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Experimental Characterization of the Action of an Artificial Wind on a Wind Turbine and Optimization of the Storage Efficiency of Compressed Air in Hybrid PV/Wind Turbine Systems

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Abstract: The general idea of this work is to improve the performance of CAES (compressed air energy storage) for its application in solar and wind systems through a restitution technique by creating an artificial wind. The efficiency of compressed air storage is often presented as a limit to its application. The present work describes a series of manipulations carried out in order to increase the yield. As the action of the artificial wind on the wind turbine is characterized by a reduced attack surface, a treated wind, a constant direction, an adjustable speed, it is therefore a question of acting on all the controllable parameters of the artificial wind to find the best way to use it to produce more energy from a certain quantity stored in a tank. The main manipulations consisted in determining: the optimal number of points of attack of the wind turbine; the nature of the action (continuous or interrupted) of the wind; the frequency of wind action and the duty cycle.

Key words: CAES, artificial wind, characterization of a system, optimization of a process.

1. Introduction

To guarantee the permanent availability of the electrical energy produced by intermittent sources, the production line is associated with an energy storage system that takes over when the main sources are no longer available. In the case of storage in the form of compressed air, it is possible to create an artificial wind to act on a wind turbine. The efficiency of compressed air storage is often presented as a limit to its application [1]. The present work attempts to find the most efficient and effective way to produce energy by the process. The action of the artificial wind on the wind turbine deserves special attention because it differs from the action of the natural wind for several reasons. If the natural wind is intermittent, steering furtively variable and blows everywhere, carrying dust and therefore uncontrollable [2], the artificial wind is on the other hand treated, regulated, acting on a precise surface and therefore perfectly controllable. The action of such a carefully directed wind should be more effective than that of a natural wind.

To verify this hypothesis in order to optimize the use of such a technology to increase the efficiency of the CAES (compressed air energy storage) in order to make it effectively competitive with current storage techniques, we will proceed to a series of manipulations.

2. Material and Methods

2.1 Presentation of the Material Used for the Manipulations

To perform the manipulations to characterize the action of artificial wind on a wind turbine, the experimental equipment that was used consists of a wind turbine, a compressor and measuring devices.

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2.1.1 The Wind Turbine Used

The wind turbine is the element on which the artificial wind created by the expansion of the compressed air acts to produce electric power again. If the action of the natural wind on a wind turbine is determined from the parameters of the wind and the wind turbine [3], we must remember here that the action of an artificial wind deserves a new study. The essential characteristics of the wind turbine used for handling are shown in Table 1.

2.1.2 The Mini-compressor Used

The compressor brand SILVERLINE and commercial reference ME130016 (TS-425689) are widely used and generally used in Maroua to inflate the tires. Easily available at a lower cost, its characteristics are presented in Table 2.

2.1.3 The measuring Devices Used

Measuring devices were used to take different measurements. The list of devices used is given in Table 3.

2.2 Description of the Methods

2.2.1 Study of the Action of the Artificial Wind on the Wind Turbine

From the knowledge of the maximum duration of the dead period, the storage device must be able to ensure the continuity of the supply of energy. The essential characteristics of this loop must be sufficiently defined:

- The power absorbed by the compressor;
- The time taken to store the desired air mass;
- The length of time during which the air tank discharges by rotating the wind turbine at a sufficient speed.

All this makes it possible to establish a relationship between the charge *R* and the energy to be stored and also to determine the storage efficiency of the compressed air.

Considering the retroactive system with its inputs (solar rays, natural wind, and compressed air flow) and its output as shown in Fig. 1, it will be necessary to study the behavior of this output.

Table 1 Characteristics of the wind turbine.

Designation	Value
Mark and type	PWG and FD2.6-600
Number of blades	3
Rated power 600 W	600 W
Rated wind speed	8 m/s
Minimum wind speed	2 m/s
Maximum wind speed	15 m/s
Safety speed	20 m/s
Length of the blades	64 cm

Table 2 Essential characteristics of the compressor.

Maximum pressure	17 bar
Power supply	12 V
Power	0, 3 HP ou 242 W
Cord length	2.8 m
Length of the pipe	5 m
Tank	20 L
Time taken to fill the tank	5 minutes

Table 3 List of measuring devices.

