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The Dimensioning of A Compressed Air Motor Dedicated to A Compressed Air Storage System

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ABSTRACT

Storage represents the key to the penetration of renewable energies especially wind and solar energy on the network electric. It avoids unloading in the event of overproduction, ensuring real-time The production-consumption balance and also improve the robustness of the electricity grid. CAES (Compressed Air Energy Storage) is a mature technology that allows to store long or short duration an amount of energy sufficient to support the number of cycles requested. The E-PV-CAES system will be presented and the modeling of the compressed air engine will also be treated in more detail in this article.

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1. INTRODUCTION

Storage in general involves a number of technologies, both old and new, which are based on a cycle of storage - daily destocking and which can extend to a seasonal storage of energy. These technologies cover a wide range of applications: Applications for improving the quality of the current and which generally have a very short response time (less than one second) and operating time of a few minutes, Such as flywheel, supercapacitors, superconductors and storage in electrochemical batteries, - Applications which improve the profitability of the production system and which have a slightly longer response time (a few tens of seconds to a few minutes) and an operating time of a few hours, such as pumping water and compression air. The latter is based on the storage of compressed air in caves. Renewable electricity or electricity produced during periods of low energy demand is used by compressors and stored in conventional tanks and produced in case of need by means of a compressed air engine. Using the power of compressed air has many advantages. First, as a power source, the compressed air is both clean and safe. Second, it can also be used for various tasks such as actuating tools and pistons in order to move or cool materials [1][2][10][11].

2. PRESENTATION OF THE SYSTEM PROPOSED

In conventional gas turbines widely used in the generation of electrical energy (especially in the event of peak demand), there are two phases: A first where the air is compressed before an expansion phase where, after injection of combustible Then the hot gases thus obtained pass through a turbine, supplying mechanical energy which can then be transformed into electrical energy [3][14]. The CAES operates in the same way by decoupling these two phases. Thus, the energy to be stored is used to compress the air by a compressor and to store it, often in a natural cavity,The expansion of the air will then make it possible to produce electrical energy by the same process as a gas turbine. Compressed air energy storage can store large quantities of energy for long periods of time, making it an alternative to hydro-electric storage. In addition, installation costs are lower than those of the latter technology, although safety tests often require significant means and, like hydroelectric storage, CAES generally requires a particular geographic environment (cavities Groundwater, aquifers, etc.) to store compressed air (although storage methods above ground are increasingly extended to large-scale storage) [1][4][15][16].

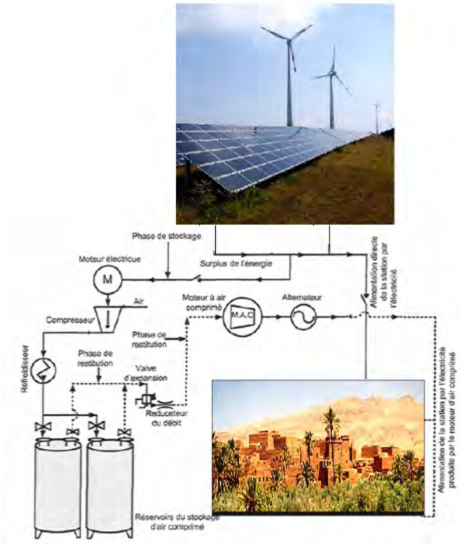

Figure 1. Schema of the principal of function of a compressed air storage system

3. TYPES OF COMPRESSED AIR MOTOR

The compressed air motor (CAM) transforms compressed air from Electricity via an alternator associated with its pneumatic part. It performs the reverse function of a compressor. Different types of CAM can be distinguished as motors with pallets as shown in Figure 2, a piston engines , geared motors or turbine engines [2][6][15].

