# Hybrid Supply For Automotive Application Using Supercapacitors

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***Abstract*-in this article the replacement of the car battery by a hybrid supply is proposed. The specific power of the supercapacitors makes it very attractive for the startup of the car. This component has very high lifetime (1 million of cycles) what can improve the lifetime of the starter and the starter-alternator supply. After the identification of the ICE torque developed at the startup, the validation of the hybrid supply interest is proved by the simulation of the system using PSIM software. Finally, a test bench is developed in the laboratory to validate the simulation results.**

## I. INTRODUCTION

Until now the battery is the main storage system used like sources for the automotive applications. This component is dimensioned for many constraints like turn-on, acceleration, braking and energy recovery. All these constraints give us an oversized component with a very high energy compared to that required for this application. This energy oversizing is due to the stiff link between the power and the energy of this technology. The main solution for this problem consists to use two types of storage system. This paper deal with the conception of hybrid power supply for the vehicle starter or Starter-Alternator. For that two kind of storage system are used, battery us energy tank and supercapacitors us power source. This design allows to increase the lifetime of the supply or to downsizing this last one. The hybrid source can be used with starter making the battery and the supercapacitors in series through two choppers. In this case the supercapacitors is charged by the battery and discharged during the starting-up of the vehicle. For the second supply topology, the two storage systems are connected in parallel to supply the starter (or Starter-Alternator) . When the vehicle is turned-on, the Starter-Alternator charges the battery.

The suspercondensator is one of the most powerful components with a high specific power, which can reach 17kw/kg. The capacitance of this component exceeds the 5000F for a lower voltage (3V). To use this component in power applications, we must make some elements in series. In addition to these advantages, the supercondensateurs have a very high lifetime which can reach the 1 million cycles.

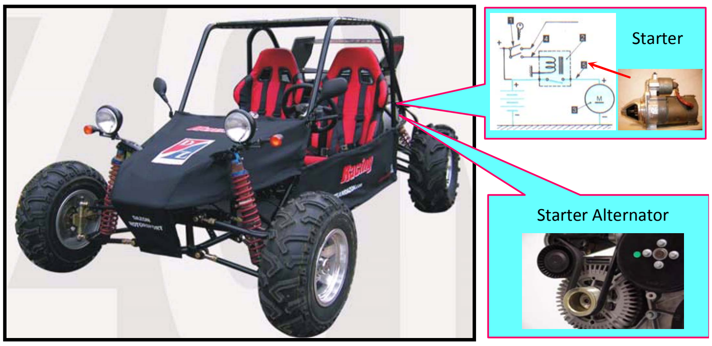


Fig. 1. Using the hybrid supply with starter or starter-alternator

## II. STARTUP TORQUE MEASUREMENT

During the starting-up, the ICE develops a resistive torque applied to the starter or the starter-alternator. The computation of this torque allows us to validate the hybrid supply interest. To estimate this resistive torque we need to know the evolution of the starter torque according to its current.

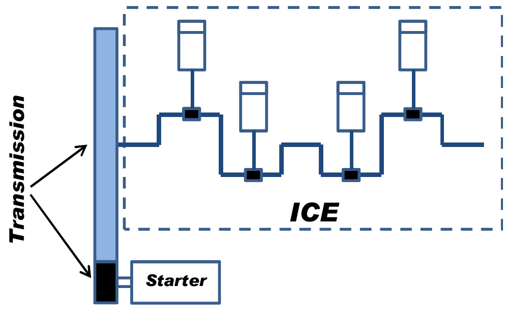


Fig. 2. The transmission between the starter and the ICE

### A. *Formula of the starter Torque*

Because of their high starting torque, the series DC motors is used like a starter for the automobile applications. The torque developed by this motor can be written as follow:

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$$T_{starter} = K\,\Phi\,\,I \qquad (1)$$

The relation between the current and the flux of this type of motors complicates the identification of this torque. For that, this motor (starter) is transformed to a separate-wound DC motor.

