Hybrid Energy Storage Systems based on Compressed Air and Supercapacitors with Maximum Efficiency Point Tracking

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Keywords: Energy storage, Compressed air, Hydro-pneumatic, Supercapacitors, Maximum Efficiency.

Abstract

Beside the high-capacity storage facilities based on hydro-power technologies, electrochemical solutions are the today's candidate for storage for renewable energy sources. However, limited life-cycles and sustainability of batteries are often inhibiting factors. This paper presents a hybrid energy storage system with high life cycle, based on Compressed Air Energy Storage (CAES). The storage and discharge are done within maximum efficiency conditions. As the maximum efficiency conditions impose the level of converted power, an intermittent time-modulated operation mode is applied to the thermodynamic converter to obtain a variable converted power. A smoothly variable output power is achieved with the help of a supercapacitive auxiliary storage device used as a filter. The paper describes the concept of the system, the power-electronic interface circuits and especially the Maximum Efficiency Point Tracking (MEPT) algorithm and the strategy used to vary the output power. In addition, the paper describes the principles of higher efficiency storage systems where the air machine is replaced by an oil hydro-pneumatic converter, used under isothermal conditions. Practical results are reported, that have been recorded from a low-power pneumatic motor coupled to a small DC generator for the purely pneumatic system, and from a first prototype of the oil-hydraulics and pneumatic system. Some economical considerations are also made, through a comparative cost evaluation of the presented hydro-pneumatic systems and a lead acid batteries system, in the context of a stand alone photovoltaic home application. This evaluation confirms the cost effectiveness of the studied hybrid storage systems.

1. Introduction

World wide, considerations have been made on energy resources, about traditional generation and distribution systems as well as renewable means. Traditionally, energy storage has been of high interest, like in the case of not flexible nuclear or thermal power versus daily cycles. In this context of power generation, the issues of fast and strong load variations have also been studied [1], [2] and leaded to the necessity of storage means. For future concepts of energy production and distribution, like decentralized generation, balancing of production and consumption is one of the main concerns. In fact the concept of decentralized generation could present some risks, because of the loss of the effect of a "statistical mean value" of loads, that normally smoothes their profile. This will reinforce the need for storage facilities. Recently several new storage technologies have appeared, and are integrated in real networks [3], [4]. CAES technologies belong to these innovative developments, with their high potential of producing less problematic waste materials. In fact, they have been proposed from longer date, in the middle and high power range, for electrical power generation as well as transportation applications. Ultra-large size facilities have been proposed recently based on dedicated turbo machinery [5]. Several small size accumulators have also been proposed using intermediary mechanical/hydraulic conversion with the so-called "liquid piston” principle. [6]

Considering the integration of renewable means, like photovoltaic and wind power, that are intermittent power sources, additional storage facilities are also required. In this particular context, sustainability and impact on environment of storage devices are important concerns. Therefore, beside classical criteria like energy density and power density, important considerations should be made on mid and long term effects. So far, electrochemical batteries have been the main storage solution for renewable sources support, but they are still far to fulfil theses mid and long term requirements because of their limited life cycles and difficulties to be recycled [7]. The development of an alternative solution to classical batteries is the main motivation of the current research project which tries to optimize simple physical processes, like the compression/expansion of gas with the help of modern power electronic, control and storage technologies.

The studied solution combines Compressed Air Energy Storage with a supercapacitive auxiliary storage device. Criteria like energy-efficiency and energy-density have finally leaded to the use of a hydro-pneumatic conversion system. The concept and principle of the hybrid storage system is described first, then the Maximum Efficiency Point Tracking algorithm is presented and finally, a strategy for varying the electric output power is proposed. The performances of a high efficiency storage device, where the pure pneumatic machine is replaced by an oil-hydraulics and pneumatics converter used under isothermal conditions is being evaluated. The first results of these investigations will be presented too.

2. Principle of hybrid CASCES system

The idea of associating a high capacity energy storage medium (compressed air), and a high power density storage device (Supercapacitors), was firstly implemented at the EPFL's LEI in the context of an off-line UPS system whose principle is presented in figure 1. This system has been used for the investigations on CASCES technology, even though the energy efficiency of the air compressor/motor was known to be very low as presented in the following paragraphs. The main goal was to develop methods for operating the compressed air energy converters at their highest efficiency conditions.

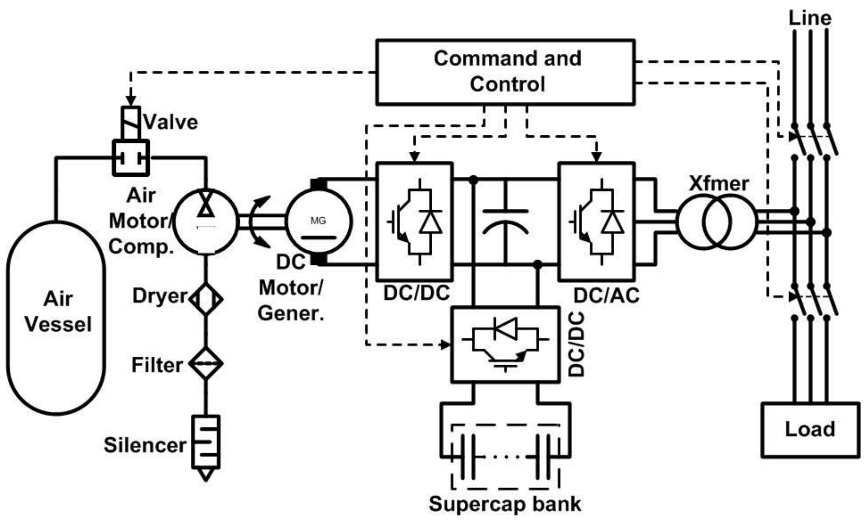


Fig. 2 Principle of Compressed Air and Supercapacitors Energy Storage system (CASCES)

