HYBRID STORAGE AND DISSIPATION SYSTEMS BASED POWER MANAGEMENT STRATEGIES IN A LOCAL DC POWER DISTRIBUTION SYSTEM OF MORE ELECTRIC AIRCRAFT

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Abstract

The electrification of modern aircrafts is becoming a major objective due to increased reliability of electromechanical actuators replacing mechanical, hydraulic and pneumatic actuators. Thus, a local DC Power Distribution System has to be able to sustain unidirectional or even bidirectional power flow to and from electromechanical devices. Because the mechanical source (Turbine Engine) is unidirectional, some storage and dissipation systems are necessary to store or/and dissipate the returned energy to maintain the DC bus voltage to the reference value. Different power management strategies are proposed and compared. The development of experimental test benches is necessary to validate these strategies. In this paper, we present a 3kW test bench, emulating a unidirectional source that supplies a bidirectional load with the help of a hybrid system using supercapacitors and a dissipation system.

1 Introduction

The aeronautic transportation burns a good part of the world's oil resources, being a major source of pollution. A solution for energy economy is to use smart on-board system management strategies in order to reduce oil consumption and the emissions of greenhouse gas. Also, by increasing the energy efficiency of air transportation and storing the energy recovered from the electrical machines, we are contributing to this reduction in consumption.

In this context, the More Electric Aircraft (MEA) has been put forward. It becomes the trend of the future aircraft. Thanks to the progress of power electronics allowing more reliable and high performance energy conversion, there are more and more electrical equipments installed in the aircraft. The replacement of mechanical, hydraulic and pneumatic actuators by an electrical equivalent is one of the most important innovations [1] of MEA. In MEA, a generator driven by the reactor offers a variable frequency AC power because the Constant Speed Drive (CSD) has been removed for mass reduction reasons [2]. Currently, the main network in the airplane remains a 400Hz AC network. The use of a local DC Power Distribution System (PDS) makes it possible to reach the subsystems optimum in order to get some benefits, like a weight reduction for example. Indeed, a DC network needs only 2 power cables to transport electrical power whereas the AC network needs 3 power cables. It allows us to reduce the number of electronic power converters and cable insulation. Currently, this DC system is not totally reversible, but for optimization reasons (efficiency and availability increase for example), it could be reversible in the future. Some storage and dissipation systems are then

