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Looping of Hybrid PV/Wind Turbine Power Plants by a Compressed Air Storage System and Creation of Artificial Wind to Ensure the Permanent Availability of Energy in the Tropical Zones

Bello Pierre Ngoussandou[1], Hamandjoda Oumarou[2] and Noel Djongyang[1]

1. The National Advanced School of Engineering of Maroua, University of Maroua, Maroua P.O. Box 46, Cameroon

2. The National Advanced School Engineering, University of Yaounde, Yaounde P.O. Box 8390, Cameroon

Abstract: In general, the energy storage in facilities to intermittent sources is provided by a battery of accumulators. Having found that the duration of life of chemical accumulators is strongly shortened in the northern regions of Cameroon and that this has a considerable impact on the operating costs and the reliability of power plants to intermittent sources, this work proposes to find an alternative to these chemical accumulators rendered vulnerable by the high temperatures. It reviews all energy storage techniques and makes a choice (the CAES (compressed air energy storage)) based on thermal robustness. It proposes a new technique of restitution of the energy by producing an artificial wind from the compressed air. The feedback loop thus obtained by the compressor-tank-wind subsystem is studied from a series of manipulations and its efficiency is determined. To automate the operation of this system, a controller is required. The operating logic of the controller is provided in function of the precise states of the load, the tank and the natural sources.

Key words: Battery duration life, compressed air energy storage, artificial wind, thermal robustness.

1. Introduction

To guarantee the permanent availability of the electrical energy produced by intermittent sources, the generators are associated with an energy storage system that takes over when the main sources are no longer available. It is usually a battery that provides this essential function. However, in tropical areas, the life of chemical accumulators is strongly shortened because of high temperatures [1]. This has a considerable impact on the operating costs and reliability of intermittent power plants.

To find an alternative to these chemical accumulators made vulnerable by high temperatures, we propose to loop the production line of a hybrid PV/wind turbine power plant using a compressor that stores energy in the form of air compressed. As well, when the natural sources are no longer available, the stored air is used to create an artificial wind which runs the turbine. Such systems have the advantage of being thermally more robust [2]. In our approach, we first made a review of energy storage techniques to justify the choice we made on compressed air. Then we present the material while indicating the methods used. The results obtained are finally presented last.

Corresponding author: Bello Pierre Ngoussandou, Ph.D. student, research fields: energy storage, renewable energy.

2. State of Energy Storage Techniques and Justification of the Choice of Compressed Air

Energy storage consists of preserving a quantity of energy for later use. By extension, the expression can also mean the storage of the material containing the energy. Because of the intermittence or fluctuation of renewable energies, this operation ensures the continuity of the availability of energy. Energy, stored when its availability is greater than the needs, can be restored at a time when demand is greater.

Storage techniques depend on the nature of the energy source. Fossil resources (coal, gas, oil) are already available as reservoirs of stocks in their natural state. Even when they are extracted, they can easily be isolated, transported and stored. On the other hand, the volatile and intermittent nature of renewable resources makes their storage difficult.

Moreover, when the primary source (fossil or renewable) is transformed into electrical energy, the storage is more complicated. We cannot conserve electricity in a container such as oil or wood! Several technologies are therefore implemented to ensure the storage of electrical energy [3].

While the sunlight and wind are never available at any time, their daily production peaks do not always correspond to energy consumption peaks [4].

The increase of interest in volatile and intermittent renewable sources leads inevitably to the increase of electrical energy storage. Four main types of energy storage techniques are used [2]: The storage in chemical form, the storage under thermal form, the storage under electromagnetic form and the storage in mechanical form.

2.1 The Storage of Electricity in Chemical Form

2.1.1 Batteries

The storage of energy in batteries is the most common technique in stand-alone installations. A battery is set up of two electrodes immersed in a saline solution or acid called electrolyte. The electrode connected to the positive pole is the cathode while the anode is connected to the negative pole. Batteries are assembled to store more electrical energy from the flow of ions between anode and cathode through the electrolyte, and electrons in the circuit connecting the electrodes [5]. This mode of storage is based on the reversible conversion of electrical energy into chemical energy, based on an oxidation-reduction reaction. The lifetime of the battery is shortened by the chemical degradation of the reactions.