All the devices of the system are reversible. The following technical solutions have been implemented to improve the reliability and efficiency of the system:

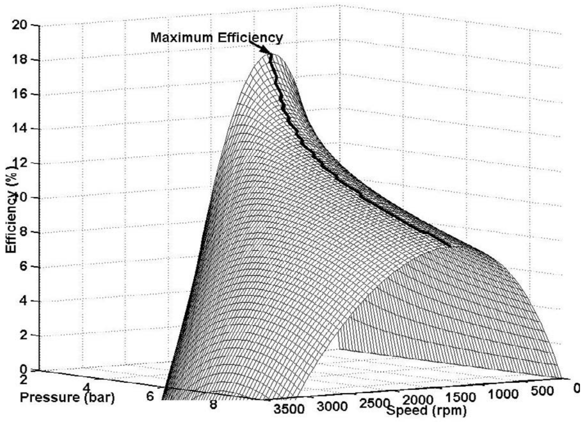
- There is no pressure regulation device between the air tank and the pneumatic machine in order to avoid the additional losses in such a device. The motor inlet pressure therefore varies continuously.
- An efficiency optimization algorithm has been developed to control the pneumatic machine through variable speed, so as to always keep it at the maximum efficiency operating point.
- Since the maximum efficiency operation is conditioning the magnitude of the converted power, an intermittent operation mode is used to modulate the produced power as a function of the output demand.
- The supercapacitive auxiliary storage device is therefore necessary to obtain a smoothly variable, high quality output power through the regulation of the capacitive intermediary stage voltage.

3. Strategy of efficiency optimization

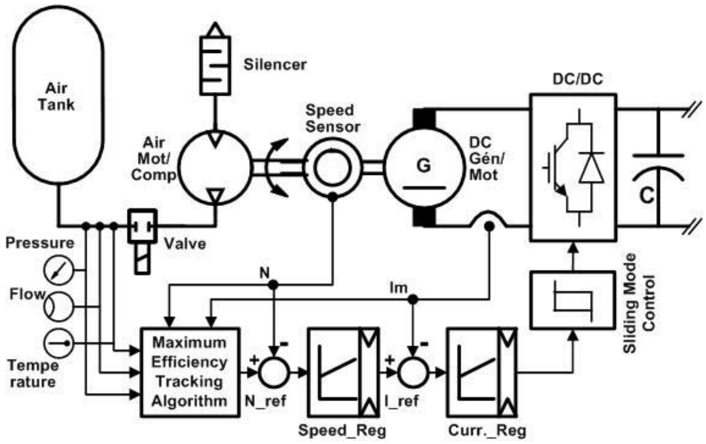
The continuous changes in pressure and load affect the pneumatic machine's performances namely the efficiency as it can be seen on figure 2a. The purpose of the efficiency optimization strategy is to control the operating point so as to optimize the energy conversion. The principle of this Maximum Efficiency Point Tracking (MEPT) strategy is presented in figure 2b. On the basis of various measurements (pressure, flow rate, speed, etc), the maximum efficiency-tracking module determines the optimal speed, which corresponds to the maximum efficiency. This optimal speed serves as reference to the speed control module. The optimal speed is achieved by acting on the electromagnetic torque of the DC generator through the current regulator of the motor inverter drive. Figure 2c above presents the flow chart of the MEPT algorithm which is mainly based on two techniques:

- The Quadratic Interpolation (Q.I) that exploits the quadratic shape of the efficiency at start up.
- The well-known Perturbation – Observation (P.O) technique for the optimum speed tracking.

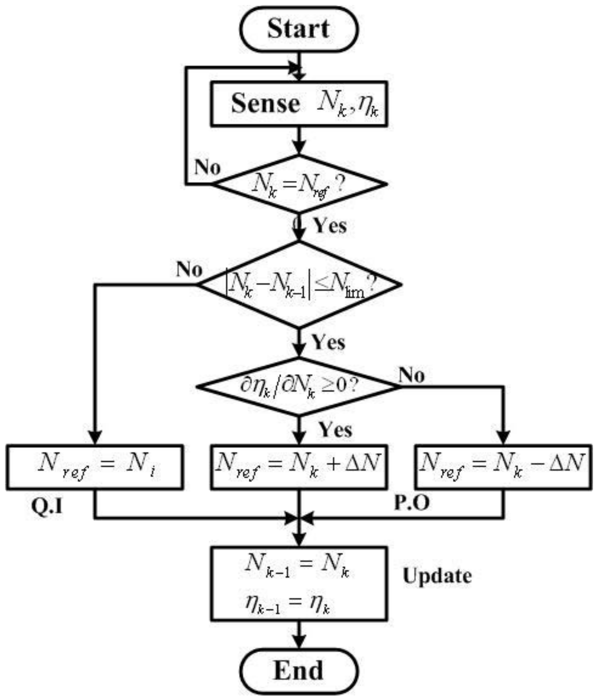
In addition the proposed MEPT algorithm uses no parameter of the controlled machine; thus it is suited for the control of any kind of volumetric machine as it will be shown in the next paragraphs. Furthermore, the proposed control strategy can be easily adapted to control the motor in two other operation modes: The Maximum Power Point Tracking (MPPT) mode and the Random Power Point Tracking (RPPT) mode. The experimental results recorded from a small vane type air motor are shown in figure 2d. As it can be seen, there is a very good match of the experimental and analytical optimal speeds which confirms the effectiveness of the proposed MEPT algorithm.



