generation

A time scaling step is performed after the profile generation in order to fulfil the constraint related to the time duration, i.e. $\Sigma\Delta t_n=\Delta t_{compact}$. Finding a compact fictitious profile of an environmental variable consists in finding all segment parameters so that the generated profile fulfils all target indicators on the reduced duration $\Delta t_{compact}$. This results in solving an inverse problem with $2N$ parameters where N denotes the number of segments in the compact profile. This can be done using evolutionary algorithms [4] and especially with the clearing method [5] well suited to treat this kind of problem with high dimensionality and high multimodality. It should also be noted that the number N of segments can be itself optimized through a self-adaptive procedure [3].

III. APPLICATION TO COMPACT PROFILE SYNTHESIS OF WIND SPEED

In this section the synthesis process is applied on an actual wind speed profile of 200 days duration with the aim of generating a compact profile on a reduced duration $\Delta t_{compact}$. Two different approaches are investigated depending on the choice of the target indicators used for generating the fictitious compact wind speed profile.

A. First method: target indicators are related to storage system features

The global sizing of the storage system is related to the three following variables: $P_{BAT\text{MAX}}$, $P_{BAT\text{MIN}}$ and ES which respectively denote the maximum and the minimum storage powers in the battery $P_{BAT}(t)$ and the maximum energy quantity imposed to this storage. These variables are extracted from the simulation of a 8 kW passive wind turbine system and used as target indicators in the synthesis process.

Note that the reference value of the storage useful energy ES_{ref} is defined as follows:

$$ES_{ref} = \max E(t) - \min E(t) \tag{1}$$

where $E(t) = \int_0^t P_{BAT}(\tau)d\tau \qquad t \in [0, \Delta t_{ref}]$

Note that $E(t)$ is a saturated integral, with 0 as upper limit so that the battery storage is only sized in discharge mode to avoid oversizing it during wide charge period (huge winds with reduced load). An additional target indicator is considered to take account of statistic features of the reference wind cycle. We use the Cumulative Distribution Function $CDF(V_{ref})$ [6]-[8] computed from the corresponding probability density function (PDF_{ref}) related to the reference wind speed behaviour.

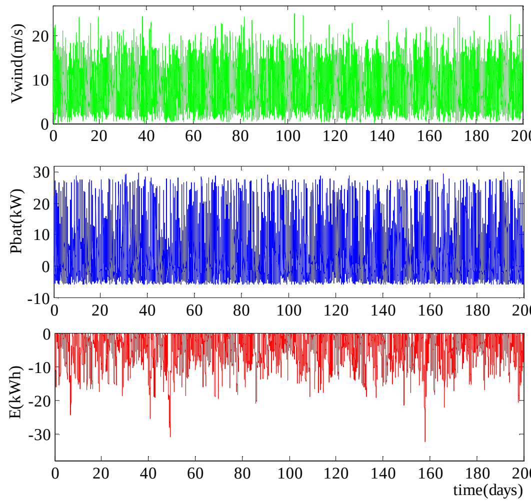


Figure 3. Actual 'reference' wind speed profile, storage power and energy.

PDF_{ref} is evaluated on 20 equally spaced intervals between 0 and the maximum wind speed value $V_{ref\max}$. Finally, the global error ε to be minimized in the synthesis profile process can be expressed as:

$$\varepsilon = \left(\frac{P_{BAT\,MAX} - P_{BAT\,MAX\;ref}}{P_{BAT\,MAX\;ref}}\right)^2 + \left(\frac{P_{BAT\,MIN} - P_{BAT\,MIN\;ref}}{P_{BAT\,MIN\;ref}}\right)^2 + \left(\frac{ES - ES_{ref}}{ES_{ref}}\right)^2 + \varepsilon_{stat} \tag{2}$$

where the statistic error ε_{stat} denotes the mean squared error between both *CDF*s relative to reference and generated wind speed profiles:

$$\varepsilon_{stat} = \frac{1}{20} \times \sum_{k=1}^{20} \left(\frac{CDF(k) - CDF_{ref}(k)}{CDF_{ref}(k)}\right)^2 \tag{3}$$

All 'ref' indexed variables are based on the reference wind profile of Figure 3. The inverse problem has been solved with the clearing algorithm [5] using a population size of 100 individuals and a number of generations of 500 000. Multiple optimization runs were performed with different compaction time $\Delta t_{compact}$. In particular, the minimum compaction time (i.e. min $\Delta t_{compact}$) was determined using dichotomous search in order to ensure a global error ε less than 10^{-2}. Table I shows the values of the global error ε versus the compaction time. It can be seen that the lowest value for $\Delta t_{compact}$ ensuring the fulfillment of the target indicators with sufficient accuracy is about 10 days. We give in Fig. 4 the characteristics of the generated wind profile obtained from the aggregation of 109 elementary segments fulfilling all target indicators. It can be seen from this figure that the *CDF* of this compact wind profile closely coincides with that of the reference wind profile.