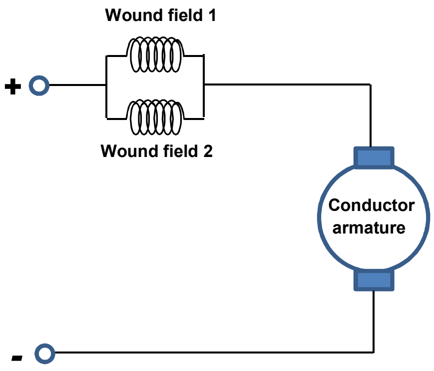


Fig. 3. Electrical diagram of starter (series motor).

Figure 4 presents the transformation of the series DC motor to a separate-wound DC motor. This transformation allows us to identify their torque.

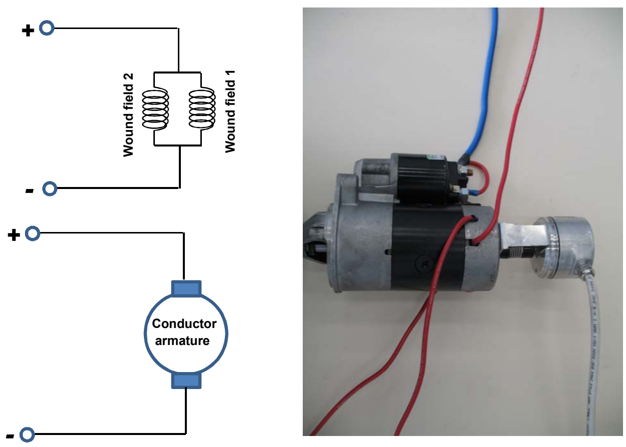


Fig. 4. Transformation of the series DC motor to a separate-wound DC motor

Measuring the armature voltage, the armature current and the starter velocity at deferent wound current allows us to plot the evolution of the ratio K Φ according to the current (fig. 5).

$$E = V - R\,I = K\,\Phi\,\,\Omega_{starter} \qquad (2)$$

According to the results plotted on the figure 5, the ratio K Φ can be written as follow:

$$K\,\Phi = -2\,E-9\,I^3 + 3\,E-7\,I^2 + 9\,E-5\,I + 0.0063 \qquad (3)$$

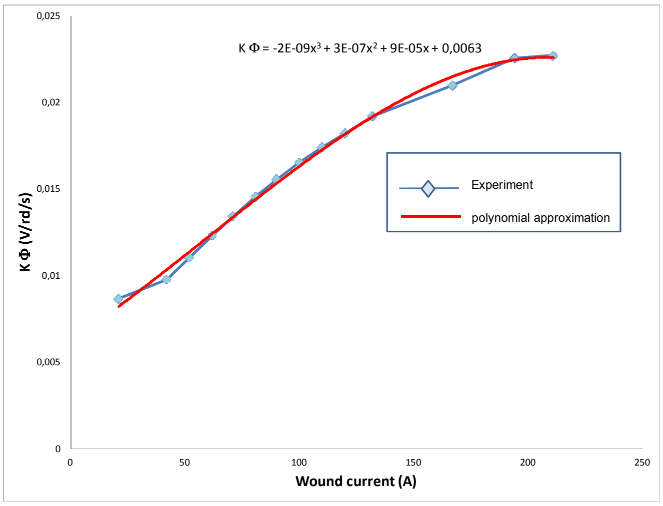


Fig. 5. Evolution of the ratio K Φ according to the wound current

## B. *Formula of the startup torque*

To identify the resistive torque developed by the ICE during the starting-up phase, tow starting-up tests are made. The first it's without the spark plugs and the second it's with compression (with spark plug).

The first test (fig. 6) allows us to estimate the inertia and the friction torque of the ICE. Using the mechanic equation we can compute the tow parameters (J and f).