a) Air motor's efficiency surface



b) Bloc diagram of the MEPT strategy control



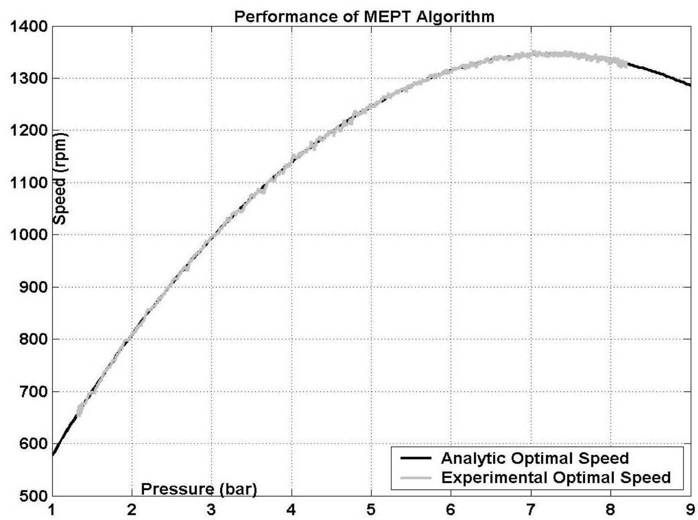


Fig. 2 c) Flow chart of the MEPT algorithm d) Comparison of experimental and analytical results

Despite the implementation of the efficiency optimization strategy, the energy efficiency of the pneumatic motor remains very low as it can be seen on figure 2a, due to non isothermal processes in the machine and important leakage and friction. In addition its limited pressure rating does not allow the achievement of high energy density and makes this kind of machine definitely not suited for energy storage application. Therefore another conversion solution needed to be found and oil-hydraulic machines appear as ideal devices; but they require an oil-to-air interface which is not always easy to implement.

4. Oil-Hydraulics and Pneumatics: key components for a higher efficiency

Hydraulic accumulators are well known components in the field of industrial applications. They are based on the use of high-pressure bladder or piston vessels, where nitrogen is compressed by injecting high-pressure oil in the shell or the body, using a gas/liquid separation device like a membrane or a piston. These equipments are generally designed for high instantaneous power and are not well suited for battery-type energy storage due to their high price. On the other hand, hydraulic motors are highly interesting devices in the field of CAES, because they have exceptional performances regarding the energy-efficiency. More over, their relative high pressure rating makes them interesting for reaching higher energy densities for the global storage device. Typical efficiency curves are given in figure 3a, also related to the operating pressure.

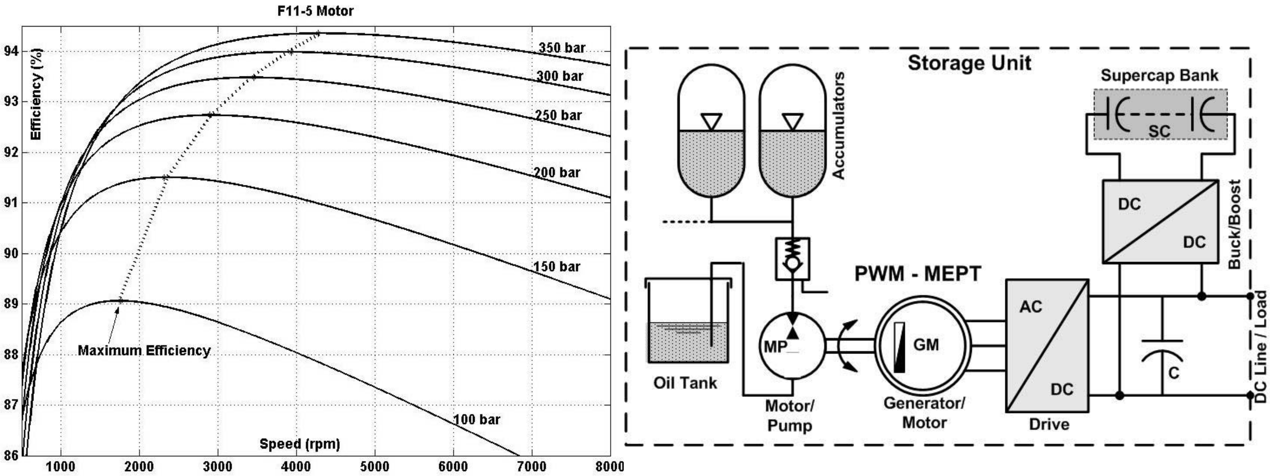


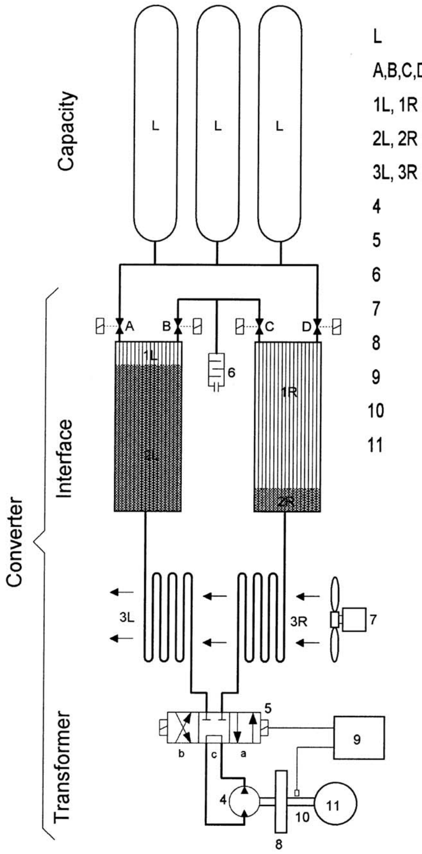
Figure 3 a) Typical hydraulic motor Energy efficiency b) Global scheme of BOP-A storage System

Combining these two hydraulic components, a hydraulic/pneumatic storage device can be realized, where interesting performances can be achieved. For a final industrial application, the accumulator must be realized in a cheaper technology, better suitable with the concerned power levels. The global scheme of such a device is illustrated by figure 3b, where an additional supercapacitive storage is again used. The reason for this hybridization is the same as in the CASCES system presented in section 2, which is the possibility to modulate the power from the optimal tracked level. From the efficiency curves in figure 3a, it is evident that high conversion efficiency can be achieved by using a MEPT algorithm and speed adaptation.

