Principle of Hybrid Energy Storage Systems Based on Hydro-Pneumatics and Supercapacitors for Distributed Generation and Renewable Energy Sources Support

S. Lemofouet (Industrial Electronics Laboratory (LEI), Swiss Federal Institute of Technology, Lausanne, Switzerland); sylvain.lemofouet@epfl.ch
A. Rufer (LEI)

Abstract

This paper presents hybrid energy storage systems based on hydro-pneumatics and Supercapacitors with high potentials regarding life cycle and impacts on environment. These so called "Batteries with Oil-hydraulics and Pneumatics (BOP)" systems exploit the high performances of oil-hydraulics machines to store energy into compressed air. In the first system, the BOP-A, compression and expansion of a trapped volume gas take place in the storage vessel. A Maximum Efficient Point Tracking algorithm is used to optimise the efficiency of the oil-hydraulic machine. As the maximum efficiency conditions impose the level of the converted power, an intermittent time-modulated operation is applied to the pneumatic-to-electric conversion subsystem to obtain a variable mean 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 principle of the Maximum Efficiency Point Tracking (MEPT) algorithm and the strategy used to vary the output power. Practical results are reported, that have been recorded from a first prototype of BOP-A. In addition, the paper introduces the second and more promising system, the BOP-B, where compression and expansion of fresh air are done in liquid-piston work-chambers with integrated heat exchangers. This leads to an almost isothermal process and therefore to high efficiency and high energy density. Finally, some economical considerations are made, in the context of a stand alone photovoltaic home supply, through a comparative cost evaluation of the presented hydro-pneumatic systems and a lead acid batteries system. This evaluation confirms the cost effectiveness of the studied hybrid storage systems.

Introduction

Distributed Generation together with the expansion and integration of renewable energies has been considered as the future scenario of sustainable electrical energy production and distribution. It is a common agreement that, storage is a key technology for this concept to become a reality. In fact, storage can increase the value of renewable energies by making them more available and less fluctuating [1]. In that context, the integration of renewable energies, which are considered as high quality sources in term of life cycle and impact on the environment, will be effective only if the associated storage technologies are of the same quality level to that respects. Beside the high-capacity storage facilities like pumped hydro technologies, electrochemical solutions are the today's main storage candidate for renewable sources support. However, because of their limited life-cycles and their difficulties to be recycled, electrochemical batteries are far to fulfil these mid and long term requirements [2].

Recently, several alternative storage technologies have appeared, and are being integrated in real networks [3], [4]. Ultra-large size facilities have been also proposed based on dedicated turbo machinery [5] as well medium and small size accumulators using hybrid thermal and compressed air storage(TACAS) [6], or using intermediary mechanical/hydraulic conversion with the so-called "liquid piston" principle [7]. The two hybrid storage systems presented in this paper deal with this last innovative approach and are intended to address these mid and long term issues. These so called "Batteries with Oil-hydraulics and Pneumatics (BOP), type A (BOP-A) and type B (BOP-B)" storage systems associate simple, reliable and mature hydro-pneumatic technologies with modern and intelligent power electronics and control. This association yields to flexible and high performances storage systems with high life cycle and environmental compatibility. The concept of the BOP-A and strategies of efficiency optimisation and output power variation are presented first, then the BOP-B is introduced and finally some economical considerations are made in the context of a PV application.

1-Principle of the Battery with Oil-hydraulic & Pneumatics, type A: BOP-A.

The concept of BOP-A with Supercapacitive auxiliary storage system is presented in Figure 1. In this system, compression and expansion of a trapped volume nitrogen take place in the storage vessel. During storage, the PMS motor drives the hydraulic pump to compress the gas in the accumulators with oil. During generation, the compressed gas is expanded and the oil expelled from the accumulator drives the hydraulic machine, which works as a motor to drive the electric machine as a generator. There is no pressure regulator to avoid the important losses associated with such a device. The hydraulic motor/pump inlet/outlet pressure therefore varies continuously and this affects its performances as it can be seen on Figure 2. A Maximum Efficiency Point Tracking (MEPT) algorithm is used to control the speed, so as to always keep it at the optimal operating point for any pressure. As the maximum efficiency operation imposes the level of the converted power, a strategy to vary the output power is therefore necessary. It consists of applying a time modulated on-off operation to the pneumatic-to-electric conversion subsystem to modulate the converted power as a function of the output power demand. The auxiliary supercapacitive storage device is used to smooth the modulated power through the regulation of the capacitive intermediary stage voltage.