Device	Size measured	unit
Stopwatch	Time or duration	second
Anemometer	Wind speed	m/s
Flowmeter	Flow rate	m^3/s
Manometer	Pressure	Pascal
Tachometer	Number of rounds	rd

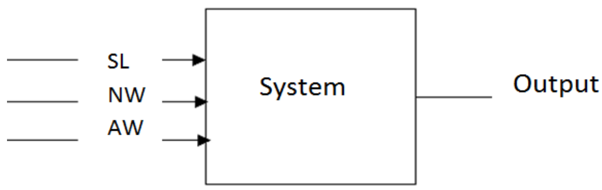

Fig. 1 The system input/output model.

The output curve will then allow us to determine during the year the periods during which the hybrid power plant will not be able to supply the power required by the load and the maximum duration of supply of the load from the stored energy.

Feedback loop performance: filling the tank and rotating the turbine to power the compressor only.

The last part of the study will be devoted to the optimization of the action of the artificial wind on the wind turbine, it will be necessary to determine:

- the most appropriate position and angle of attack of the wind source relative to the blades;

- the most efficient mode using one or more valves;
- the most effective action by letting the air escape continuously or interrupted.

2.2.2 Feedback Loop Performance Study

To analyze the performance of this loop, the following two questions should be simply answered:

- How much electrical energy does the compressor use to store a given mass of air?
- How much energy is produced by using this stored air mass?

The storage loop is therefore considered as a system whose input is the energy required to store the desired air mass and the output as the total energy produced by the wind turbine under the effect of the only artificial wind.

$$r = \frac{E_{out}}{E_{in}}$$

3. Results

3.1 Determination of the Ideal Position of the Valve

One of the differentiating elements of the artificial wind with the natural wind is also its localized action on a blade. If the natural wind attacks all parts of all the blades, the opening of a valve can attack only a small area of the blades. It is for this reason that the first manipulation relating to the restitution of stored energy is concerned with the position of the valve relative to the axis of the wind turbine. The work of D. Le Gourières [4] shows that the most effective angle of attack is 90° or π/2 rd.

It is therefore a question of attacking the blade at a position distant from *d* with respect to the axis or with respect to the end of the blade (Fig. 2).

The procedure for this manipulation consists of:

- Fix the air flow at a constant;
- Arrange the valve at a position a distance *d* from the axis;
- Rotate the wind turbine and wait for normal operation;
- Time the time taken to complete a complete turn.

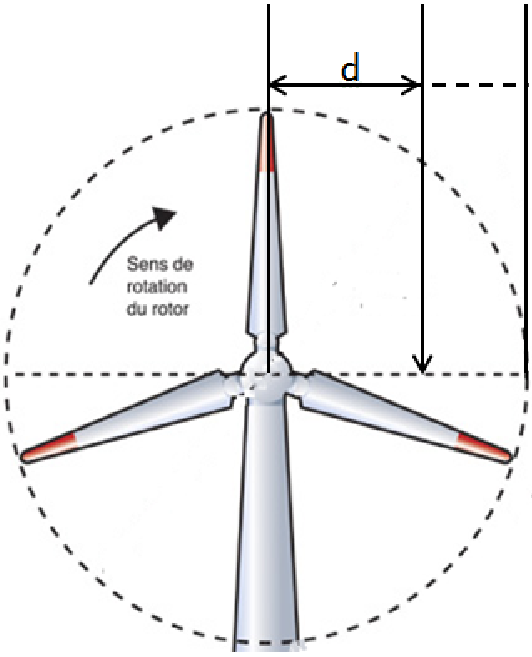

Fig. 2 Position of the valve with respect to the rotor axis.

The different values of time and position are shown in Table 4.

From this manipulation, the following observations are made:

- The speed of rotation of the blades increases with the distance between the valve and the axis of rotation;
- At the end of the blades, the speed is not optimal.

One can draw a first conclusion that the optimal position of the valve is close to the end. The last line of Table 4 also concludes that the rotational speed is an increasing function of the position; it is almost linear.

The drop at the end is explained by the fact that part of the air flow coming out of the valve no longer attacks the blade. The attacked surface has considerably diminished; causing a loss of energy.

The distance separating the end of the valve from the circle described by the end of the blade must also be as small as possible. By further moving the valve away from the blades, the wind loses speed and therefore energy. In Table 5, the manipulation was resumed to determine the centimeter the ideal distance. Fig. 3 shows that the speed of rotation increases with the distance from the axis.