This hydro-pneumatic system which is also called "Battery with Oil-Hydraulics & Pneumatics (BOP-A)," can achieved very high efficiency if it functions in isothermal cycles. These conditions will be realised when the charging time of the accumulator is much higher than the time-constant needed for the thermal exchange between the accumulator's internal chamber and the surrounding. Typically, photovoltaic generators would charge the accumulator within up to 8 hours, while the thermal exchange will need a tenth of minutes. This will lead to isothermal conditions and therefore yields high-value efficiency. However, for such an accumulator, the closed nitrogen cycle together with the needed compressing oil volume would lead to a very low energy density. A system with a much higher energy density can be realized by using an open gas-cycle, with air from the atmosphere, operating with a low oil-volume reciprocating compression/expansion interface. This system must be designed with an integrated heat exchanger that can achieve nearly isothermal air compression and expansion. This system is described in the next paragraph, as well by [8].

5. The BOP-B: a high performance battery with oil-hydraulics and pneumatics

In order to exploit all the promising features of pneumatic storage, a converter is needed which would compress and expand the air with high efficiency, acting as interface to standard forms of energy like rotating shafts. The key to high conversion efficiencies is to maintain almost constant temperatures during compression or expansion (a swerve of 30 ºC induces an efficiency drop of 5 %). So far, only multi-stage positive displacement machines could be fitted with intermediary heat exchangers which would allow nearly isothermal cycles. If the reciprocator is a liquid piston, the provisions for good and simple heat exchange in work-chambers are quite easy and reliable, and the efficiency will rise as no seal friction is involved. The working principle of such a converter is shown in figure 4, in a simplified manner in order to explain the sequences of one cycle.



During discharge (expansion), the compressed air enters through the opened valve (D) in the work-chamber (1R) of the right cylinder comprising the liquid piston (2R), the said valve (D) being controlled so as to admit exactly the portion of compressed air which – once expanded – will reach the external pressure. The pressure established in the right cylinder is transmitted through the exchanger coil (3R) to the hydraulic motor (4), passing the 4-vay valve (5).This valve remains in the position (b) and thus activates the motor port. This leads to the expulsion of the air in the work-chamber (1L) by the return flow from (4), which joins the muffler (6) through the opened valve (B).

The air in the right-handed work-chamber (1R) is squeezed between metal plates when expanding: these metal plates just emerge from the thermally stabilized liquid, so any cooling down of the air is seriously hampered (the same would happen during compression, where a temperature rise would be limited, as the external exchanger (3R) always tends towards the surrounding temperature of the fan air flow. As the stroke ends, the 4-Way-Valve (5) inverts the interface flow by switching to the position (a) without changing the rotational direction of the hydraulic motor, the inertia of the liquid pistons being negligible.

Fig. 4 Principle of the BOP-B system with nearly isothermal compression/expansion

The fast torque-change can be smoothed by a special flywheel (8) mounted on the shaft or directly absorbed by an auxiliary storage device using Supercapacitors as will be described in the following sections. This process simply reverses during storage (compression), the hydraulic machine working as pump and always turning in the same direction thanks to the 4-way valve (5).

6. Strategy of Output Power Variation

6.1 Principle

The principle of the output power variation is described on the base of the operation of the pneumatic motor, but has been reused in a similar way for BOP storage systems. As mentioned earlier, the variation of electric output power P_L is based on the intermittent, time-modulated operation of the compressed air conversion subsystem. The excess of the resulting power P_e is stored in the supercapacitive device and used to supply the load during the stop-time of the pneumatic machine, or as power-assistance during peak power demand. The control-scheme of this strategy is presented in figure 5a. By maintaining the intermediary voltage U_{inter} constant, the voltage regulator automatically compensates the lack or excess of produced power, allowing thus the output power to vary freely. The PWM on-off operation of the thermodynamic conversion is made through the electro-valve control module. There are two possible operation-modes: the Fixed-frequency operation mode and the Free-oscillating operation mode. These operation modes are described in the following paragraphs, considering the discharge operation.

6.2 Fixed-Frequency Operation Mode

In this mode, the cycle period T is constant. The converted energy W_e is then proportional to the duty cycle D as presented in figure 7b. As the reservoir pressure drops during operation, the produced power P_e decreases. Assuming that the system is suitably controlled and neglecting the losses, the energy W_s stored during the running time t_{on} is equal to the energy W_r required by the load during the stop time t_{off}.

$$W_s = W_r \Leftrightarrow \int_0^{D.T} P_e dt = \int_0^{T} P_L dt \qquad (1)$$

If we consider the simple but improbable case where the produced power P_e and the load power P_L remain constant, we can get from equation (1) the Duty cycle of the main storage subsystem PWM operation:

$$D = P_L / P_e \quad (2)$$

Since it's not possible to predict the behaviour of the load power, D is determined once at the beginning of each cycle using relation (2). This approach is accurate only if the cycle period T is small enough compared to the time constant of the power variations. It may happen that the load power increases strongly within a cycle in such a way that the stored energy becomes insufficient to supply the load. In that case, the pneumatic machine is turned on as soon as the minimum allowable value of the supercapacitive bank voltage is reached. It's also turned off at its maximum value and at the minimum operating pressure.