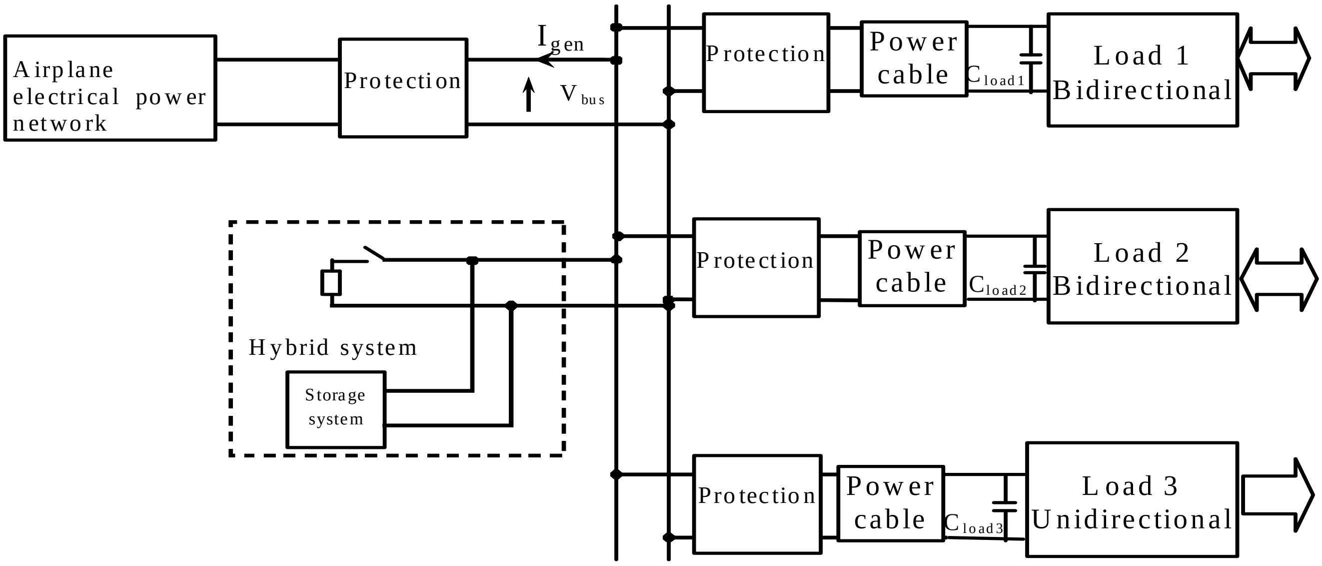

Fig. 1. Local DC on-board network with hybrid storage and dissipation system.

necessary to store or/and dissipate the returned energy to maintain the DC bus voltage.

Some power management strategies with hybrid energy storage systems (batteries and supercapacitors) are presented in [3] and [4] for electric vehicles. The objectives of these power management strategies are to increase efficiency and to minimize energy requirements. But the dynamic of the load profile in the aeronautic domain is faster than in other application fields (hybrid electric vehicles, power distribution systems and wind power) [2]. In this context, a hybrid storage and dissipation system is investigated to ensure dynamic compensation and security [5]. Some control and supervision strategies are proposed in this paper with the objectives to ensure DC bus voltage in the range of acceptable tolerance and to optimize energy efficiency.

Different supervision strategies are proposed, based on simple PI controller or on fuzzy logic. Fuzzy logic allows us to ensure simultaneously different objectives like voltage stability, energy efficiency and storage availability, for instance. Fuzzy logic is a well adapted tool to design multi-objective management strategies as shown in [3], [6], [7] and [8].

2 Power System Under Study

The DC local power distribution system under study is shown in Fig. 1. This network

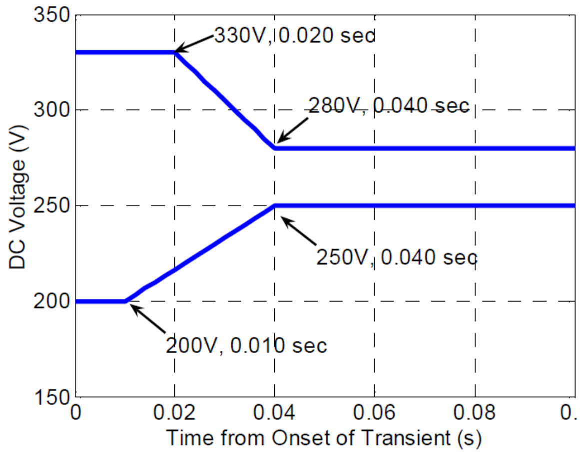

Fig. 2. Voltage standard of MIL-STD-704.

includes 2 independent unidirectional sources and 3 loads in which 2 are bidirectional, and a hybrid storage and dissipation system. The GCU (Generator Control Unit) ensures the voltage control of the PDS.

The rated voltage of DC bus is 270 V, but the acceptable tolerance is between 250 V and 280 V as shown in Fig. 2 according to the standard MIL-STD-704 [9].

As the mechanical source (Turbine Engine) is unidirectional, the Permanent Magnet Generator (PMG) cannot regenerate power. When the sum of returned power of load1 and load2 is greater than the power consumed by load 3, the anti-runback devices will stop the returned power, which will be stored in the capacitors. It will cause an over-voltage of the DC bus.

The hybrid storage and dissipation system (shown in Fig. 1) can be used to solve this problem. A resistor associated with a chopper can compensate the dynamic weakness of the storage system. It also ensures the security of the system in case of DC voltage increase when the storage system is saturated.

3 Power Flow Management Strategies

3.1 Supervision strategies

Different power management objectives may be considered:

- To maintain the DC bus voltage in the range of acceptable tolerance;
- To optimize energy efficiency and then to minimize the dissipated power;
- To ensure the availability of the storage system.

The design of the supervision strategies has to take into account different constraints:

- The PMG with anti-runback diodes is unidirectional source;
- The voltage standard MIL-STD-704;
- The capacity of the storage system;
- The dynamic of the storage system.