Table 4 Variation of the speed of rotation of the blades according to the position of the valve.

Distance *d* (m)	0	8	16	24	32	40	48	56	64
Time *t* (s)	∞	43	22	15	10.5	8.5	7	6	8
Speed (rd/min)	0	1.40	2.73	4.00	5.71	7.06	8.57	10.00	7.50
d.t	-	344	352	360	336	340	336	336	512

Table 5 Determination of the ideal position of the valve.

Distance *d* (m)	0	8	16	24	32	40	48	56	60	62	63
Times *t* (s)	∞	43	22	15	10.5	8.5	7	6	5.5	5.3	5.7
Speed (rd/min)	0	1.40	2.73	4.00	5.71	7.06	8.57	10.00	10.91	10.95	10.5

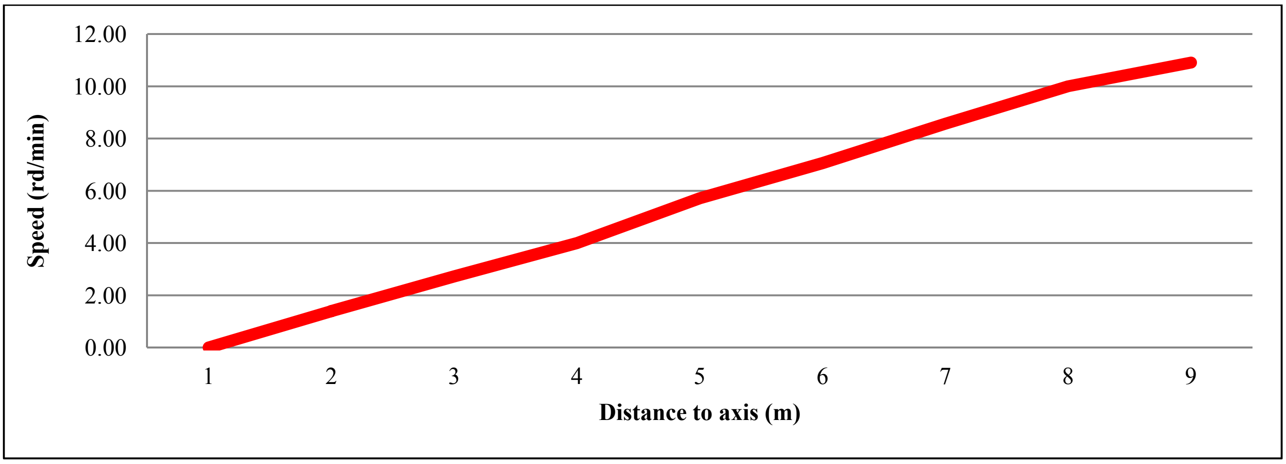

Fig. 3 Evolution of the speed of rotation as a function of distance.

3.2 Determining the Optimal Number of Points of Attack

The purpose of this manipulation is to determine if, instead of a single valve that drives the wind turbine to a specific point, a flow-sharing valve torque is more efficient. And if so, does the increase in the number of attack points lead to an increase in this efficiency?

Under the conditions of the manipulation described in Part 3.1 above, a bypass of the air duct makes it possible to use two valves arranged so as to produce a force torque. The air flow is then shared equally between the two valves. This ensures that the amount of air stored will run out at the same time for both scenarios. Then we add a second couple and so on under the same conditions.

The measurements are co-signed in Table 6. The results of this manipulation show that a torque of force as indicated in Fig. 4, that is to say two valves, rotates the wind turbine faster than a single valve. By increasing the number of valve pairs, the speed does not change. It can be concluded that the optimum number of valves for this application is 2. Both valves are arranged to produce two torsional forces.

3.3 Comparative Analysis of the Continuous and Interrupted Actions of the Valves

This manipulation aims to compare the efficiency of the actions of the artificial wind on the wind turbine according to whether the opening of the valves is permanent or interrupted.

It is clear that keeping the same flow rate, the speed of rotation is smaller if the valves are occasionally closed or reduced. However, it has been noted that the wind turbine takes less time to reach steady state while it takes twice as long to turn when even the wind source is stopped. This observation led us to make this manipulation whose results are recorded in Table 7. From data of Table 7, we get the curves of the evolution of the times to up and to down in Fig. 5.