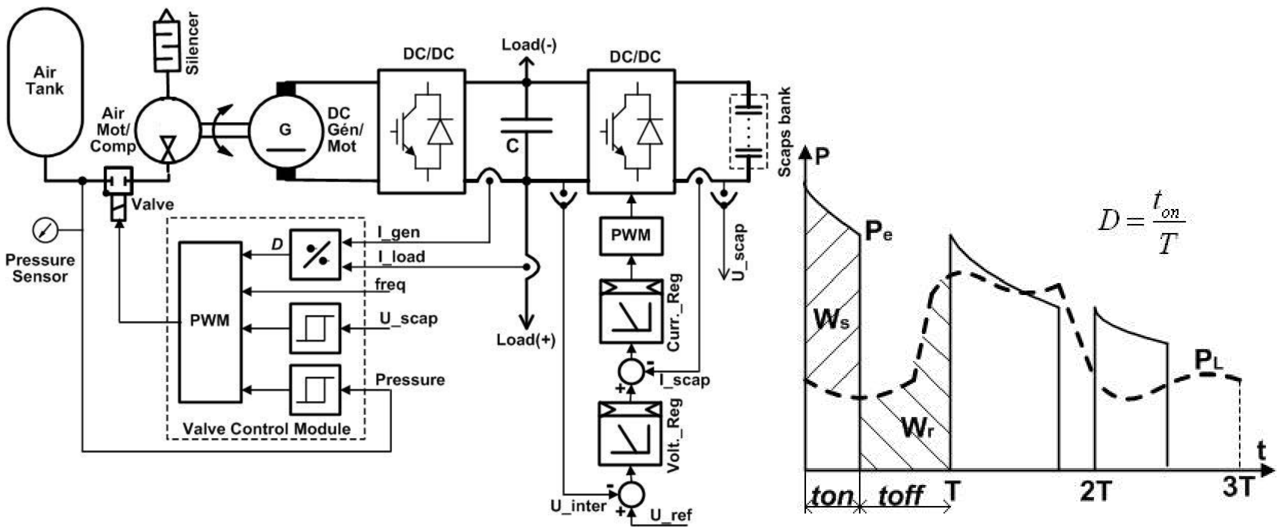


Figure 5: a) Principle of output power variation b) Power modulation

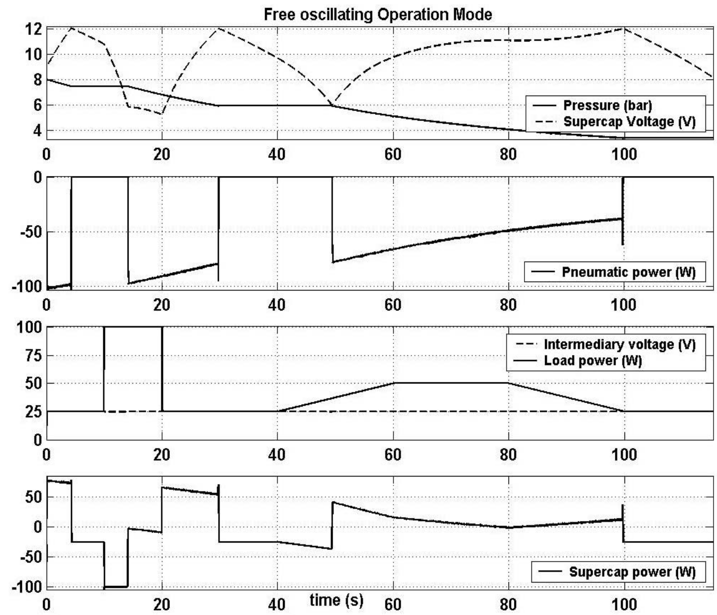


Fig. 6 Simulation results of free oscillating operation mode

6.3 Free-oscillating Operation Mode

In this mode, the operation cycle's period is not constant. The only control parameter is the supercapacitive bank voltage. When it reaches the minimum value, the electro-valve is opened, and when it reaches the maximum value, the electro-valve is closed. As the intermediary voltage is held constant, the frequency and duty cycle of the operation cycle follow automatically the ratio between P_e and P_L. This is the simplest way of modulating the produced power. The simulation results presented in figure 6, and in the same generation conditions, the number of turn-on and offs of the pneumatic machine is smaller than in the previous mode.

6.4 Sizing the Supercapacitive bank

The supercapacitive bank must be able to provide the energy W_{Loff} required by the load during the stop time t_{off}. This energy is given by the following equation:

$$W_{Loff} = \int_{D.T}^{T} P_L dt \tag{3}$$

The most critical case is when $D = 0$ and $P_L = P_{Lmax} = C^{ste}$. In that case, we have:

$$W_{Loff\max} = T.P_{L\max} \tag{4}$$

The maximum amount of energy W_{Scmax} that can be stored in a supercapacitive bank of total capacitance C_T and maximum voltage U_{Tmax} is:

$$W_{Sc\max} = \frac{1}{2} C_T U_{T\max}^2 \tag{5}$$

But, because of the losses in the Supercapacitors and the minimum voltage U_{Tmin} required by the interface converter, this energy cannot be restored totally. If we consider a depth of discharge ratio d

$$d = \frac{U_{T\min}}{U_{T\max}} \times 100 \tag{6}$$

And total discharge efficiency η_d, the maximum useful energy is:

$$W_{u\max} = \frac{1}{2} \eta_d C_T U_{T\max}^2 \left[1 - \left(\frac{d}{100} \right)^2 \right] \tag{7}$$

From equations (4) and (5) we can get the value of C_T:

$$C_T = \frac{2T.P_{L\max}}{\eta_{cd} U_{T\max}^2 \left[1 - \left(\frac{d}{100} \right)^2 \right]} \tag{8}$$

This design criterion takes into account that internal losses are produced inside the supercapacitive bank, because of the internal series resistance [10]. A more accurate design should include the losses inside the interface converter and should take into account the fact that the power flow for storage cycles implies many cycles for the auxiliary storage subsystem.