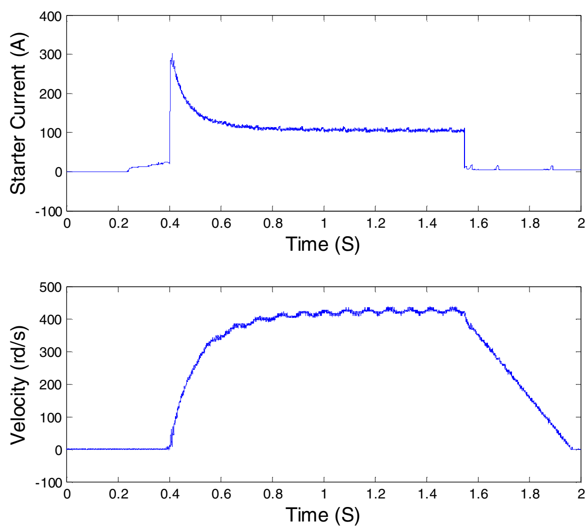


Fig. 6. Evolution of the current ant the starter velocity for the test without spark plugs

$$J\,\frac{d\Omega}{dt} = K\,\Phi\,I - f\,\,\Omega - C_0 \qquad (4)$$

Using the current and the starter velocity, we can compute the parameters J, f and C0.

$$\begin{cases} J = 1.5\,E-3\ Kg\,m^2 \\ f = 4.2\,E-3\ Nm/rd/s \\ C_0 = 0\,Nm \end{cases} \quad (5)$$

The second test (fig. 7) allows us to estimate the rippled torque (Tcomp) due to the compression on the ICE motor.

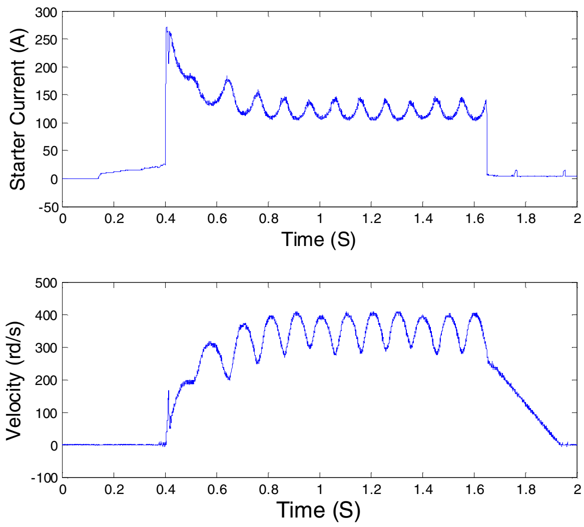


Fig. 7. Evolution of the current ant the starter velocity for the test with spark plugs

Using the parameters computed at the first test (J, f and C0), the current and the starter velocity, we can compute the parameters the torque due to the compression (Tcomp):

$$J\,\frac{d\Omega}{dt} = K\Phi I - f\ \Omega - C_0 - T_{comp} \quad (6)$$

Figure 8 presents the wave form of the compression torque Tcomp. This can be written as:

$$T_{com} = 1 + 5.9\sin(0.190 * \theta_{starter}) \quad (7)$$

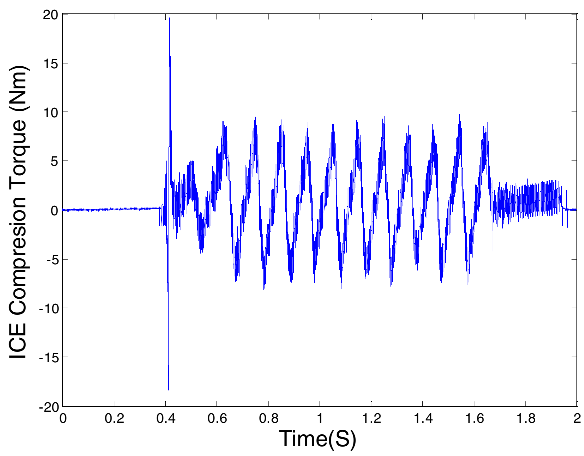


Fig. 8. wave form of the compression torque Tcomp

## III. Topology of the Power System

The use of supercapacitors like power sources allows us to reduce considerably the size of the battery which will be used just like an energy source. On the other hand, the use of the converters ensures a good control of the starting-up dynamics (control of the current).

Two topologies can be distinguished for the power supply which depends to the association of the two storage components (battery and supercapacitors): in series or parallel.

For the series topology (fig. 9) which will be presented in this article, the two storage systems are putted in series. In this case, the supercondensator module is charged by the battery through a chopper (Boost). The starting-up is only assured by the suspercapacitors through a chopper in the case of the starter and through the inverter in the case of the starter-alternator. This topology allows us to reduce the size of the coil which is sized for a current of 20A.