The bidirectional load, the storage system and the dissipation system are controlled in power. This power reference will be determined by the supervision system. Two levels of power management strategies will be considered individually as shown in Fig. 3. The first level determines the total absorbed or generated power reference of the hybrid system, P_{total_ref} by measuring generation current I_{gen}, bus voltage V_{bus}, State Of Charge (SOC) of the storage system and the output power of the storage system P_{stor_out}. The second level splits the P_{total_ref} in two parts: the part to store, P_{stor_ref}, and the part to dissipate, P_{dissi_ref}.

For each level, two strategies are proposed: a basic strategy with a single objective and a more complex strategy targeting more objectives, based on fuzzy logic. Fuzzy logic allows us to ensure simultaneously different objectives like voltage stability, energy efficiency and storage availability [3], [6], [7] and [8].

For the first level I, the proposed strategies are the following:

- A simple Proportional Integral controller (PI) which controls the DC bus voltage (single objective);
- A Minimum supplied Power (MP) strategy which also controls the DC bus voltage, but maintains the PMG working and takes into account the SOC. Due to these multi-objectives approach, fuzzy logic has been used to develop this strategy.

For the second level, the proposed strategies are the following:

- A Full Compensation (FC) strategy which compensates the dynamic weakness of the storage system by considering a simple power balance;
- A Voltage Band (VB) strategy which optimizes energy efficiency by maximizing storage. The voltage standard tolerance is considered with the help of a fuzzy logic approach.

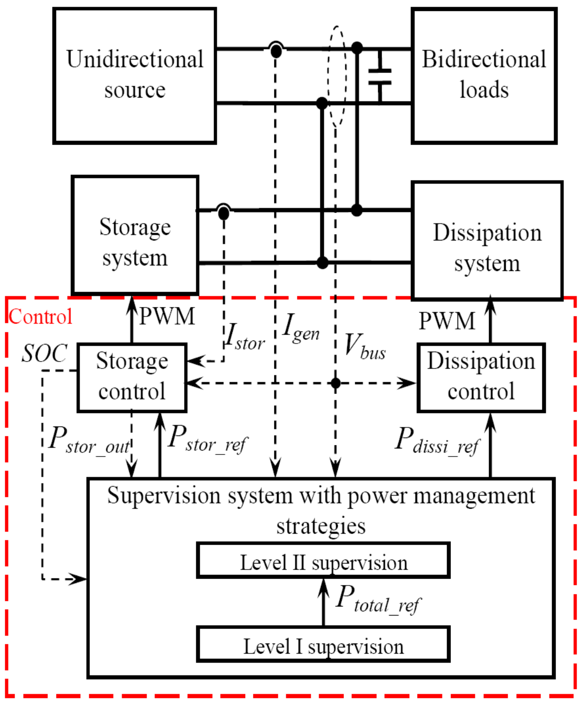

Fig. 3. Supervision architecture.

Fig. 4 shows the global structure of the different power management strategies presented in the supervision system of Fig. 3. The input variables are determined by the objectives of each strategy. Finally, by combining the different proposed strategies, four global supervision strategies may be considered. The detail of each strategy will be presented in the following parts.

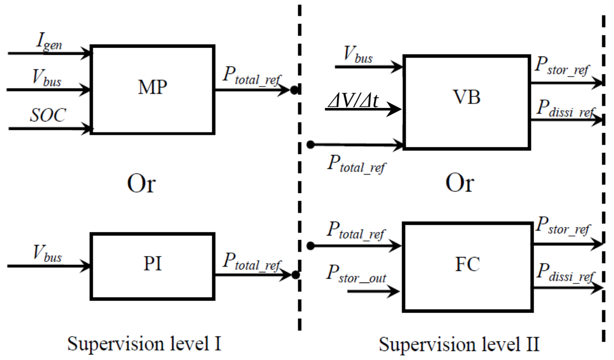

Fig. 4. Global structure of each power management strategy

3.2 Supervision Level I

The aim of the first level is to determine the total needed power reference to balance consumed power and supplied power.