7. Practical results

In order to verify the performance of the proposed systems and especially the use of a hybrid configuration with a hydro-pneumatic main storage unit associated to a supercapacitive auxiliary storage unit, a dedicated setup has been realized. The schematic diagram given in Figure 7 shows the main storage subsystem composed of the power MOSFET inverter drive, the PMSY motor/generator, the hydraulic pump/motor, the oil tank and the hydraulic accumulator. In the lower part of this figure, the auxiliary storage device is represented with the power MOS chopper and the Supercapacitors bank. At the same level, an active load realized with a transistor and a dissipation resistor is represented. For the evaluation of the system in the lab, a line source circuit is used with a transformer and diode rectifier. The energy source for real applications is represented in the form of a photo-voltaic panel with interface. Of course a correct design should consider the necessity to use this last converter, in comparison with a direct connection of the PV panels to the DC circuit of the inverter.

The represented equipment has been realized with the goal to experiment the alternating operation of the two storage devices, and to further implement the MEPT algorithm. PWM operation of the complementary conversions is also possible. An additional extension of this equipment for the realization of a BOP-B system is expected, and will be presented in a later contribution. The experimental storage device with motor/pump, Hydraulic/pneumatic accumulator and the whole power-electronic equipment is shown on the photograph in figure 8b. The basic operation of the system is illustrated with the curves of figure 8a. In this figure, the storage operation is represented with the alternating operation of main and auxiliary sources. The pressure of the gas in the accumulator is represented, as well as the speed of the rotating machines. When the main storage subsystem is charging the gas-accumulator by oil injection, the relatively high power of the pump is provided by the auxiliary storage device (Supercapacitors). When the oil-pump is stopped, the Supercapacitors are recharged by the low power primary source that could be the PV-system. The PWM operation allows varying the mean value of the used or produced power, as well as compensating the variations of the stored power due to the change of the gas pressure.