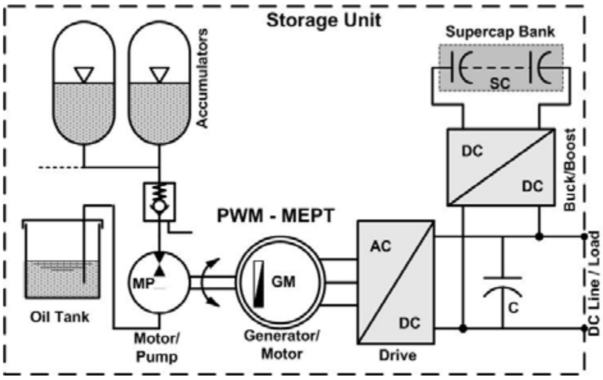


Figure 1: Principle of BOP-A

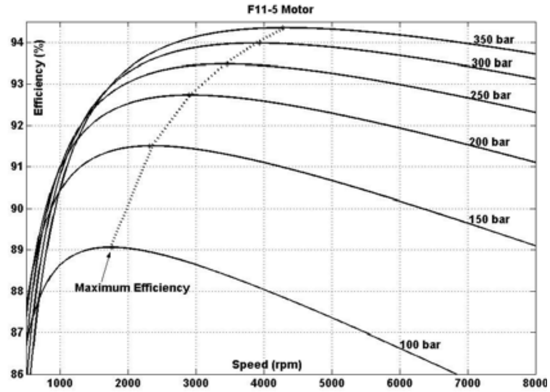


Figure 2: Efficiency characteristic of a hydraulic machine

2- Short description of the strategies of efficiency optimization (MEPT) and Output power variation

These strategies were developed during previous work with air machines and published in [8]. Figure 3 shows the principle of the strategy of efficiency optimization applied to the hydraulic machine of BOP-A. On the basis of various measurements (Pressure, Flow, Speed, etc), the MEPT module determines the optimal speed which corresponds to the maximum efficiency. This optimal speed serves as reference to the speed control module and is achieved through the control of the torque of the PMS machine. The MEPT algorithm consists in the combination of two techniques: Quadratic Interpolation during start up and the so-called “Perturbation-Observation” technique for tracking.

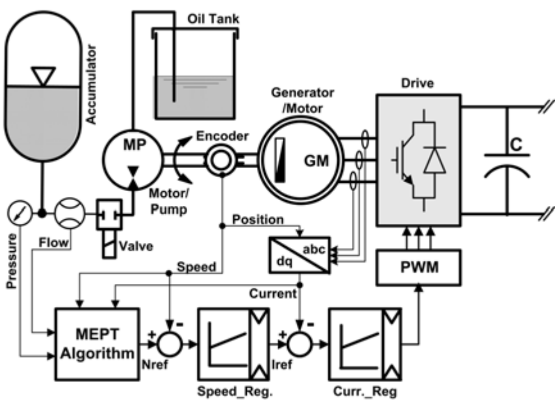


Figure 3: Principle of Efficiency optimisation (MEPT)

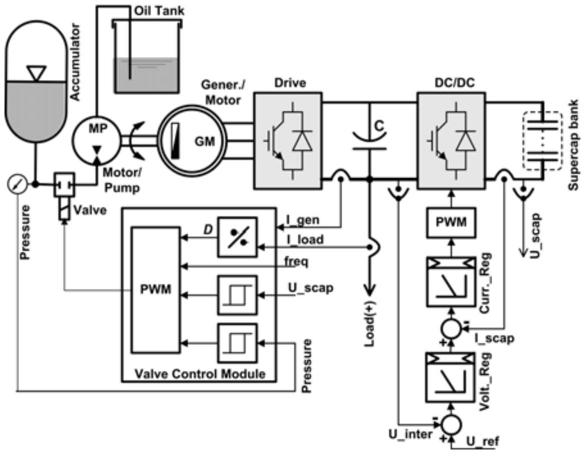


Figure 4: Principle of output power variation

The control scheme of the strategy for output power variation is presented in Figure 4. As mentioned earlier, this variation is based on intermittent, time-modulated operation of the pneumatic-to-electric conversion subsystem. This PWM on-off operation is achieved through the electro-valve control module. The operation duty cycle is proportional to the ratio of the load and source powers and the converted power. The excess or lack in the converted power is stored or provided by the supercapacitive storage [9], [10]. By regulating the DC bus voltage, the voltage regulator automatically compensates the lack or excess of converted power, allowing thus the load power to vary freely.