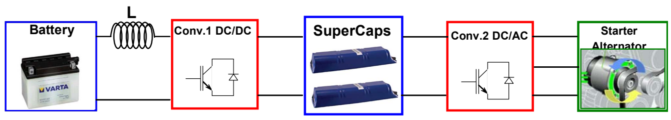


Fig. 9. Topology of the series hybrid supply for automotive application

## IV. Sizing of the Supercapcitors Module for the Startup

The supercapacitors sizing is based on the energy and power required for the starting-up of the vehicle. Figure 10 presents the evolution of the current and the voltage of the Buggy starter at the starting-up phase. At the beginning of this phase, the battery voltage deceases to reach 9V. At the same time, the current exceeds the 250A. All that gives us a maximum power of 2400W.

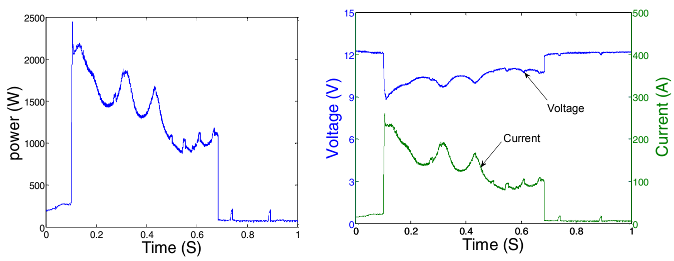


Fig. 10. Power and energy required for the starting-up of the vehicle

In order to ensure the working of the boost chopper, the minimum voltage of the supercondensator should not decrease lower than 12V (battery voltage). To take a safety margin, the minimum supercapacitors voltage is chosen about 15V. For this component, more than 75% of energy is stored between the maximum voltage of supercapacitors

(Vmax_SupCaps) and the half of this voltage (Vmax_SupCaps/2) :

$$V_{\min\_SuperCaps} = V_{\max\_SuperCaps} / 2 \;\Rightarrow\; = V_{\max\_SuperCaps} = 2\,V_{\min\_SuperCaps} = 30V \quad (8)$$

The power integral on all the starting-up duration allows us to compute the energy required for this phase.

$$E_{start} = \int P_{start} dt = 250\,mWh \quad (9)$$

The supercapcitors efficiency reaches 80% for 250A of RMS current.

By the neglecting of the Conv.2 losses, the starting-up energy can be written as follow:

$$E_{start} = \eta_{sc} \frac{1}{2} C_{sc} (V^2_{\max\_SuperCaps} - V^2_{\min\_SuperCaps}) = \frac{3}{10} C_{sc} V^2_{\max\_SuperCaps} \quad (10)$$

$$C_{sc} = \frac{10}{3} \frac{E_{start}}{V^2_{\max}} = \frac{10}{3} \frac{900}{30^2} \approx 3{,}34F \quad (11)$$

The best component for this application can be chosen using the characteristics of all Maxwell cells. The element 2,5V/310F gives us the best compromise between the power and the energy of the component.

| | 2,5V/4F | | 2,5V/10F | | 2,5V/120F | 2,5V/140F | 2,5V/310F | 2,5V/350F | 2,7V/650F | 2,7V/1200 | 2,7V/1500 | 2,7V/2000 | 2,7V/3000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tension (v) | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| Capacité d'un élément (F) | 4 | 4 | 10 | 10 | 120 | 140 | 310 | 350 | 650 | 1200 | 1500 | 2000 | 3000 |
| Courant (A) | 1 | 8 | 2.5 | 19 | 730 | 530 | 1500 | 1100 | 3500 | 3750 | 3900 | 4300 | 4800 |
| Nombre d'élément en série | 11 | 11 | 11 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| Nombre de branches en parallèle | 240 | 30 | 96 | 13 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Capacité globale (F) | 87.2727273 | 10.9090909 | 87.2727273 | 11.8181818 | 10 | 11.666667 | 25.833333 | 29.166667 | 54.166667 | 100 | 125 | 166.66667 | 250 |
| Volume unitaire (l) | 0.0015 | 0.0015 | 0.003 | 0.003 | 0.027 | 0.027 | 0.053 | 0.053 | 0.211 | 0.294 | 0.325 | 0.373 | 0.475 |
| Volume global (l) | 3.96 | 0.495 | 3.168 | 0.429 | 0.324 | 0.324 | 0.636 | 0.636 | 2.532 | 3.528 | 3.9 | 4.476 | 5.7 |
| Temps de charge à 20A | 103.125 | 12.890625 | 103.125 | 13.96484375 | 14.0625 | 16.40625 | 36.328125 | 41.015625 | 88.846875 | 164.025 | 205.03125 | 273.375 | 410.0625 |
| Resistance interne RMS (mOhm) | 18.33333333 | 146.6666667 | 20.625 | 152.3076923 | 60 | 86.4 | 26.4 | 38.4 | 9.6 | 6.96 | 5.64 | 4.2 | 3.48 |