2.1.2 Hydrogenation Storage

Hydrogen does not exist in its natural state but is very abundant in atomic form (water, hydrocarbons, etc.). Electrolysis, which consists of breaking down the water molecule into hydrogen and oxygen using the equation $2H_2O = 2H_2 + O_2$, consumes electrical energy. This hydrogen is then compressed, liquefied or stored as metal hydride [5]. There are then three different ways to get again electricity from the stored hydrogen:

- the first means consists in feeding a fuel cell;
- the second is to synthesize natural gas using the methane process;
- the third is to use hydrogen directly in a specially designed gas plant to create electricity.

2.2 Storage in Thermal Form

Heat or cold appliances are usually quite powerful compared to most home appliances. The storage of electrical energy in the form of heat or cold then makes it possible to shift the demand from the periods of high consumption to off-peak periods. For example, domestic hot water can be produced from electricity for use a few hours later.

In addition, the conversion of electricity in heat can also be performed via the use of heat pumps or radiators. The networks of heat and electricity are also paired via the use of cogeneration plants producing both electricity and heat [6].

2.3 Storage in Electromagnetic Form

2.3.1 Storage by Supercapacitors

The principle of the supercapacitor is based on the storage of energy by distributing ions from the electrolyte in the vicinity of the surface of the two electrodes. Unlike battery, there is no oxidation-reduction reaction. A supercapacitor can store electrostatic energy [7].

2.3.2 Storage by Superconducting Inductors

The principle of SMES (superconducting magnetic energy storage) is also based on the creation of an electrochemical double layer by the accumulation of electrical charges at the interface between an electrolyte and an electrode. There is also no oxidation-reduction reaction. Exploiting the properties of a short-circuited superconducting coil, this system does not lose energy thanks to the absence of any resistance. The energy is stored in the form electromagnetic field created by the coil travelled by a current [7].

2.4 Energy Storage in Mechanical Form

The mechanical form of energy is the most known natural form. It has for long time and always been used by men to carry out various works. Moreover, electrical energy has always been used in a large proportion to perform mechanical work. It is still mechanical energy that is transformed by the alternators of the dams to produce electricity. This means that the convertibility between the mechanical and electrical forms is very common. This is why several technologies have been used to store electrical energy in mechanical form. The most known technologies are [7]:

- the stations of energy transfer by pumping (SETP);
- the CAES (compressed air energy storage);
- storage by flywheel.

2.4.1 The Stations of Energy Transfer by Pumping

The stations of energy transfer by pumping convert electrical energy into potential energy via two water reservoirs located at different altitudes and connected by a pumping/turbining system. The latter makes it possible to pump the water towards the upstream reservoir during the off-peak period, and to pump it to the downstream reservoir during a full period, in an operation similar to that of a hydroelectric power dam [8].

2.4.2 The Storage by Compressed Air

The CAES principle uses electricity to compress air through a compressor system. The air, which is highly compressed and whose temperature has increased by several hundred degrees, is then stored in a tank [9]. It can then be re-injected into a natural gas combustion chamber, driving a turbine connected to an alternator producing electricity [9]. The air compression phase is therefore separated from a process similar in every respect to that of a conventional gas plant.

2.4.3 Inertial Storage

Storage by flywheel allows transforming electrical energy into a kinetic energy of rotation. The steering wheel consists of a cylindrical mass, rotated about a fixed axis. The mass is connected to an electric motor to increase the speed or reduce it while producing electricity. As the kinetic energy is proportional to the mass as well as the square of the speed, the technologies can primarily use heavy materials or operate at high speed, depending on the friction and fracture resistance constraints [10].

2.5 Justification of the Choice of the CAES

The analysis of the techniques implemented to ensure this storage was initiated in order to make a choice based on the problematic and in a context where high temperatures are harmful. It is agreed that the mechanical means are thermally more robust [11]. In addition the scarcity of water in these areas combined with the permanent availability of air has allowed selecting the CAES.

3. Material and Methods

The interest of this work lies in the use of compressed air to produce electricity again by operating the same wind turbine that helped to store it.

3.1 Description of the System

For a PV/wind hybrid power plant with a battery, this one behaves as a load while charging, sometimes as a secondary source during its discharge. During this discharge, the battery can be electrically isolated from the main generators. As far as our system is concerned, the production of electricity by stored energy goes through one of the main generators (the wind turbine); forming a loop.