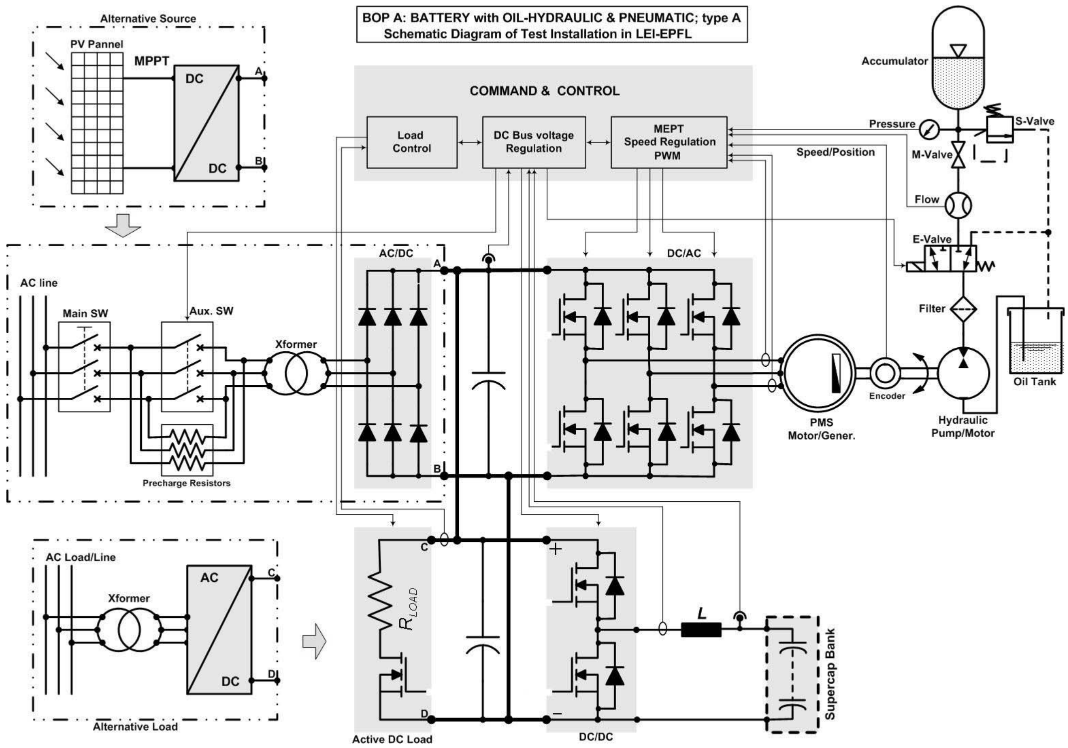


Fig. 7 Schematic diagram of the experimental set-up for BOP-A at EPFL's LEI

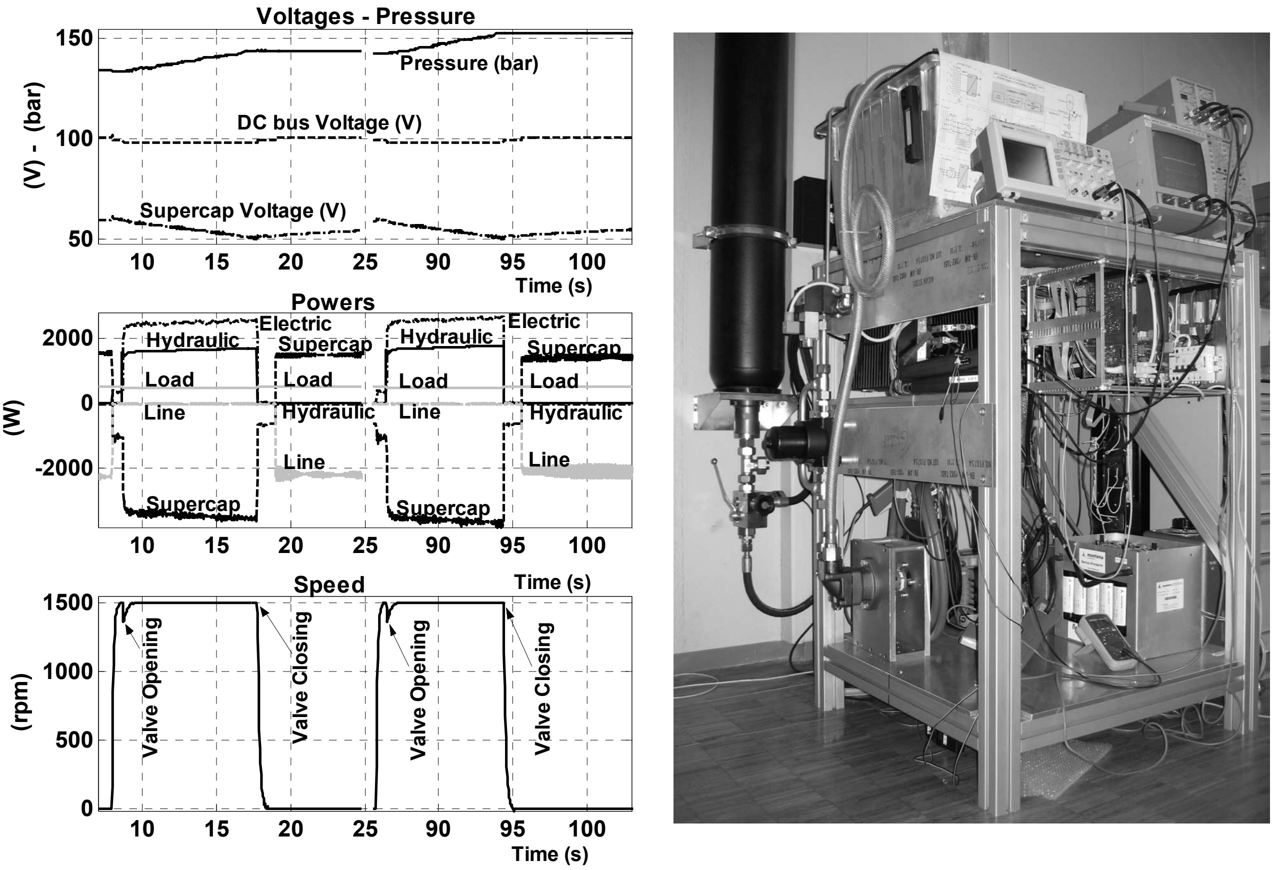


Figure 8: a) Basic operation curves b) Experimental set up of the BOP-A storage facility

8. Economical considerations: Comparative cost evaluation

8.1 Studied case's specifications

A comparative storage-cost evaluation has been made for a Day-to-Night power shift in a Photovoltaic supplied home application. The daily scenario of the application is shown in figure 11a for a normal sunny day. The mean power of the system is 4kW, the storage peak-power 10kW and the discharge peak-power 5kW. 3-days autonomy is required, which lead to a storage capacity of 60kWh. Three storage technologies are considered with DC voltage output: A tubular plate lead acid batteries system as shown in figure 11b, a BOP-A system as shown in figure 5 and a BOP-B system as shown in figure 6 but with Supercapacitors auxiliary storage instead of Flywheel. The minimum life cycle requirement is 3’500 cycles.

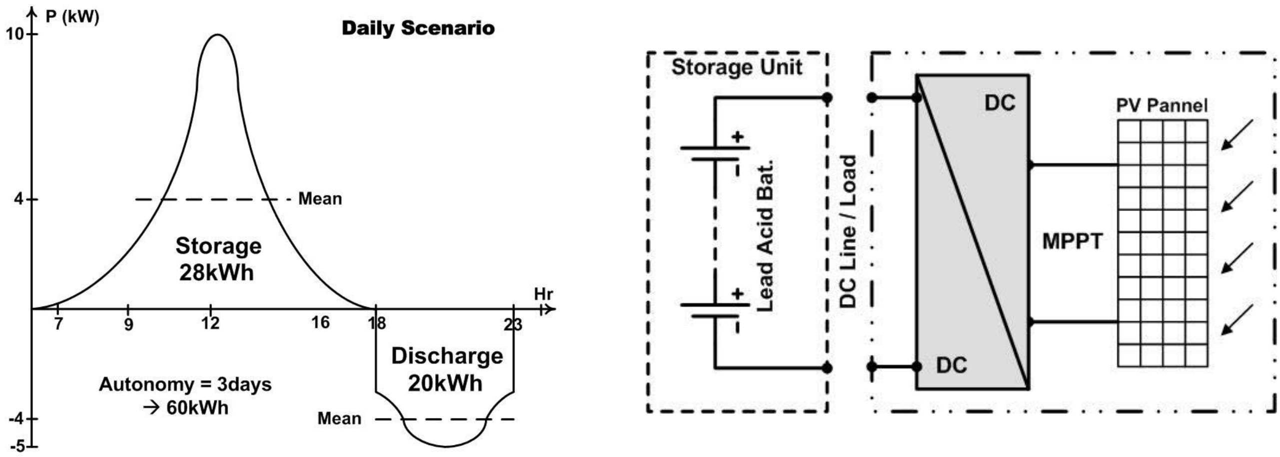


Figure 11: a) Daily scenario b) Principle of the PV supply with the Batteries storage