TABLE I. INFLUENCE OF $\Delta t_{compact}$. ON THE GLOBAL ERROR ε

$\Delta t_{compact}$ (days)	40	20	10	5
Global error ε	$\approx 8.10^{-3}$	$\approx 9.10^{-3}$	$\approx 9.10^{-3}$	$\approx 7.10^{-2}$

TABLE II. TARGET INDICATORS OF THE GENERATED WIND SPEED PROFILE.

	Reference profile	Compact profile	Error (%)
P_{BATMAX} (kW)	30	30	0
P_{BATMIN} (kW)	–5.88	–5.82	0.1
ES (kWh)	32.36	32.4	0.12

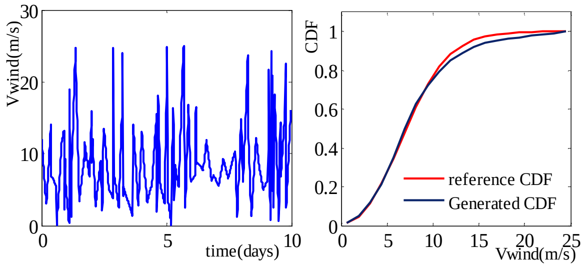


Figure 4. Generated wind speed with corresponding CDF.

Table II compares the values of the target indicators related to the battery sizing for the reference and the fictitious profile generated with the clearing algorithm. A good agreement between those values indicates that the compact wind profile will lead to the same battery sizing as the reference wind profile on larger duration.

B. Second method: target indicators only related to the wind features

In this second approach target indicators are only related to the wind features. We first consider three indicators V_{max}, V_{min} and $<V^3>$ representing the maximum and minimum speed values and the average cubic wind speed value. Note that $<V^3>$ is used instead of the average wind speed value $<V>$ because the power produced by the wind turbine is directly proportional to the cubic wind speed value. Similarly to the previous approach, we also add as target indicator the *CDF* associated with the wind profile in order to take account of the wind statistic. Finally, we consider as last indicator the variable E_V which is defined as:

$$E_V = \max_{t\in[0,\Delta t]} E(t) - \min_{t\in[0,\Delta t]} E(t) \qquad (4)$$

where $E(t) = \int_0^t (V^3(\tau) - <V^3>)d\tau \qquad t \in [0, \Delta t]$

V^3 being proportional to the power provided by the wind turbine, E_V will be called "intermittent wind energy" in the following. In fact, E_V plays a similar role with *ES* in the previous approach for the storage system.

The global error ε to be minimized with this second approach can be expressed as:

$$\varepsilon = \left(\frac{V_{max} - V_{max\ ref}}{V_{max\ ref}}\right)^2 + \left(\frac{V_{min} - V_{min\ ref}}{V_{min\ ref}}\right)^2 + \left(\frac{<V^3> - <V^3>_{ref}}{<V^3>_{ref}}\right)^2 + \left(\frac{E_V - E_{V\ ref}}{E_{V\ ref}}\right)^2 + \varepsilon_{stat} \qquad (5)$$

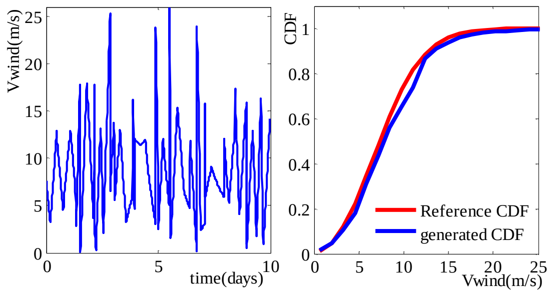


Figure 5. Generated wind speed with corresponding CDF.

where ε_{stat} is computed according to (3) and where the reference intermittent wind energy E_{Vref} is scaled according to the compact profile duration:

$$E_{V\ ref} = \frac{\Delta t_{compact}}{\Delta t_{ref}} \times E_{Vref}(\Delta t_{real}) \qquad (6)$$

The inverse problem was solved with the clearing algorithm with the same control parameters as in the previous subsection. Multiple optimization runs were performed with different compaction time $\Delta t_{compact}$. The minimum value for this variable ensuring a global error less than 10^{-2} was identical to that found with the previous approach (i.e. 10 days). Fig. 5 shows the characteristics of the generated wind profile obtained from the aggregation of 130 elementary segments fulfilling all target indicators. The good agreement between the compact generated profile and the reference profile can also be observed in this figure in terms of CDF. Finally, Table III shows that the values of the target indicators are very close in both cases.

For comparison with the previous approach, we also give the sizing of the battery obtained from the simulation of the compact profile. It should be noted that contrarily to the first approach, the second one does not include correlations between wind and load profiles because it only considers wind speed variations to generate the compact wind speed profile. Consequently, the second approach does not ensure to find the most critical constraints on the storage device. This can be *a posteriori* done by sequentially shifting the obtained wind profile on its 10 days time window in compliance with the deterministic load profile day to day repeated. The maximum storage energy quantity *ES* is computed for each phase shift and the highest value is returned (See Fig. 6). By this way, a value of 34.4kWh is obtained for *ES* which is very close to that resulting from the reference profile simulation (i.e. 32.3kWh).