Considering the links that may exist between the various elements, the block diagram of the system may be presented as well as it follows (Fig. 1).

3.2 The Material Used for the Manipulations

To carry out the manipulations, the experimental equipment that has been used consists of a wind turbine, a mini compressor and measuring devices. If the action of the natural wind on a wind turbine is determined from the parameters of the wind and the wind turbine, 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.

The characteristics of the SILVERLINE brand compressor and commercial reference ME130016 (TS-425689) are presented in Table 2.

Measuring instruments consist of: a stopwatch, an anemometer, a flow meter, a manometer incorporated in the compressor and a tachometer.

3.3 Methods

We consider the retroactive system with its inputs (sunlight SL, natural wind NW and artificial wind AW) and its output (shown as Fig. 2).

Depending on the combinations of the possible states of the inputs, the state of the output must be determined. The output can take the following values:

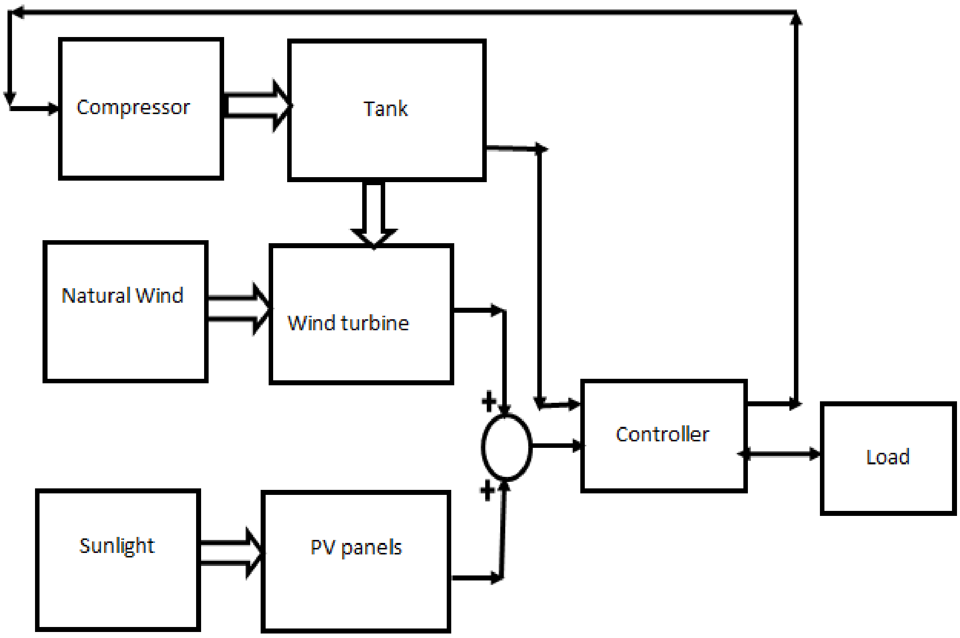

Fig. 1 Block diagram.

Table 1 Characteristics of the wind turbine.

Designation	Value
Brand/Type	PWG/FD2.6-600
Number of blades	3
Rated power	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.

Designation	Value
Maximum pressure	17 bar.
Power supply	12 volt
Power	242 W
Cord length	2.8 m
Length of the pipe	5 m
Tank	20 L
Time taken to fill the tank	5 minutes

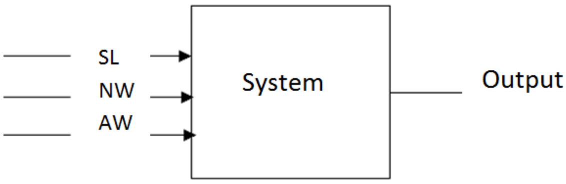

Fig. 2 The system input/output model.

(a) Sufficient to supply the load and the compressor;

(b) Sufficient to supply the load but not the compressor;

(c) Insufficient.

The characterization of the system will consist in studying the action of the artificial wind on the turbine: it will be to determine the most appropriate position of the artificial wind source and the blades angle of attack.

To determine the efficiency of this storage loop, we measure the amount of electrical energy consumed by the compressor to store a given mass of air; then the quantity of energy produced by the use of this mass of air. 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.

$$r = \frac{E_{out}}{E_{in}} \quad (1)$$

4. Results

Our device behaves as an artificial source of wind for the wind turbine which can then continue to rotate. While the natural wind is characterized by fluctuating speed and direction, the artificial wind created is subject to adjustment: its direction, its speed and its frequency are perfectly adjustable.