3.2.1 Proportional Integral controller (PI)

The objective of this strategy is to maintain DC bus voltage. When the bidirectional loads return power and when the total returned power is greater than the consumed power, the diodes are turned off and the voltage controller of the PMG cannot control the bus voltage any more. The hybrid system plays the role of bus voltage controller. Bus voltage is measured to calculate the power which should be consumed or stored in order to balance exceeding power. The PI controller can be used to calculate this reference power value P_{total_ref}. As the impedance value of the power cable is relatively small in comparison with the capacitor value, the PI controller is calculated with the help of a first order model of the equivalent bus capacitor.

3.2.2 Minimum supplied power (MP)

In the previous control strategy, when recovered power is greater than consumed power, the power supplied by the generator becomes null because the anti-runback diodes are turned off. If the current is always nonzero, the PMG will take over the voltage control. The description of this function is shown in Fig. 5. The power convention is defined as follows: consumed power is positive and generated power is negative.

As shown in Fig. 5, the total loads power is shown in solid line. When the returned power of bidirectional loads is greater than the consumed power of the unidirectional load, the power will be negative. The supplied power of the PMG without the MP strategy is shown in dashed line. When the total loads power is negative, the primary source PMG does not supply power any more. The supplied power of the PMG with the MP strategy is shown in dash-dot line. When the total loads power is greater than a “minimum supplied power”, the supplied power is equal to the total loads power. When the total loads power is less than the minimum supplied power, the hybrid system will play a role of consumer to make sure the diodes do not turn off.

In the distribution system, there are always some unidirectional loads that consume quasi constant power. The value of the “minimum supplied power” is configured according to this “minimum consumed power”.

The objectives of this strategy are then:

- To slow down the decreasing tendency of the supplied power in order to avoid turning off the diodes.
- When the diodes are turned off, the hybrid system should take over the bus voltage control because the PMG cannot continue to control the bus voltage any more.
- The storage system can also help the primary source, PMG, to supply the peak power requirement of the loads.

Moreover, the power management strategy should take into account the limited capacity of the storage system.

According to these objectives and constraints, the generator current I_{gen}, the bus voltage V_{bus} and the *SOC* should be supervised. These variables are the inputs of this strategy and the total power reference P_{total_ref} is the output variable. Fuzzy logic is well adapted to develop this multi-objective supervisor.

Fig. 6 shows the evolution of P_{total_ref} vs. the *SOC* and the generator current I_{gen} when V_{bus} is equal to 300V. It shows the relationship between input and output variables obtained with fuzzy logic.