TABLE III. TARGET INDICATORS OF THE GENERATED WIND SPEED PROFILE.

	Compact profile	Reference profile	Error (%)
V_{max} (m/s)	25.1	25.9	3.58
V_{min} (m/s)	0	0	0
$<V^3>$ (m^3/s^3)	876.4	871.4	0.57
E_V (m^3/s^2)	3.7	3.716	0.44

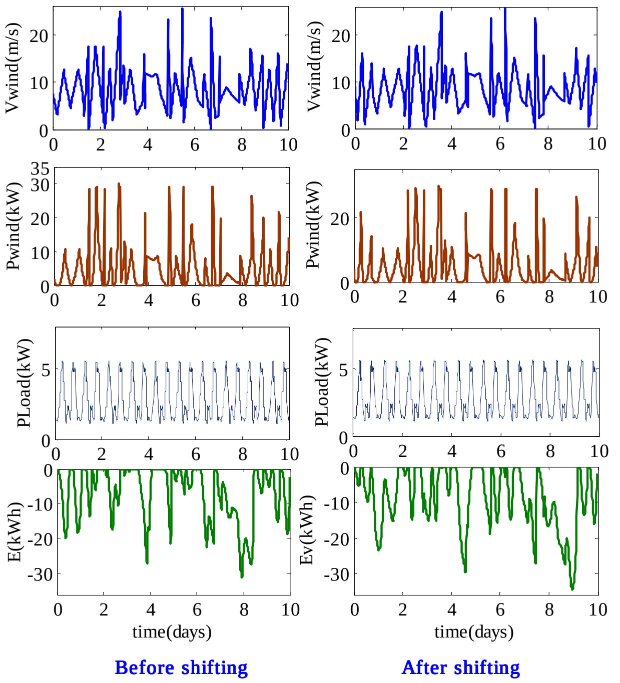


Figure 6. Illustration of the phase shift of the wind profile (generated with the second method) on the battery sizing.

C. *Validation of the previous results for various wind turbine sizes*

In order to validate the effectiveness of the previous approaches, the compact wind profiles obtained in both methods are used to estimate the battery sizing for various wind turbines. Three wind turbines are considered with nominal power of 7 kW, 8 kW and 9.5 kW. Tables below summarize the results obtained for the battery sizing variables (i.e. P_{BATMAX}, P_{BATMIN} and *ES*) for each wind turbine sizing with the reference profile of 200 days duration and with the compact profiles resulting from both approaches developed in the previous sections. A good agreement between those variables is obtained in all cases whatever the sizing of the wind turbine. This indicates that compact profiles generated by our synthesis process can be used instead of the reference one for the battery sizing. They allow a significant reduction of the computational time due to the compaction of the wind speed profile (i.e. 10/200 days). In our case, the time window of the wind speed profile has been divided by 20. It can also be observed from these tables that P_{BATMIN} always reach the value of –5.8 kW whatever the wind turbine size. This corresponds to the maximum battery discharge power which occurs when the load power is maximal and when the wind equals zero (i.e. a null wind power whatever the turbine size). On the other hand P_{BATMAX} increases with the increase of the wind turbine sizing at a value corresponding to the maximum power delivered by the wind turbine (at maximum wind speed) when the load power equals 0. It can be verified that both reference and compact wind profiles are able to provide the critical conditions in terms of powers and energy imposed to the storage. Finally, it should be mentioned that these conditions are always obtained for the same phase shift in the second approach.

TABLE IV. RESULTS OBTAINED FOR A 7KW WIND TURBINE.

	Reference profile of 200 days	Method 1 for 10 days	Method 2 for 10 days
P_{BATMAX} (kW)	26.3	26.3	26.3
P_{BATMIN} (kW)	–5.88	–5.83	–5.83
ES (kWh)	46.9	46.2	46.8

TABLE V. RESULTS OBTAINED FOR A 8KW WIND TURBINE.

	Reference Profile of 200 days	Method 1 for 10 days	Method 2 for 10 days
P_{BATMAX} (kW)	30	30	30
P_{BATMIN} (kW)	–5.88	–5.82	–5.2
ES (kWh)	32.36	32.4	34.4

TABLE VI. RESULTS OBTAINED FOR A 9.5KW WIND TURBINE.

	Reference profile of 200 days	Method 1 for 10 days	Method 2 for 10 days
P_{BATMAX} (kW)	34.8	34.8	34.8
P_{BATMIN} (kW)	–5.82	–5.82	–5.82
ES (kWh)	26.14	28.9	28

IV. CONCLUSION

In this paper, two different approaches have been developed for compacting wind speed profiles. These approaches consist in generating compact wind profiles by aggregating elementary parameterized segments in order to fulfil target indicators representing the features of a reference wind profile of larger duration. The inverse problem involving the determination of the segment parameters is solved with an evolutionary algorithm. It is shown that both approaches are able to represent the main features of the reference profile in terms of wind farm potential and are also relevant for evaluating the critical conditions imposed to the battery storage (i.e. power and energy needs) in a hybrid wind turbine system. From these compacts profiles, subsequent reduction of the computation time should be obtained in the context of the optimization process of such systems.

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