$$C_{component} = 310F; \quad V_{component} = 2{,}5V;$$

$$N°_{elements-en-series} = 12; \quad N°_{Branches} = 1 \quad (12)$$

$$Volume = 1l; \quad RMS = 26\,m\Omega;$$

To reach 30V for the supercapacitors module, we must make 12 elements in series, what give a capacitance module about 26F:

$$C_{module} = \frac{310\text{F}}{12} = 26\text{F} \quad (13)$$

With this component, we can make 8 starting-up without reloading the component:

$$N_{start} = \frac{26F}{3{,}34F} \approx 8 \; starting - up \quad (14)$$

## V. SYSTEM SIMULATION

Before developing a test bench for this application, a simulation of the operated system is carried out using PSIM software.

### A. *Simulation of the hybrid supply with the starter*

In this case, the supercapacitor is charged by the battery with 20A constant current and the startup is provided by the supercapacitor.

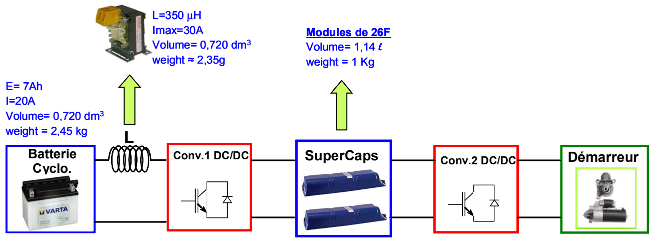


Fig. 11. Topology of the series hybrid supply associated with starter

During startup, the average voltage of the battery is controlled and kept constant at 9V. Another control loop is used to limit the startup current.

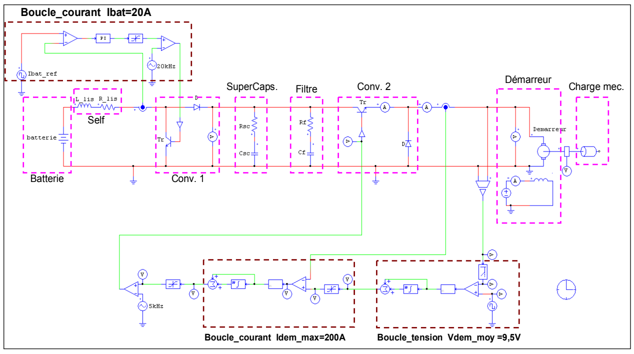


Fig. 12. Simulation of the system using PSIM

The simulation results are presented in Figure 13. At startup, the starter voltage is kept constant 9V and the current does not exceed 200A. At the same time the supercapacitor is discharged and the voltage at the end of starting process passes from 28V to 26.7 V.