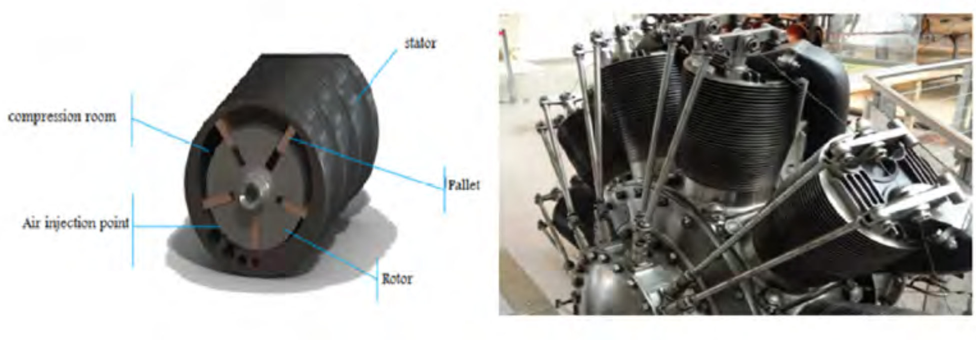

Figure 2. Schema of compressed air motor with piston (right)and compressed air motor with (left)

The characteristics of the CAM are shown in torque-speed (C-N) and power-speed (P-N) curves as shown in Figure 3. The pressure on the pistons, pallets or teeth being proportional to the pressure, and the pressure varying as a function of the pressure drops in the machine, which are proportional to the square of the air velocity (that is to say the Square of the rotation speed), it follows that the torque-speed curve (C - N) theoretically has a parabolic shape. This curve always has a negative slope: the torque decreases as the speed increases, to cancel out at the speed of runaway. The useful power being the product of the torque by the speed, it therefore increases to pass through a maximum and vanishes for the Speed of runaway [7][2][8].

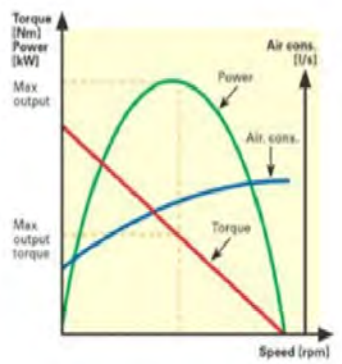

Figure 3. Schema of The performance curve for an air motor operating at a constant air pressure

4. ADVANTAGES AND LIMITS OF THE COMPRESSED AIR MOTOR

The advantage of this system is that it produces locally no polluting emissions, whether particulates, oxides of nitrogen or CO2. However the compressed air does not exist naturally. Therefore it must be produced, which requires energy and raises the same problems as the production of hydrogen: The non-renewable nature of sources of energy, the production of pollution, greenhouse gas or radioactive waste by power plants, energy losses during the conversion in pneumatic energy, etc.
Besides, if the compressed air engine is very used on certain sector (pneumatic drill, dentist's drill ...), its application in autonomous vehicles is still at the stage of development. Indeed, the compressed air contains not much energy and, even with a reservoir of 300 liters at 300 bars, the autonomy of such a vehicle is very small. Therefore, these are the ways of the hybridization electric/compressed-air and bi-fuel engines oil-fuel/compressed-air which are currently being explored [3][2].

5. THE POWER SELECTED COMPRESSED AIR MOTOR

The power of the compressed air motor is 8kW. Indeed, this power has been selected to feed The isolated site with 5kW and the rest (3kW) takes Considering the mechanical and energy losses between the MAC and its alternator on the one hand And serves, on the one hand, to heat heating resistors placed after each stage of The compressed-air engine to heat the air after the expansion and Formation of frost on the air circuit and damage to the latter.

6. THE MODELING OF COMPRESSED AIR MOTOR TYPE PISTON

In order to analyze and simulate the pneumatic energy conversion process, it is essential to determine the model of the compressed air motor (CAM) used. The ideal model should take into account all the physical phenomena involved in the conversion of energy. The compressed air motor chosen for this study is of the ”piston” type Because it is the most mature, reliable, cheaper and allows full use of the polytropic expansion of compressed air in the cylinder especially if the relaxation of the air is done in several stages [2][6][13].

6.1. Operating mode

The compressed air reservoir has sufficient pressure, its energy Potential can be converted into mechanical energy on the motor shaft and into electrical energy On the alternator shaft. The cycle of the pneumatic motor is carried out in three stages: load Cylinder, expansion and exhaust. The following figure shows, the basic function CAM with piston and the P-V diagram idealized for the cycle of air injected into the engine [5] [12]. The cycle of compressed air injected into a compressed air motor of the type ”piston” Comprises the following three steps:

Cylinder load:
The load valve is open from point 1 to point 3 (figure 5)