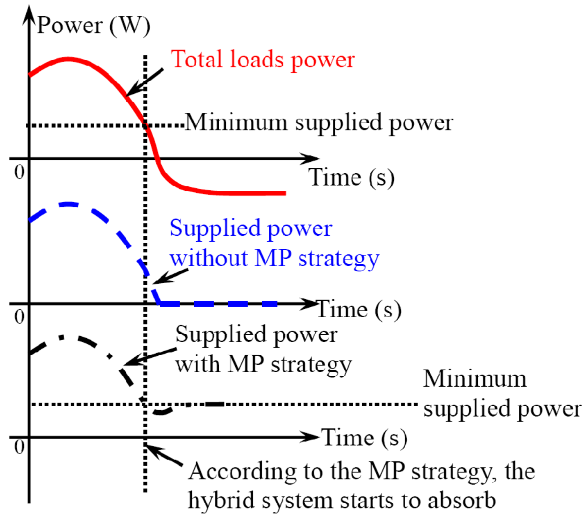

Fig. 5. Strategy of Minimum supplied power

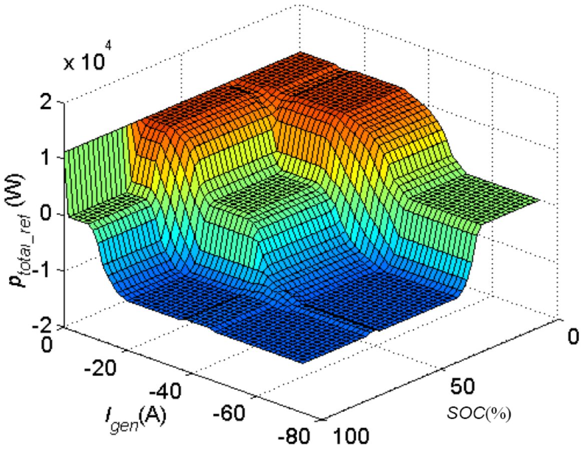

Fig. 6. Generated surface of MP strategy for *Ptotal_ref*

3.3 Supervision Level II

The objective of the supervision level II is to split the P_{total_ref} between the storage and the dissipation systems in order to achieve the objectives of minimizing the dissipated power and to compensate the dynamic of the storage system.

3.3.1 Full Compensation (FC)

The objective of this strategy is to compensate the dynamic weakness of the storage system. Because of the storage system dynamics, its output power, P_{stor_out} , cannot reach the power reference instantly. In this case, the dissipation system is used to dissipate the exceeding power P_{dissi_ref}. This strategy is expressed in (1).

$$
\begin{aligned}
&Pstor\_ref = Ptotal\_ref \\
&Pdissi\_ref = Ptotal\_ref - Pstor\_out \qquad (1)
\end{aligned}
$$

3.3.2 Voltage Band (VB)

The objectives of this strategy are to minimize dissipated power and to compensate the slower dynamic behavior of the storage system.

The rated voltage of the bus is 270 V, but the acceptable tolerance is between 250 V and 280 V as shown in Fig. 2 according to the standard MIL-STD-704 [9]. An objective of this strategy is to use the dissipation system as little as possible. A fuzzy logic supervisor is used in this strategy to determine a partition coefficient k in order to create the P_{stor_ref} and P_{dissi_ref} references as expressed in (2).

$$
\begin{aligned}
&Pdissi\_ref = k*Ptotal\_ref \\
&Pstor\_ref = (1-k)*Ptotal\_ref \qquad (2)
\end{aligned}
$$

The bus voltage and its evolution ($\Delta V/\Delta t$) are considered as the inputs of the supervisor.

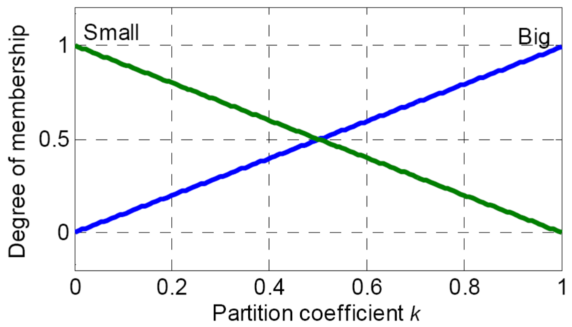

Fig. 7 Membership functions of output variable k for the VB strategy

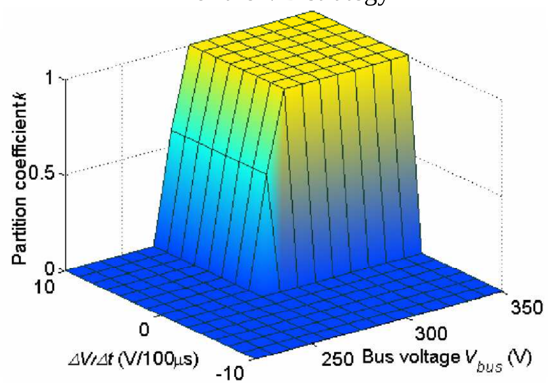

Fig. 8 Generated surface for the partition coefficient of strategy VB

4 Experimental Results

A 3kW test bench has been developed to emulate an on-board network (Fig. 17). Thanks to its high dynamics, long lifetime and good efficiency, supercapacitors are chosen to play the role of the storage system.