4.1 The Controller

The main role of the controller in such installation is to enable or disable the compressor supply line taking into account certain predefined conditions.

Serving both electrical and logic connector, the controller has 4 inputs and 2 outputs. These six links, however, convey information of two natures. In a first sense, they serve as electrical connections between the production line and the load and the compressor and in a second sense, they convey logical information on the states of the different blocks (production, reservoir and load). Seen as a combinational logic circuit, the operation of the controller is described by the truth Table 3.

Table 3 Controller's truth table.

In				Out	
X	P	W	T	C	V
0	0	0	0	0	1
0	0	0	1	0	1
0	0	1	0	0	0
0	0	1	1	0	0
0	1	0	0	0	0
0	1	0	1	0	0
0	1	1	0	0	0
0	1	1	1	0	0
1	0	0	0	IS	1
1	0	0	1	IS	1
1	0	1	0	1	0
1	0	1	1	0	0
1	1	0	0	1	0
1	1	0	1	0	0
1	1	1	0	1	0
1	1	1	1	0	0

P	Photovoltaic energy	1 if sufficient to power the load
W	Wind energy	1 if sufficient to power the load
X	Excess energy	1 if P + W is sufficient to supply the load and the compressor
T	Tank	1 if full
C	Compressor	1 if powered
V	Valve	1 if open
IS	Impossible state	If there is no wind neither sun, there will be no excess energy

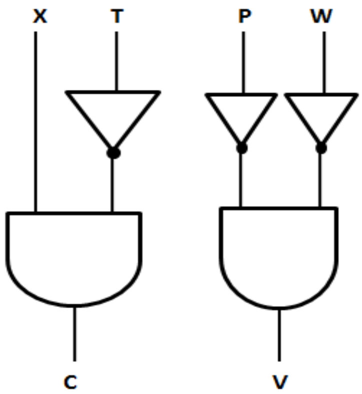

Fig. 3 Logic diagram of the controller.

The logical equations of the two outputs can then be defined from the truth Table 3 as follows:

$$C = \overline{T}.X \quad (2)$$

$$V = \overline{P}.\overline{W} = \overline{P + W} \quad (3)$$

Similarly, we can draw up the flow diagram of the two outputs, shown as Fig. 3.

4.2 The Tank

The tank is a container or tank for accumulating the air produced by the compressor. It ensures, thanks to its tightness, the maintenance of a certain volume of air which will be used to produce artificial wind intended to turn the wind turbine. For large installations, the tank may be an underground cavity [9]. It is provided with two orifices that must be distinguished by their role. A valve for storing air and a valve to let out the air that creates the artificial wind. Its state must be known and controlled at all times to ensure the proper functioning of the system. The indicators must provide information on his condition so that he knows at all time whether he is or not full, in charge or in relaxation.

4.3 Lifetime and Cost of CAES

The average life of chemical accumulators is estimated at 12 years compared with 40 years for CAES according to the work of Jakiel et al. [12]. This duration of the accumulators takes into account the optimal conditions of use (depth of discharge and temperature). Due to the high temperatures, this time increases from 12 years to 40 years at the sites we studied [46]. It is obvious that the temperature does not significantly degrade the life of a CAES. In addition, there is no limit for the discharge of the tank [12].

Estimates of kW/h storage costs are also made by Jakiel et al. [12]. These costs vary very little from one system to another. It is obvious that if two systems have the same cost of installation, the most economical system is the one whose life is longer, the data are shown in Table 4.

4.4 Wind Position and Angle of Attack of the Blades

The artificial wind is distinguished from the natural wind by its action located 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 we are interested in the position of the valve with respect to the axis of the wind turbine. The work of Le Gourières [14] shows that the most effective angle of attack is 90° or π/2 rad. It is therefore a question of attacking the blade at a position distant from *d* with respect to the axis of the blade.

The procedure for this manipulation consists of:

(1) Fix the air flow at a constant;

(2) Arrange the valve at a position, a distance *d* from the axis;

Table 4 Comparative data of different electricity storage systems [13].

Technology	Rendement	Cost in kW/h	Life time
CAES	50%	500-1,000 €	40 years
Li-ion battery	75%	1,000 €	12 years

Table 5 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
Rotation 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 6 Determining the ideal position of the valve.