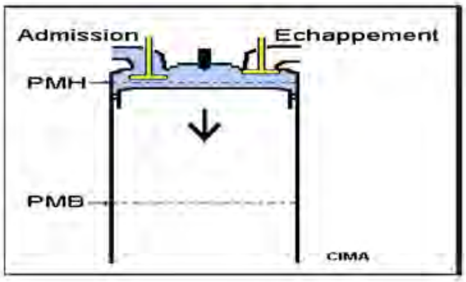

Figure 4. Schema of the basic function CAM with piston

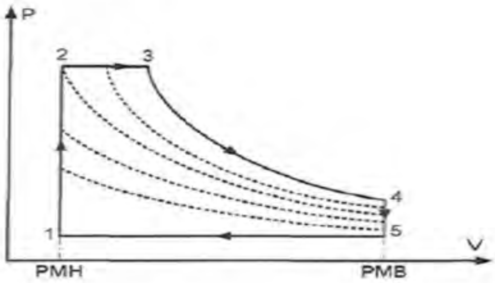

Figure 5. Schema ofthe P-V diagram idealized for the cycle of air injected into the CAM

From point 1 to point 2, air from the tank is expanded in the cylinder.
From point 2 to point 3, the expansion continues at constant pressure and equal to the pressure Of the tank (Assuming that the volume of the reservoir is much higher than the volume Of the cylinder).
The work of the pneumatic motor cycle can vary continuously in Adapting the closing angle of the load valve (Figure, lines dotted).

Relaxation:

The load valve is closed from point 3 to point 4 (Figure 5): the Load air relaxes. The total relaxation stroke (step 2 to step 4) produce the work Of the cycle.
In order to achieve a complete relaxation of the air charge, the angle of Closing of the load valve must be optimized in such a way as to superimpose the Points 4 and 5.

Exhaust:

The exhaust valve opens at point 4 (Figure 5). Point 4 at point 5, the cylinder air expands in the exhaust (open to atmosphere Or other low-pressure storage tank) and the potential energy of the air At point 4 is lost.
From point 5 to point 1, the exhaust stroke Mass of residual air in the exhaust duct at atmospheric pressure Or to the pressure of another low-pressure storage tank.

7. THE WORK OF THE COMPRESSED AIR MOTOR

The work of the pneumatic motor cycle is the sum of the work during all Phases of the cycle shown in figure 5 .

$$W = W_{1-2} + W_{2-3} + W_{3-4} + W_{4-5} + W_{5-1} \tag{1}$$

By definition, the work exchanged between the cylinder gases and the piston is defined by:

$$W = -\int P dv \tag{2}$$

As a result, the work of an isochore (constant volume) transformation is zero and Therefore :

$$W_{1-2} = W_{4-5} = 0 \tag{3}$$

Transformations 4-5 and 1-2 shown in the P-V diagram (Figure5) As being isochorous are in fact adiabatic transformations representative of the expansion and compression which the air undergoes respectively at the end of the expansion after opening of the exhaust soup and at the end of exhaust at the moment Of the opening of the intake valve.

7.1. Work during the admission

The intake (2-3) is an isobaric transformation which takes place at a constant pressure $(P = P_2 = P_3)$. The work of the piston during this phase is calculated as follows:

$$W_{2-3} = -\int_2^3 P_2 dV = -P_2 \int_2^3 dV = -P_2(V_3 - V_2) = P_2 V_2 (1 - \frac{V_3}{V_3}) \tag{4}$$

By replacing the ratio of volumes by its expression,$\alpha = \frac{V3}{V2}$ Work of the isobaric admission then becomes:

$$W_{2-3} = -P_2 V_2 (\alpha - 1) \tag{5}$$

7.2. Working during relaxation

Relaxation is a polytropic transformation characterized by Laplace's law Allows to write:

$$PV^\gamma = P_3 V_3^\gamma = P_4 V_4^\gamma \tag{6}$$

$$P = \frac{P_3 V_3^\gamma}{V^\gamma} \tag{7}$$

Then:

$$P = \frac{PV_4}{V_3^\gamma} V^\gamma \tag{8}$$

By replacing the ratio of the volumes by its expression $\beta = \frac{V_4}{V_3}$, the exchanged work Between the air and the piston during the expansion is then calculated from the following formula:

$$W_{3-4} = -\int_3^4 PdV = -\int_3^4 \frac{P_3 V_3^\gamma}{V^\gamma} dV = \frac{1}{\gamma - 1}(P_4 V_4 - P_3 V_3) = \frac{P_3 V_3}{\gamma - 1}(\beta^{1-\gamma} - 1) \tag{9}$$