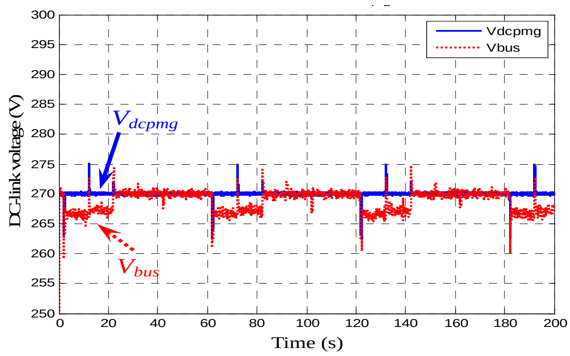

Fig. 9 DC-link voltage evolution with PI+FC strategy

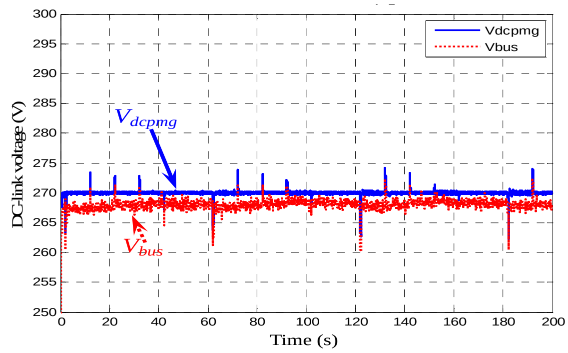

Fig. 13 DC-link voltage evolution with MP+VB strategy

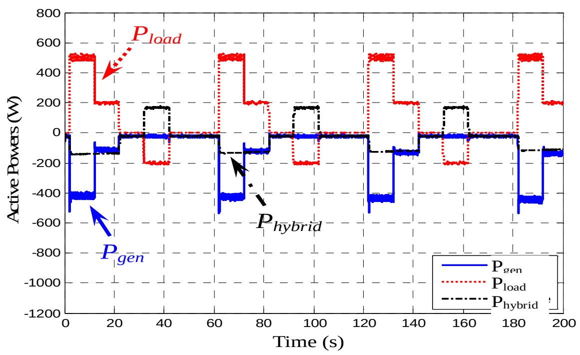

Fig. 10 Active powers of generator, bidirectional load and hybrid system with PI+FC strategy

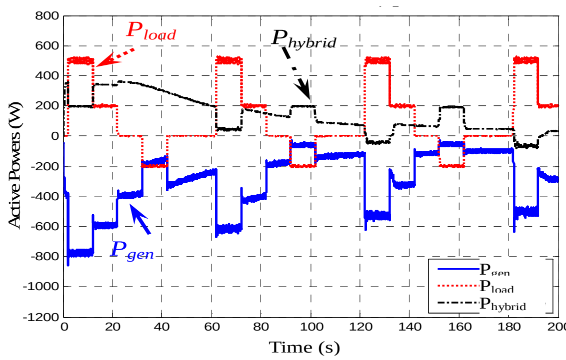

Fig. 14 Active powers of generator, bidirectional load and hybrid system with MP+VB strategy

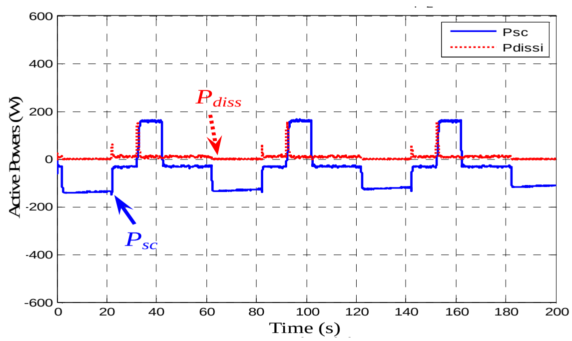

Fig. 11 Active powers for the hybrid storage and dissipation system with PI+FC strategy

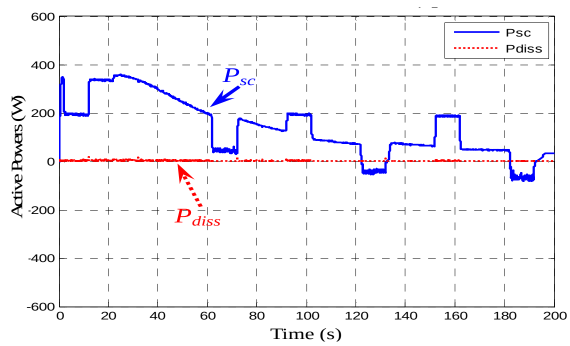

Fig. 15 Active powers for the hybrid storage and dissipation system with MP+VB strategy