3- First practical results

In order to verify the performance of the proposed systems and especially the use of the hybrid configuration with a hydro-pneumatic main storage unit associated to a supercapacitive auxiliary storage, a dedicated setup has been realized. The schematic diagram of which is given in Figure 5, where the main storage subsystem is shown and composed of the power MOSFET inverter drive, the PMSY motor/generator, the hydraulic pump/motor, the oil tank and the hydraulic accumulator. The auxiliary storage device is also shown, with the power MOS chopper and the Supercapacitors bank. An active load realized with a transistor and a dissipating resistor is used. For operation in the lab context, a line source circuit made of a transformer and diode rectifier feeds the system. For real applications, the source could be the photovoltaic panel with its interface and the load any DC or AC load interface with an inverter.

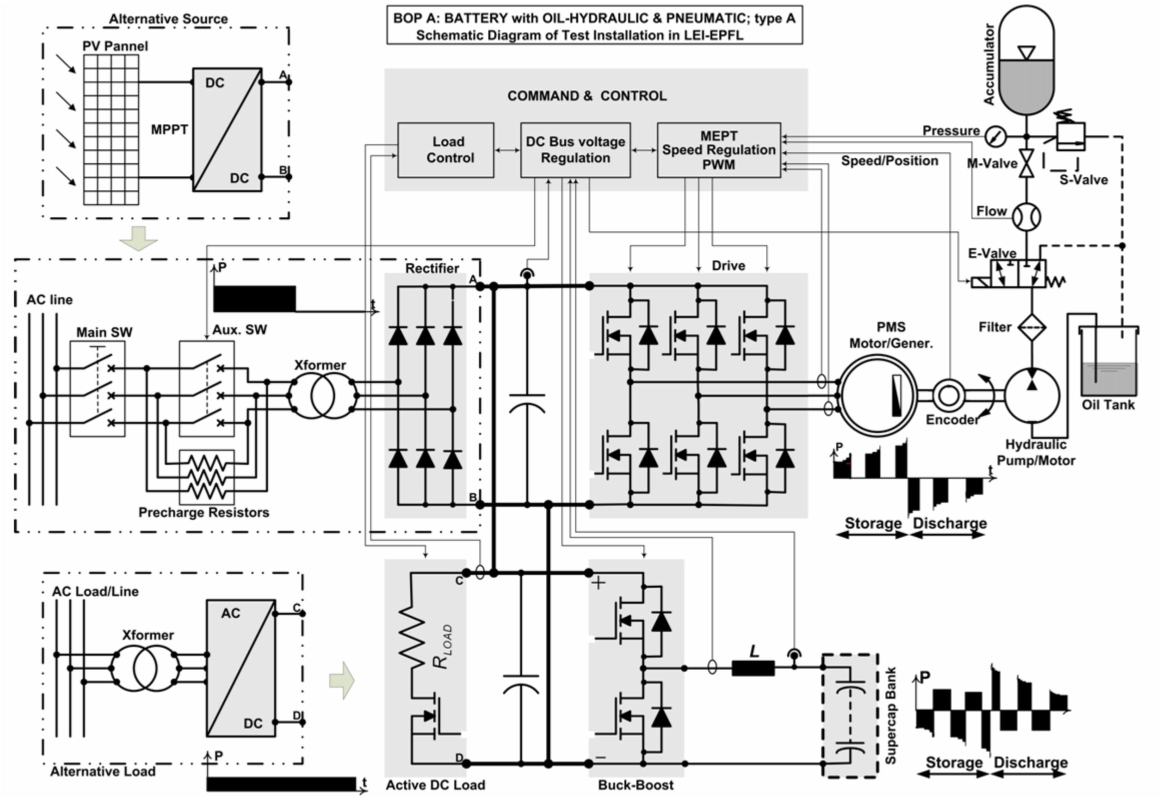
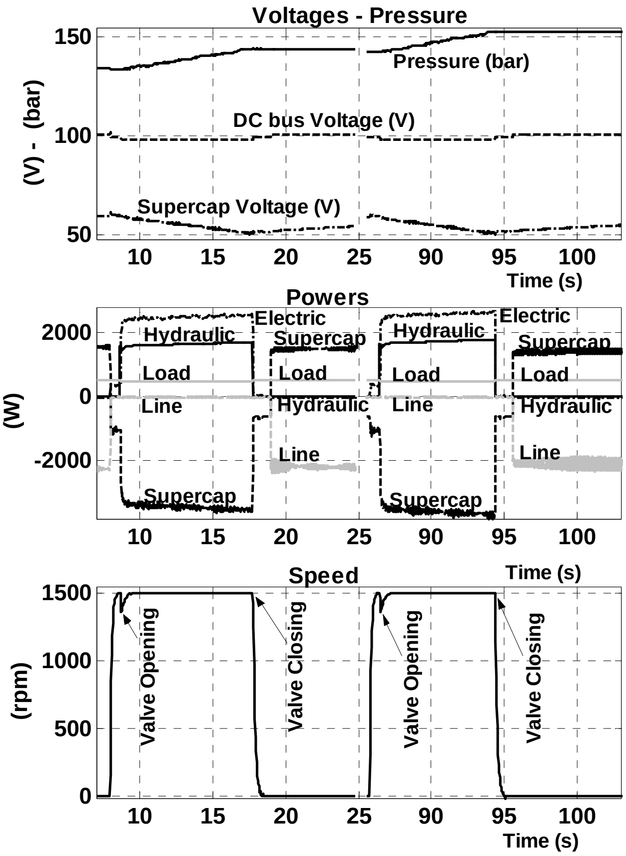