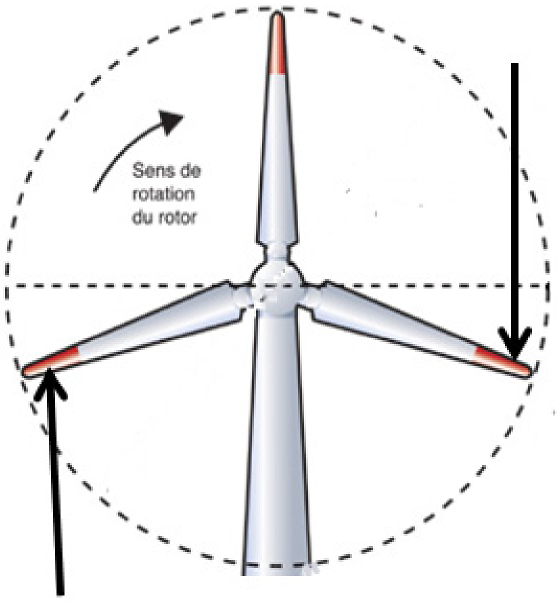

Fig. 4 Action of a couple of artificial wind on the wind turbine.

Table 6 Evolution of the speed according to the number of points of attack.

Number of couple of valves	0.5	1	2	3
Corresponding number of valves	1	2	4	6
Time for 1 round (s)	6	5	5	5
Speed (rd/min)	10	12	12	12

Table 7 Time comparison of transient walking and stopping regimes.

Manipulation number	1	2	3	4
Speed (rd/min)	6.00	8.00	10.00	12.00
Time to reach steady state Tm (min)	1.00	1.33	1.67	2.03
Time to reduce speed by half $T_{1/2}$ (min)	1.52	2.09	2.53	3.13
Time to stop Ta (min)	2.51	3.42	4.19	5.07
$T_{1/2} - T\text{m}$	+0.52	+0.76	+0.86	+1.10
$T\text{a} - T\text{m}$	+1.51	+2.09	+2.52	+3.04

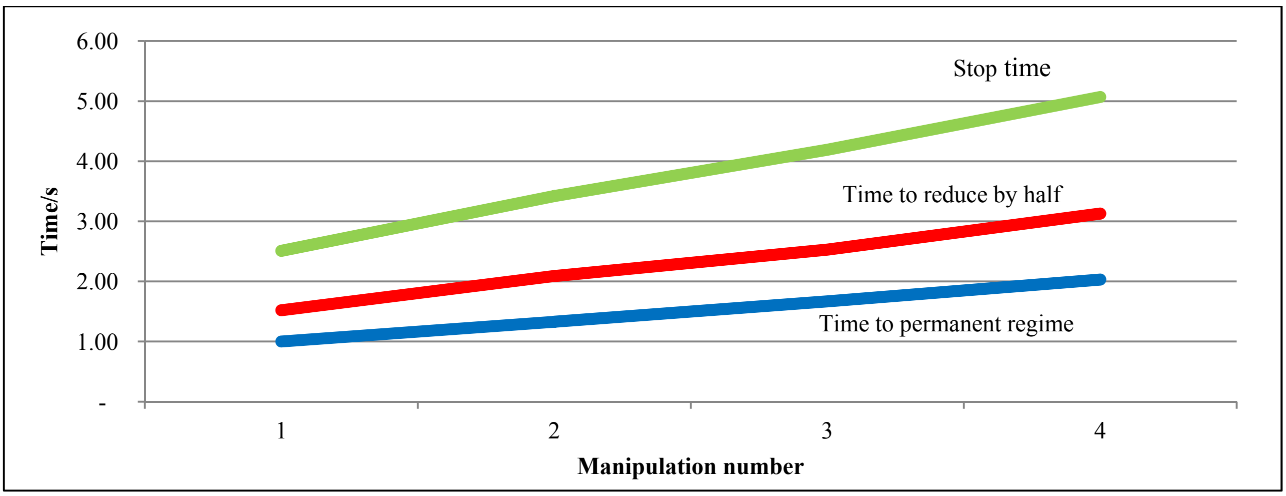

Fig. 5 Time evolution curves of transient gating and stopping regimes.