Distance *d* (m)	0	8	16	24	32	40	48	56	60	62	63
Time *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

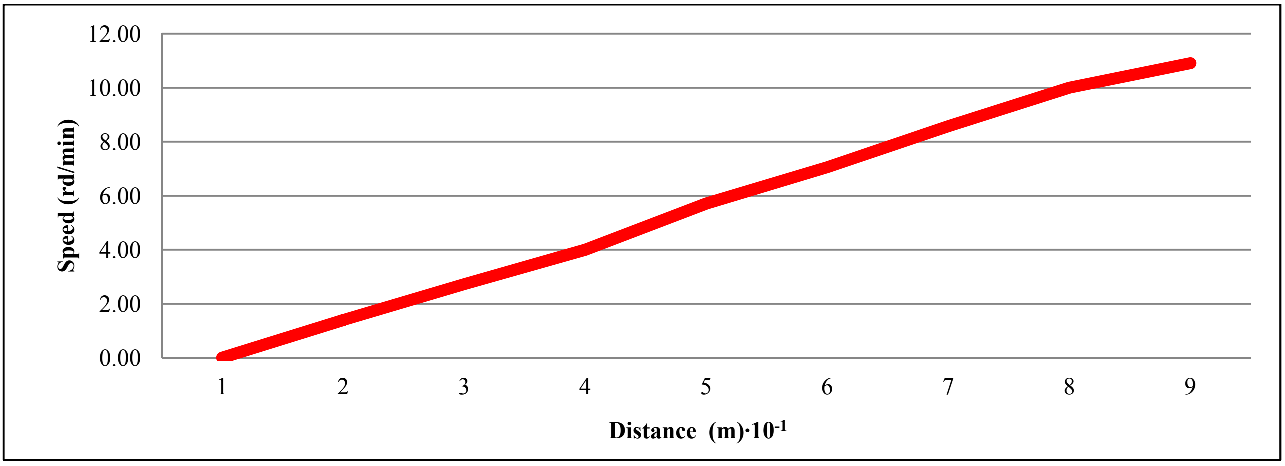

Fig. 4 Evolution of the speed of rotation as a function of distance.

Table 7 Study of the performance of the storage loop.

	Test	1st test	2nd test	3rd test	4th test	Average
Inputs	Engine power	221	221	221	221	221
	Time taken to fill the tank (min)	5.5	5	5.5	5.5	5.375
	Energy consumed (Wh)	1,216	1,205	1,216	1,216	1,213.25
Outputs	Wind output rated power (W)	600	600	600	600	600
	Speed of the blades (rd/min)	10.3	10.5	10.4	10.4	10.4
	Developed power (W)	412	420	416	416	416
	Operating time (min)	42	40	41	41	41
	Energy produced (Wh)	288.40	280.00	284.27	284.27	284.23
	Ratio (%)	23.72%	23.24%	23.38%	23.38%	23.43%

(3) Rotate the wind turbine and wait for normal operation;

(4) Time the time taken to complete a complete turn.

The different values of time and position are shown in Table 5.

From this manipulation, the following observations are made:

(1) The speed of rotation of the blades increases with the distance which separates the valve from the axis of rotation;

(2) At the end of the blades, the speed is not optimal;

(3) One can draw a first conclusion that the optimal position of the valve is close to the end. The last line of Table 6 also concludes that the rotational speed is an increasing function of the position; it is almost linear (Fig. 4);

(4) 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.

(5) 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. The manipulation was resumed to determine to the centimeter of the ideal distance.

4.5 Performance of the Storage System

The duration of 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 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 7.

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. 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 is abundant cannot be a concern. We do not buy the sunlight, neither the speed of the natural wind!

5. Conclusions

The essential element of this study is the storage loop. Its components have been identified and described for more easy comprehension.

Unlike other storage technologies that isolate the main source when the stored energy is in use, the new system relies on one of the generators of the main chain to form a feedback loop. The operations of the two main elements controlled (compressor and valve) according to precise conditions were analyzed. A brief comparison between storage by accumulators and CAES was made in terms of cost and service life.

The artificial wind created by the relaxation of the stored air is completely mastered. Its direction, its speed and its frequency are controllable and should allow a more effective action on the wind turbine.

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