Figure 5: Schematic diagram of the experimental setup for BOP-A



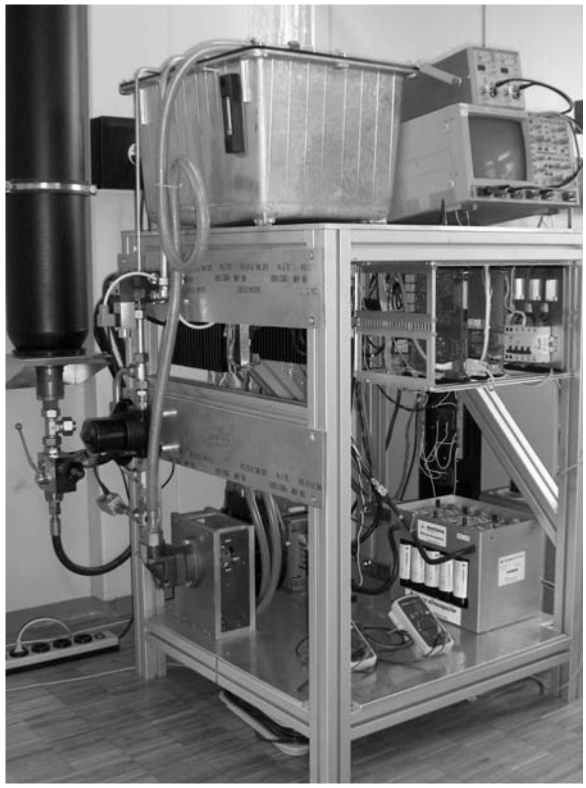


Figure 6: a) Basic operation curves **b) View of the experimental setup in EPFL-LEI**

A view of the setup is shown in figure 6-b and the basic operation is illustrated with the curves of figure 6-a, for a 1500rpm, constant speed storage mode. These curses show the intermittent operation of the main storage subsystem, the very good management of the energy transfer between the different units and the effectiveness of the strategy for output power variation. 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 changes in gas pressure. The strategy of efficiency optimisation is being implementing and the results of which will be presented soon in a coming contribution.

The long time constant of the compression and expansion processes leads to isothermal conversion and therefore to high efficiency [11], [12]. However, the important volume of compressing oil needed results in low energy density (approximately 3Wh/L), which makes the BOP-A more suitable for stationary applications where volume and weight are not critical. But this limitation is break with the second and more promising system, the BOP-B.

4- Principle of the Battery with Oil-hydraulic & Pneumatics, type B: BOP-B.

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 7 as well as described in [13], in a simplified manner in order to explain the sequences of one cycle.