The results in Table 7 make it possible to surmise that by cutting the source from time to time, more power will be produced because the operating time increases. Indeed, the time set to reach the steady state is much lower than the time taken for the total stop. It is also lower than the time taken for speed to halve. It can be concluded that by interrupting the artificial wind from time to time, the overall energy produced is greater.

3.3.1 Study of the Period of the Interrupted Action of the Valves

To make this comparison convincing, we use the same amount of air stored in similar conditions to run the wind turbine in different ways: without interruption of the valves, with periodic interruption of variable T period and duty cycle constant α, then with periodic interruption of constant period T and cyclic ratio α variable. Each time, we record the parameters used to determine the energy produced.

For a first case, we set the duty cycle to $\alpha = ½$. In other words, the valve is alternately open and closed for a duration T/2.

The 50-liter tank of the compressor is filled to 5 bar. This air mass has fed the wind turbine continuously and the rev counter displays 384 and the total running time is 32 minutes. The durations of the transient regimes are respectively Tm = 2 minutes and Ta = 5 minutes.

This manipulation led to the data of Table 8 and the histogram of Fig. 6 provided two pieces of essential information:

• periodically interrupted action of the artificial wind is more energy efficient than continuous action;

• the period of action must be chosen between the two terminals, which are the rise time or duration of the transient operating regime and the time of descent or duration of the transient stopping regime.

3.3.2 Study of the Cyclic Ratio of the Interrupted Action of the Valves

In a second manipulation, we keep the constant period at one of the appropriate values belonging to the above-mentioned range (5 minutes). It is the cyclic ratio that becomes the experimental variable. All other parameters are those of the previous manipulation.

Table 8 Determination of appropriate periods.

Period T (min)	-	1	2	4	6	8	10	12
Wind duration per period (min)	-	0.5	1	2	3	4	5	6
Number of rounds	384	508	532	586	585	586	543	502
Running time (min)	32	64	63	62	63	63	62	62
Mean speed (tr/min)	12	7.94	8.44	9.45	9.29	9.30	8.76	8.10

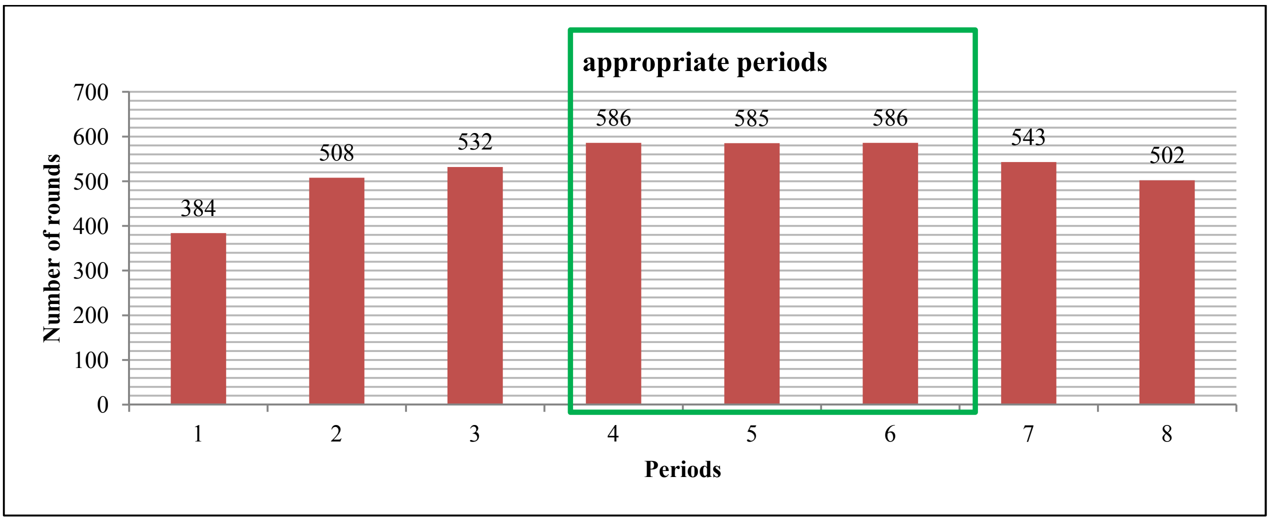

Fig. 6 Histogram of the appropriate periods.

Table 9 Determination of the appropriate cyclic ratio range.