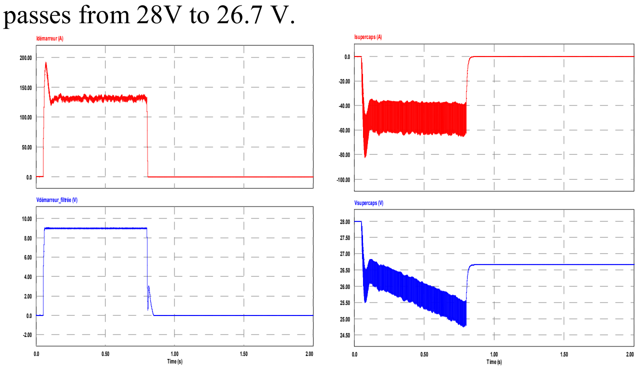

Fig. 13. Simulation of the hybrid supply associated with the starter

*B. Simulation of the hybrid supply with the starter-alternator*

The same system is used to supply the starter-alternator. In this case an inverter is used in place of the chopper. The starter-alternator velocity is controlled to reach the set point value (130 rd/S).

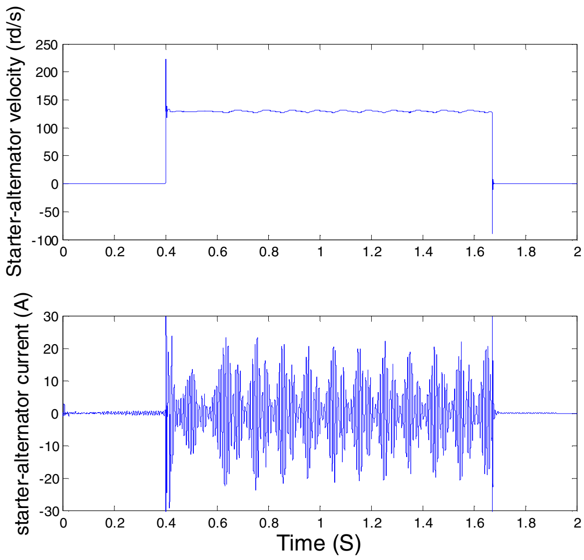


Fig. 14. Simulation of the hybrid supply associated with the starter-alternator

The simulation results are presented in Figure 14. These results show that the starter-alternator velocity follows the set point value. The current for the startup phase don't exceeds the 24A .

## VI. EXPERIMENTAL VALIDATION

The test bench developed in our laboratory allows us to validate the simulations results and carry out the energy balance. The hybrid supply system is assembled on Buggy. This type of car gives us a good accessibility to the various parts of the car.

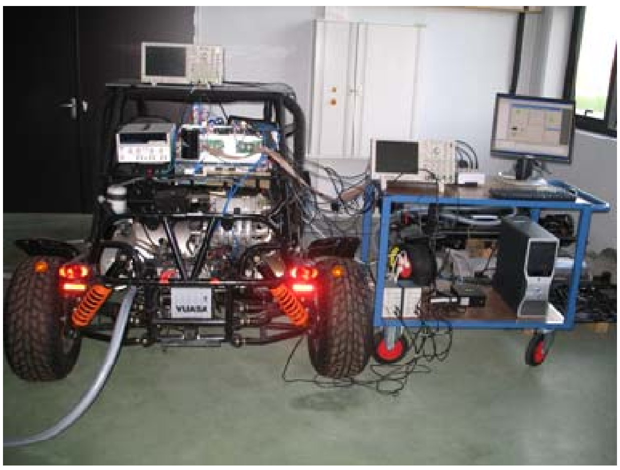

Fig. 15. Test bench developed on the mechatronic laboratory (ESTACA)

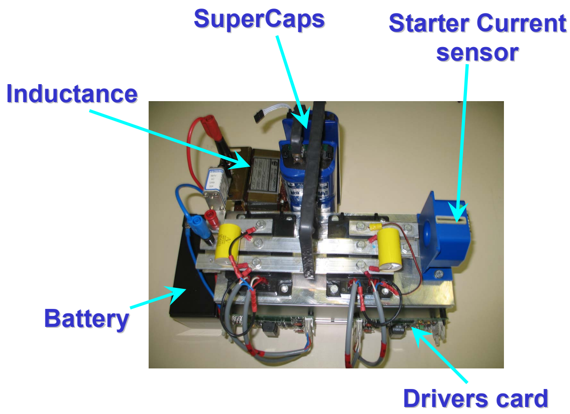


Fig. 16. Hybrid supply developed on the laboratory

The hybrid system supply is mounted on a buggy. Figure 15 shows the position of the supply on Buggy. This system is putted in this place just for validation tests. A minibike Battery (7Ah / 500g) is used as energy supply (Fig. 16). The induction coil (L = 350 µH) is sized to smooth the battery current (20A). A sensor LEM IT 400-S is used to capture the current starter. All the components used in this test bench are not adapted for automotive applications. For that another model will be developed after a CAO study.