7.3. Work during exhaust

During the phase of the exhaust isobaric $(P = P_5 = P_1)$, air is pushed out Of the cylinder during the rising of the piston. The work of the piston exchanged during this phase Calculated from the following relation:

$$W_{5-1} = -\int_5^1 PdV = -P_5 \int_5^1 dV = -P_1 V_1 (1 - \frac{V_5}{V_1}) = -P_1 V_1 (1 - \varepsilon) \tag{10}$$

C_y is the total cylinder capacity of the engine, V_m is the cylinder dead volume and ε Volumetric compression ratio defined by:

$$\varepsilon = \frac{V_5}{V_1} = \frac{V_1 + C_y}{V_1} = \frac{V_m + C_y}{V_m} \tag{11}$$

The work of the thermodynamic cycle of a CAM with piston is the sum of the work admission, relaxation and exhaust, where:

$$W = -P_2V_2(\alpha - 1) + \frac{P_3V_3}{\gamma - 1}(\beta^{1-\gamma} - 1) - P_1V_1(1 - \varepsilon) \tag{12}$$

knowing that : V_1=V_2=V_m,P_2=P_3=P_r, P_1=P_a,V_3=αV_m ,W can be writ as :

$$W = V_m((P_r(\frac{\alpha(\beta^{1-\gamma} - \gamma) + (\gamma - 1)}{\gamma - 1}) + P_a(\varepsilon - 1)) \tag{13}$$

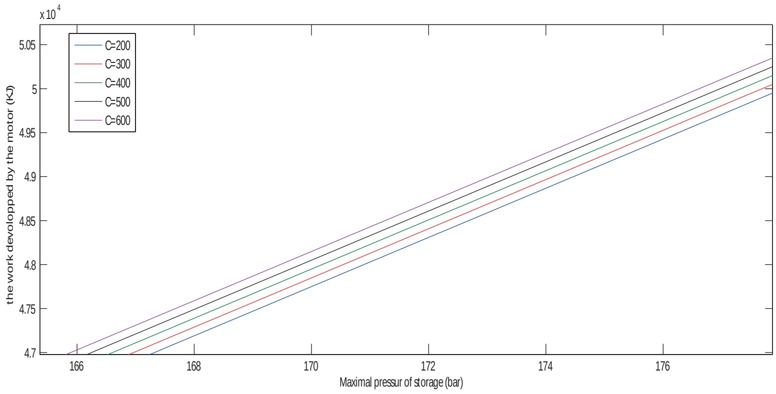

Figure 6. Schema of Work developed by CAM with piston according to the admission pressure and cylinder capacity Cy

The figure shows the variations of the work Developed by a single-cylinder CAM as a function of the air pressure at the inlet of the CAM (storage tank pressure) and Engine. It is simple to note that the work of the CAM varies linearly with tank pressure. This is because the volumetric compression ratio, ε, of the motor is fixed at a constant value equal to (10). The rotational speed of the compressed air motor is set at 1200 rpm. From this figure it can be concluded that the higher the pressure in the Reservoir decreases, plus the work developed by the CAM. This leads to the conclusion that the power supplied by the CAM will never be constant with a continuous withdrawal of the compressed air from the storage tank and consequently the CAM will no longer be able to supply an isolated site By the required electrical power (8 kW). For this reason, obtaining power Constant, it is necessary to vary the flow of compressed air injected into the CAM as a function of the Variation of the pressure in the reservoir.

8. CONCLUSION

in this paper a short presentation of the system proposed Wind-photovoltaic- compressed air storage has been motioned and the different types of the compressed air motor and their advantage and limits ,then the modeling of the compressed air engine based on special energy criteria is studied , Since it is considered as a main agent in the principle of operation of the system presented .

The hybrid system wind-photovoltaic-compressed air represents An interesting solution to environmental and resource related to the problems of energy supply to isolated sites It allows: To increase the penetration rate of wind and solar energy by taking advantage of all the available energy and by storing the excess energy in the form of compressed air instead of shedding it through compressors and Compressed air motor and significantly reduce fuel consumption and GHG emissions.

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