Cyclical ratio	1	0.75	0.625	0.5	0.25	0.125
Wind duration per period (min)	4	3	2.5	2	1	0.5
Number of rounds	384	467	586	586	539	543
Running time (min)	32	43	52	62	128	256
Mean speed (rd/min)	12	10.86	11.27	9.45	4.21	2.12

We get the values of Table 9 in which the appropriate cyclic ratio is 0.625.

3.4 Feedback Loop Performance Study

One of the most anticipated results of this thesis work is undoubtedly the efficiency of energy storage by this technique. While the appreciation of this research initiative goes beyond performance, it is one of the key parameters. Other points of interest are heard: the duration of the storage system, its cost of installation, its reliability and its capacity to be repaired

To analyze the performance of this loop, the following two questions are simply answered:

- How much energy does the compressor use to store a given mass of air?
- How much energy is produced by using this stored air mass?

The storage loop is therefore considered as a system whose input is the energy required for storing the desired air mass and the output as the total energy produced by the wind turbine under the effect of the only artificial wind.

The characteristics of the compressor include its power. It is then sufficient to time the time taken to store a certain quantity of air. Most air compressors have indications of the time taken to fill the integrated tank [5]. In the case of the compressor whose power is 0.5 horsepower, or 368 W, the manufacturer also said that the time taken to fill the tank (20 liters) is 30 minutes.

In terms of measuring the energy produced from this stored air, we can also determine the time taken by the wind turbine to run at a known average speed. Since the power supplied by the wind turbine is related to its speed of rotation, it can then be calculated and the total energy is produced obtained by the formula $W = Pt$ [6].

The nominal power of our wind turbine is 600 W; that is to say that this power is provided when the blades rotate at the nominal speed of 15 tr/min. But in the case of our handling, the blades turn at the average speed of 10.5 rpm; which corresponds to a power of 416 W.

We repeated the test four times to take average values. The results are shown in Table 10.

The overall yield of this technique is therefore estimated at 32.77%. Although apparently low, this yield is very acceptable as a hybrid photovoltaic-wind plant is still experiencing production peaks per day.

Table 10 Study of the performance of the storage loop.

	Test rank	1st	2nd	3rd	4th	Average
Inputs	Engine power	221	221	221	221	221
	Time to fill the tank (min)	5.50	5.00	5.50	5.50	5.38
	Energy consumed (Wh)	1,216	1,205	1,216	1,216	1,188
Outputs	Rated power of wind turbine (W)	600	600	600	600	600
	Speed of the blades (rd/m)	10.30	10.50	10.40	10.40	10.40
	Developed power (W)	412	420	416	416	416
	Operating time (min)	57	55	56	56	56.14
	Energy produced (Wh)	389	388	391	389	389
	Ratio (%)	32.00%	35.11%	32.17%	32.00%	32.77%

The extension of air storage is then easier than the extension of a storage battery. Just enlarge the tank. In addition, the low efficiency of such a technology that consumes a clean source and above all abundant can not be a concern.We do not buy the sun's rays, neither the speed of the natural wind!

The energy losses are recorded at several levels of transformation and transfer of the initial energy: compressor, tank, valves, artificial wind and wind turbine.

The analysis of the losses that lead to this yield makes it possible to understand that it is even greater if a heat recovery device is associated with the system [7].

The basic principle is to transfer and transform the heat generated by the compressor to use it for other useful applications for users. This may include recovering this energy to heat domestic water, to dry food or for heating warehouse etc. [8].

4. Conclusions

Devoted entirely to the analysis of the action of the artificial wind on the wind turbine to distinguish it from the action of the natural wind, the present work is a compilation of all the manipulations which have made it possible to draw concrete results on several aspects of this new technology.

After having defined the operating mode of all the experimental activities, the tables summarizing the values obtained by the manipulations are presented followed by theirs interpretations. These manipulations have effectively made it possible to determine the attack distance of the blades with respect to the axis of the wind turbine which is close to the end. The optimal number of attack points is also set at 2 while it is obvious that the interrupted action of the artificial wind is more beneficial than a continuous action. The period of the interrupted action must, however, be between the two durations of the transitional regimes.

The efficiency of the feedback loop defined as the ratio of the energy supplied by the wind turbine to the energy consumed by the compressor is about 33%. This yield is an incentive in that it involves capturing an abundant and volatile resource.

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