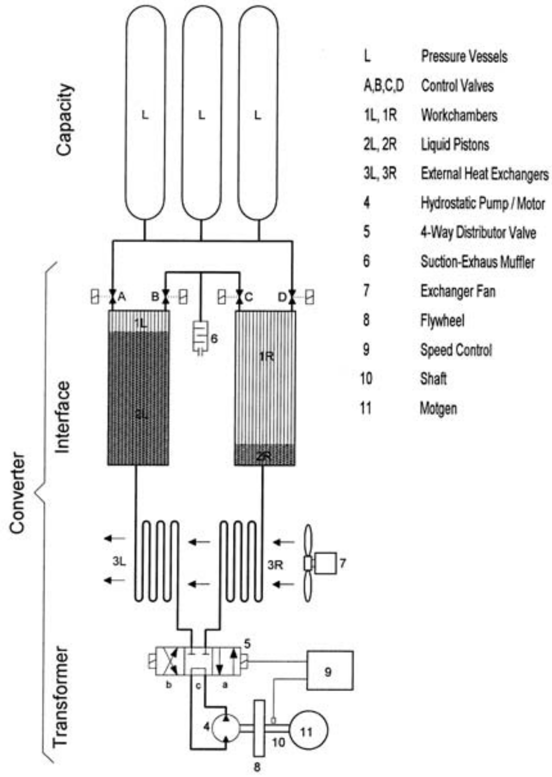


Figure 7: Principle BOP-B

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. 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). Works are in progress in our lab for the test and optimisation of the oil-to-air interface.

5- Economical considerations: Comparative cost evaluation

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 8-a, 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 8-b, a BOP-A system as shown in figure 1 and a BOP-B system as shown in figure 7 but with Supercapacitors auxiliary storage instead of Flywheel. The minimum life requirement is 3’500 cycles.