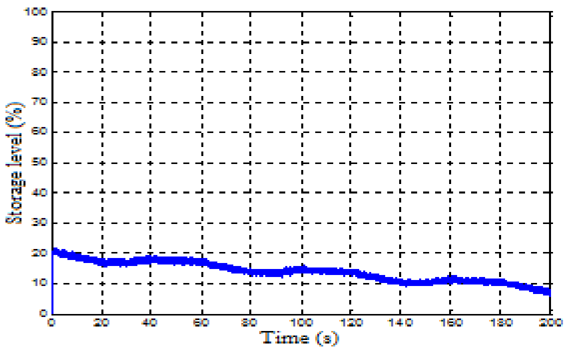

Fig. 12 Supercapacitor energy storage level for PI+FC strategy

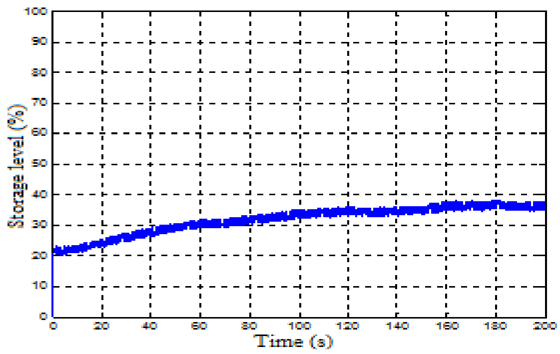

Fig. 16 Supercapacitor energy storage level for MP+VB strategy

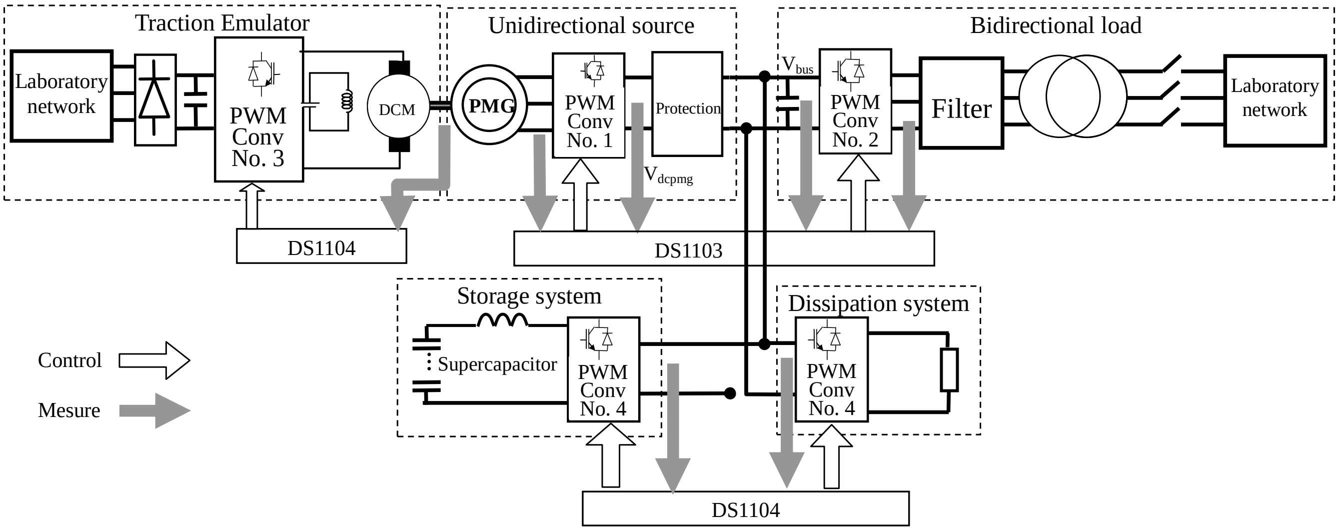

Fig. 17 Test bench with hybrid storage and dissipation system.