To validate the interest of the hybrid supply associated to the starter, a starting-up test has been made. The duration of this test is 400 mS which represents the average duration of a classic startup. Figure 17 shows the current and voltage of the supercapacitor during the startup phase. After a sudden drop in voltage due to the internal resistance of the component, the voltage decreases almost linearly. The current of the supercapacitor reach the 250A at the beginning.

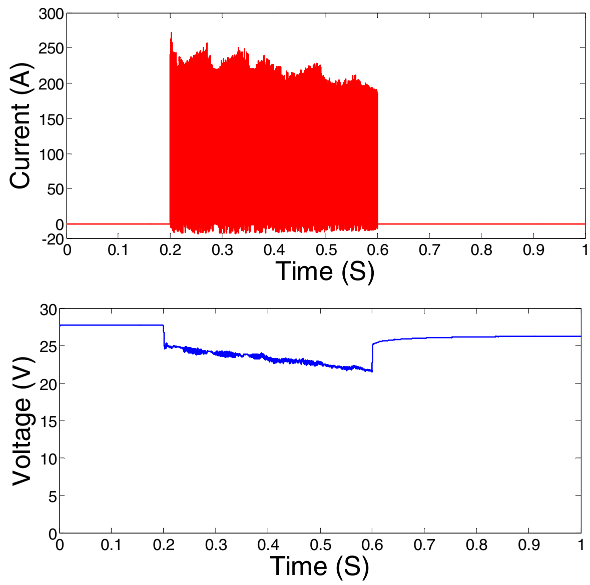


Fig. 17. Current and the voltage of the supercapacitors during the startup

According to the results presented in the figure 17, we can notice that the voltage drop between the beginning and end of the startup is very small, which demonstrates the feasibility of several starts before the complete discharge of the component. Using these results an energy balance is made.

Figure 18 shows the evolution of the power of the supercapacitor (Psc) according to time. This last one reaches 3kW at the end of startup. The integration of power Psc allows us to calculate the energy required for the startup phase:

$$E_{nec\_sc} = \int P_{sc}\, dt = 875J \qquad (15)$$

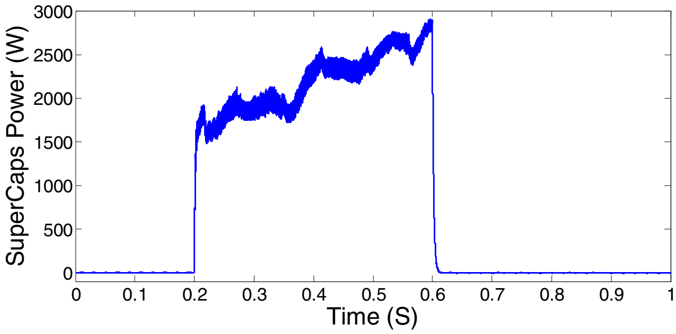


Fig. 18. Evolution of the Supercapacitors power during the startup

To calculate the converter efficiency conv.2, a multiplier with a low pass filter are used to plot the evolution of the power consumed by the starter during the startup (Fig. 19).

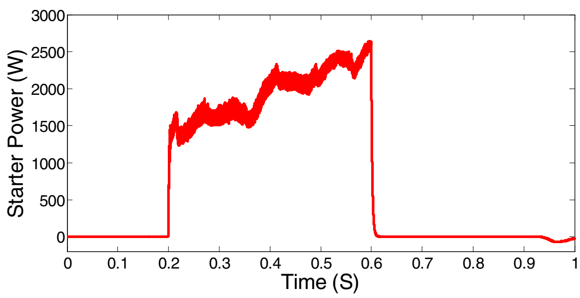


Fig. 19. Evolution of the starter power during the startup

Unlike the power at the input of the converter (Conv.2), the power at the output of this last one does not exceed 2.8 kW. The integrating of this power gives us the energy consumed by the starter:

$$E_{starter} = \int P_{starter}\, dt = 776J \qquad (16)$$

The values of the energies at the input and the output of the converter allow us to estimate the efficiency of the converter:

$$\eta_{Conv.2} = \frac{E_{dém}}{E_{nec\_sc}} = \frac{776}{875} = 89\% \qquad (17)$$