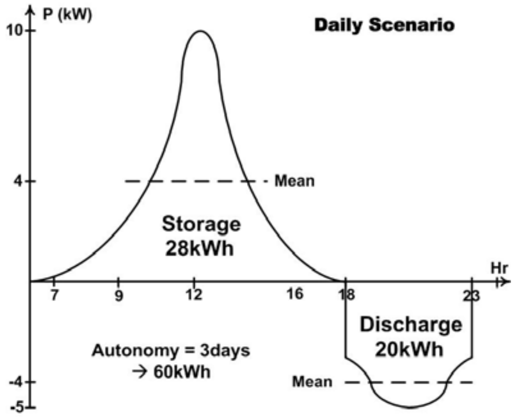


Figure 8-b: Daily scenario

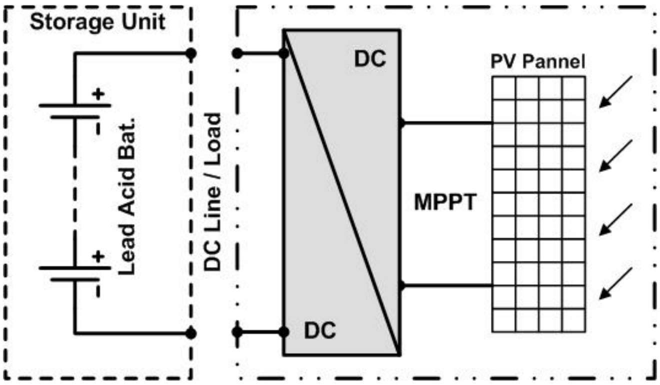


Figure 8-b: Principle of the PV supply with the Batteries storage

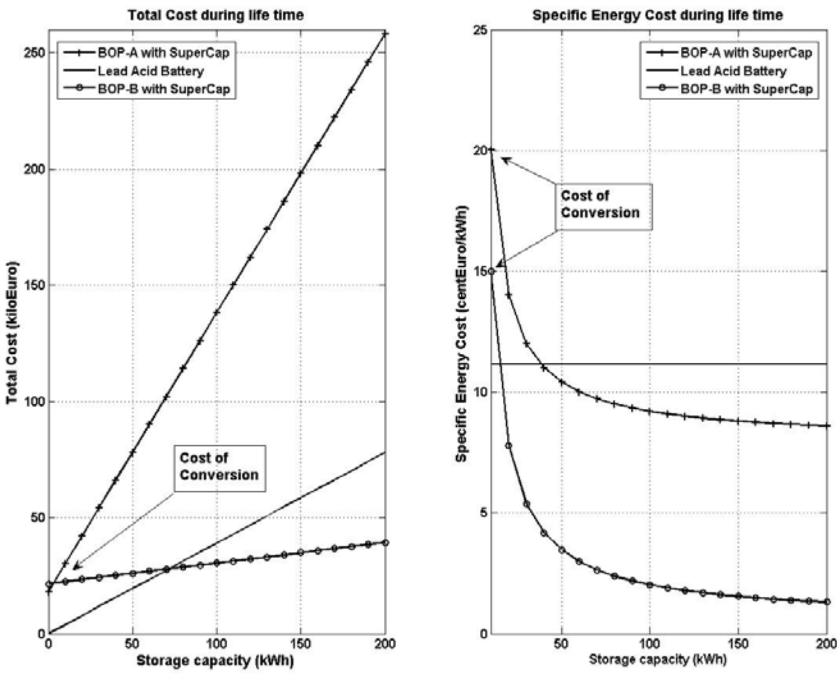


Figure 9: Total cost and specific energy cost versus storage capacity

The cost of the PV panel and its interface converter is not taken into account. Figure 9 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 fact, for BOP storage systems, the storage part is completely separated 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 and 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. In addition, BOP-A is more sensitive to the storage capacity, which makes 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 energy sources.

Conclusion

Two storage systems called “Batteries with Oil-hydraulics and Pneumatics (BOP), type A: BOP-A and type B: BOP-B” are presented, which are intended to address the issues of mid and long term effects of the today’s storage technologies associated to renewable energies. The presented hybrid systems associate some simple and mature hydro-pneumatic technologies to modern technologies like Supercapacitors and Power Electronics and Control, to build high performances and flexible storage systems, thanks to the efficiency optimization strategy (MEPT) and the output power variation strategy that has been developed and implemented.

These systems present high life cycle since no chemical process is involved and therefore no important aging effect. In addition, they are environmental friendly since they use easy to recycle material and produce no problematic waste. These high life cycle and environmental compatibility make them more suitable to application like renewable energy sources support and distributed generation. Some economical considerations are also made, through a comparative cost evaluation, for a day-to-night power shift in a stand alone photovoltaic home application. Three storage solutions are considered: the two presented BOP systems and a tubular lead acid batteries system. This evaluation confirms the cost effectiveness of the BOP storage over lead acid storage.

References

[1] European Research Community; **Energy storage: key technology for decentralized power, power quality and clean transport**; EUR 19978, RTD info, European communities, 2001.

[2] D.C.R Espinosa, A.M. Bernardes, J.A.S. Tenório; **An overview on the current processes for recycling of Batteries**; Journal of Power Sources 135 (2004) 311 – 319.

[3] W. Seele; **Batteriespeiranlagen in elektrischen netzen;** ABB – Technik, 1/1989, pp 23-28

[4] Bradshaw Ted D; **TVA Regenesis Vanadium Redox Flow**; ESA 2001, Chattanooga Te, April 2001.

[5] J. Lehmann; **Air storage gas turbine power plants, a major distribution for energy storage**; International Conference on Energy storage, Brighton UK, 04/1981, pp 327 – 336

[6] J. Saers; **Thermal and Compressed-Air Energy Storage, Next-Gen storage technology**; ESA annual meeting, May 2005, Toronto – Canada.

[7] A. Reller, I. Cyphelly ; **Speicherung gasförmiger energienträger: Eine Bestandsaufnahme** ; VDE – Berichte 1734, Energiespeicher, p.p. 37 – 45

[8] S. Lemofouet, A. Rufer, I. Cyphelly, P. Barrade, F. Grasser, **Principle of a hybrid Compressed Air and Supercapacitors Energy Storage system with Maximum Efficiency Point Tracking,** EESAT, October 2003, San Francisco, USA.

[9] A. Rufer, P. Barrade; **A Supercapacitors-based energy storage system for elevators with a soft commutated interface**; IEEE Trans. on Industry Applications, Vol. Sept October 2002

[10] P. Barrade, A. Rufer; **Current capability and power density of Supercapacitors: considerations on energy efficiency**, EPE 2003: 10th European Conference on Power Electronics and Applications, 2-4 September 2003, Toulouse, France

[11] D. R. Otis, F.T Elder; **Accumulators: the role of Heat transfer in fluid power losses**; 4th International Fluid Power Symposium, April 1975, USA

[12] A. Pourmovahed, D. R. Otis; **An experimental thermal time constant correlation for Hydraulic Accumulators**; ASME Journal of Dynamic Systems, Measurements and Control, Vol. 112, No. 1, March 1990, pp. 116 – 121.

[13] I. Cyphelly, A. Rufer, Ph. Brückmann, W. Menhardt, A. Reller; **Usage of compressed air storage systems;** Swiss Federal Office of Energy, DIS Project Nr. 100406, May 2004. Publ. Nr 240050;