8.2 Cost evaluation and comparison

60kWh - 10kW		Lead Acid	BOP-A	BOP-B
Technology	Storage	€ 18’000	€ 60’000	€ 4’500
	Conversion	/	€ 15’000	€ 18’000
	Total	€ 18’000	€ 75’000	€ 22’200
Operation & Maintenance		30% € 5’500	20% € 15’000	20% € 6’000
Total Cost		**€ 23’500**	**€ 90’000**	**€ 28’000**
Life cycle		**3’500** or 210’000 kWh	**15’000** or 900’000 kWh	**15’000** or 900’000 kWh
Energy Cost /kWh		**€ 0.11 / kWh**	**€ 0.1 /kWh**	**€ 0.03 / kWh**

Table 1: Cost evaluation for 60kWh – 10kW peak storage

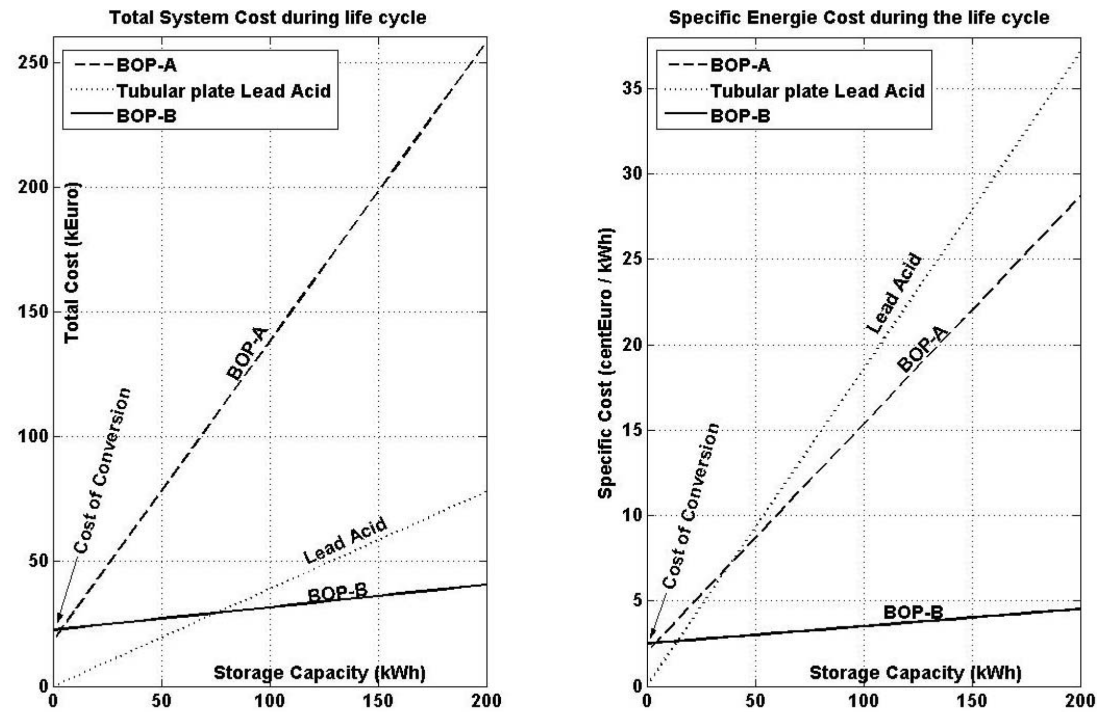


Figure 12: System-Cost and Energy-Cost evolution versus Storage capacity

The table 1 shows the cost evaluation of the considered storage technologies for the specified application. The cost of the PV panel and its interface converter is not taken into account. The first comment is that for BOP systems, the storage part is totally decoupled from the conversion part, thus offering more flexibility for the design and sizing of the storage. Secondly, the BOP-B is for far the best storage solution for this application. BOP-A is much more expensive than the other systems, because of the important storage unit due to the low energy density (approximately 2.5Wh/kg). However, compared to lead acid, this high cost is balanced by a high life cycle so that the two systems present almost the same energy cost

Figure 12 shows the evolution of the System-cost and the Energy-cost for the three considered technologies with regard to the storage capacity. As it can be seen, there is an offset-cost for BOP systems that corresponds to the conversion cost. In addition, BOP-A is more sensitive to the storage capacity, which this system more suited to low-energy high-power applications, or stationary applications where volume and weight are not critical criteria. These graphs confirm the cost effectiveness of BOP-B which makes this system very promising for future storage solutions associated to renewable energies sources.

9. Conclusions

Compressed air in vessel storage has been considered with the target to develop high life-cycle and cost effective system. The efficiency optimization strategy proposed in this study can significantly improve the efficiency of the thermodynamic conversion. The presented topology, which combines compressed air and Supercapacitors, improves flexibility and dynamic performances of the storage system and makes it suitable for a wide range of low power autonomous or grid-connected applications, like renewable support and power quality enhancement for sensitive users. The typical advantages over classical CAES plants include site independence, fuel free operation and environmental harmlessness. However, low-pressure and low-efficiency are weakness of the purely pneumatic first studied system and are mainly related to the characteristics of the pneumatic motor. To improve the efficiency and the energy density of the thermodynamic conversion and storage, the dedicated system must be able to operate at high and variable pressure in an isothermal process. For this purpose, oil-hydraulic machines offer the best performances, but they need a particular air-oil interface. Further developments are still running at EPFL's LEI, in order to verify the quality of the integrated heat exchanger for the isothermal process. Global system optimization and dedicated valve control and coordination belong also to the further expected developments. Experimental results have been presented in this paper, for the pneumatic motor based system as well as for the system using a high efficiency hydraulic motor/pump. Finally, the cost evaluation in the context of a practical application has proved the cost effectiveness of the studied hydro-pneumatic systems compared to some classical electrochemical storage technologies.

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