The voltage values before and after the startup allows us to calculate the total energy distorted from the supercapacitor during the startup:

$$V_{sc\_t0} == 27{,}74V \quad V_{sc\_end} = 26{,}28V$$
$$\Rightarrow E_{sc} \approx \frac{1}{2} C\left(V_{sc\_t0}^2 - V_{sc\_end}^2\right), \quad E_{sc} = 1025J \qquad (18)$$

The values of the two energies distorted from superCaps (Esc) and that transfered to the converter (Enec_sc) allows to calculate the efficiency of the supercapacitor:

$$\eta_{sc} = \frac{E_{nec\_sc}}{E_{sc}} = \frac{875}{1025} = 85\% \qquad (19)$$

The multiplication of two efficiency (efficiecy of the converter and the supercapacitor) gives us the global efficiency of the hybrid supply :

$$\eta_{glob} = \eta_{Conv.2} \,.\, \eta_{sc} = 76\%$$

The value of the global efficiency is used to readjust the value needed for one startup:

$$E_{glob} = \eta_{glob} \frac{1}{2} C_{sc} \left(V_{\max\_SuperCaps}^2 - V_{\min\_SuperCaps}^2\right)$$
$$= \frac{3}{8} C_{sc}\, \eta_{glob}\, V_{\max\_SuperCaps}^2 \qquad (20)$$

$$C_{sc} = \frac{8}{3} \frac{E_{dém}}{\eta_{glob} V_{\max}^2} = \frac{8}{3} \frac{776}{0{,}76.30^2} \approx 3F \qquad (21)$$

With the chosen supercapacitors component we can make 8 startups before the total discharge.

## VII. Conclusion

In this paper, the replacement of the car battery by a hybrid supply has been presented. The proposed system is composed with two storage systems. The first (supercapacitors) is used like a power supply and the second (motorcycle battery) is used like an energy supply. The power density of supercapacitors makes them very interesting for the applications which need high power during short time. The use of this component technology allows reducing the battery size and optimizing the lifetime of the supply. On the other hand, the use of converters allows good management of power flow to supply different loads.

Two architectures are possible to implement the association of supercapacitors and battery: a parallel architecture by connecting the two sources to a common bus through two choppers. The drawback of this architecture is the very large size of the induction coil in series with the supercapacitor module. In the case of series architecture (Fig. 11), the size of the induction coil used to smooth the battery current is less important because the weakness of the current charge/discharge which does not exceed 20A. This article has presented only the development of the second architecture (series).

After the choose of the architecture of the power supply, the sizing of the supercapacitors module (weight, volume, power, energy, ...) was presented in Part VI. The chosen component is the 310F / 2.5V manufactured by Maxwell. The series connection of 12 elements (module 26F/30V) gives us the characteristics needed to supplying the starter or the starter-alternator.

In the V part, the modeling of the hybrid supply associated to starter and starter-alternator is presented. For the starter modeling, the starter voltage is controlled. This voltage must follow the set point value (9V). In addition to the voltage loop, another current loop is used to limit the starter current at 200A. This strategy incorporates the standard procedure of a start by imposing a voltage equivalent to the voltage of the battery after the resistive drop (Fig. 13). This strategy has been validated in Part V of this article with a simulation in PSIM (Fig. 12).

For the starter-alternator, the velocity of this last one is controlled to follow the set point value (130rd/s). the resistive torque developed by the ICE at the startup phase is calculated in the part II. For this simulation, the startup current reaches 24A.

After numerical validation of the two systems, a test bench has been developed in the Mechatronics Laboratory to make an energy balance (part VI). The test bench is composed with laboratory components which are not specific to an automotive application.

The energy balance is realized in Part VI prove the advantage of the hybrid supply. With an efficiency of supercapacitor about 85% and 89% for the converter.

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