The experimental results presented in following figures (Figs. 9 - 16) show the behavior of the power distribution system in two cases: single objective strategy for each supervision level using PI and FC strategies, and multi-objective strategy for each supervision level using fuzzy logic MP and VB strategies.

The experimental tests are performed using the same load variation pattern for both strategies, positive for consumption and negative for generation.

Figs. 9 – 12 reveal the results for mono-objective approach using PI+FC strategies. As shown in Fig. 12 the energy level stored in supercapacitor is decreasing as no action is taken to control the energy storage level in this storage device. To visualize the partition of the power dissipated and the power stored, *Pdiss* and *Psc* are shown in Fig. 11.

Figs. 13 – 16 show the results for multi-objective strategies i.e. MP+VB. Fig. 16 demonstrate the advantage of these strategies concerning the energy level stored in supercapacitor. In this case the energy storage level is increased in order to keep a reserve for charging and discharging necessities. Also the dissipated power (Fig. 15) is neglectable in comparison with the energy stored in the supercapacitor.

For both control strategies, PI+FC and MP+VB, the DC-link voltage is well maintained around the reference value i.e. 270V, validating the assembly of the strategies proposed.

5 Conclusions

The local DC Power Distribution System of More Electric Aircraft is one of the cores of the electric power transmission. In this paper, different power management strategies have been proposed based on simple mono-objective strategies, such as PI controller, and multi-objective strategies developed using fuzzy logic. Fuzzy logic allows us to ensure simultaneously different objectives like voltage stability, energy efficiency and storage availability, for instance. A comparison between the two supervision techniques is made. The multi-objective approach (MP+VB) is more complex but gives better results especially in terms of energy management. The mono-objective approach (PI+FC) gives good results but has the handicap of energy saturation or depletion when the storage device becomes full or empty. A 3 kW test bench allows us to emulate a part of a local DC PDS of MEA including a bidirectional load and the hybrid storage and dissipation system. The proposed power management strategies have then been experimentally validated. Fuzzy logic allows us to develop a multi-objective approach and then to obtain a compromise between the different objectives, whereas a PI controller allows us only to consider one objective.

Acknowledgments

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References

[1] D. Van Den Bossche, "More Electric Control Surface Actuation" *EPE conference,* 2-4 September 2003 Toulouse, France.

[2] H. Zhang, C. Saudemont, B. Robyns and M. Petit, " Electrical features comparison between more electric aircrafts and hybrid electric vehicles", *ELECTROMOTION*, vol. 16, n°3, 9-2009, pp.111 –119.

[3] A.A. Ferreira, J.A. Pomilio, G. Spiazzi and L. de Araujo Silva, "Energy Management Fuzzy Logic Supervisory for Electric Vehicle Power Supplies System", *IEEE Transactions on Power Electronics*, vol. 23, no. 1, pp.107 –115, January 2008.

[4] J. Moreno, M.E. Ortuzar and J.W. Dixon "Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks", *IEEE Transactions on Industrial Electronics*, vol. 53, no. 2, pp.614 – 622, April 2006.

[5] H. Zhang, C. Saudemont, B. Robyns, N. Huttin and R. Meuret, "Comparison of different DC voltage supervision strategies in a local Power Distribution System of More Electric Aircraft", *9th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems ELECTRIMACS 2008*, Québec , 9-11 June 2008.

[6] G. O.Cimuca, C. Saudemont, B. Robyns and M. M.Radulescu, "Control and performance evaluation of a flywheel energy storage system associated to a variable speed wind generator", *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1074-1085, August 2006.

[7] L. Leclercq, B. Robyns and J. Grave, "Control based on fuzzy logic of a flywheel energy storage system associated with wind and diesel generators", *Mathematics and Computers in Simulation*, no. 63, pp. 271-280, June 2003.

[8] L. Karunarathne, J.T. Economou and K. Knowles, "Fuzzy Logic Control Strategy for Fuel Cell/Battery Aerospace Propulsion System" *IEEE Vehicle Power and Propulsion Conference (VPPC),* September 3-5, 2008, Harbin, China.

[9] Department of Defense of United States of America, "Department of Defense Interface Standard – Aircraft Electric Power Characteristics", *Military Standard of USA*, 12 March 2004.

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