

# Techno-economic Optimization of Flywheel Storage System in transportation

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**ABSTRACT** – Energy storage technologies in transport applications are continuously improved and updated to ensure energy demand, to decrease the fuel consumption and in order to make systems more reliable. Flywheel kinetic energy storage offers very good features such as power and energy density. Moreover, with some short-range vehicles such as buses or small ferries, this technology can be enough to supply all the energy to the power train. The challenges to be met to integrate such technology in vehicles are the mass, the efficiency and especially the cost. Then, in this paper, a techno-economic optimization of a flywheel energy storage system is presented. It is made up of a flywheel, a permanent magnet synchronous machine and a power converter. For each part of the system, physical and economical models are proposed. Finally, an economic optimization is done on a short-range ship profil, currently using supercapacitors.

**KEYWORDS** – Techno-economic analysis, energy storage, transportation, flywheel.

## 1 Introduction

Flywheel kinetic energy storage offers very good features such as power and energy density [1, 2]. Moreover, they have long lifetime in comparison to classical electrochemical storage systems. In transportation applications, high-speed flywheels as energy storage system has been largely neglected compared to other technologies such as ultracapacitors or batteries [3]. Indeed, many studies show that the flywheel is a mature energy storage technology and competitive with common storage systems [4, 5, 6]. But the design of a flywheel is relatively complex since its design must take into account many factors. Indeed, it is composed of the flywheel itself, but also of the electrical machine for electromechanical conversion, and a power converter to control the power flows. It is then obvious that the optimization of such a system requires a thorough and complete modeling of all these elements. This paper proposes a comprehensive techno-economic modeling of a flywheel energy storage system. The bulk of this work is based on an optimization of the flywheel, the electrical machine and the power converter as a whole. This optimization is not done on one typical torque-speed operating point but on an operating profile, representative of such storage systems [7, 8, 3]. In this paper, we apply this techno-economic optimization on an electric ship currently using supercapacitors as the primary source of energy [9, 10, 11].

## 2 Structure of the flywheel storage system and technical models

The studied flywheel storage system (FSS) is composed of a rotating mechanical part (the flywheel), a permanent magnet synchronous machine (PMSM) and an IGBT power converter (see Fig 1). The choice of the technology of each part of this system will be discussed and justified in the final paper [6, 3, 12, 7, 2, 13, 14].

### 2.1 Physical models and losses

In this section, the physical models of each part of the flywheel storage system are presented. These models include the sizing and the losses calculation. A special attention is payed to the permanent magnet synchronous machine, which is the critical element of such a system. Indeed, it is the interface between the mechanical energy stored in the flywheel and the electrical power train. In this paper, an original analytical sizing of PMSM is presented, taken into account the power and speed profile of the flywheel [7].

#### 2.1.1 Flywheel

The mechanical energy is classically stored in a rotating mass, made of steel or composite material. The total energy  $W$ , stored in a flywheel is expressed by the well known equation:

$$W_{exp} = \frac{1}{2} J (\Omega^2 - \Omega_{min}^2) \quad (1)$$

where  $J$  is the moment of inertia ( $\text{kg.m}^2$ ),  $\Omega_{min}$  the minimal angular velocity and  $\Omega$  is the angular velocity ( $\text{rad/s}$ ). Classical values for  $\Omega_{min}$  are between 40 to 60 % of the maximal angular velocity [6]. It permit to obtain respectively 85 and 65 % of the stored energy. Concerning the moment of inertia  $J$ , It is possible to rewrite it from the mass and shape of the flywheel. For steel rotors, the dominant shapes are the hollow and plain cylinders [1]. In this study, it is only considered plain cylinder, whose inertia expression is given by

$$J = \frac{1}{4} m_{fw} R_{fw}^2 \quad (2)$$

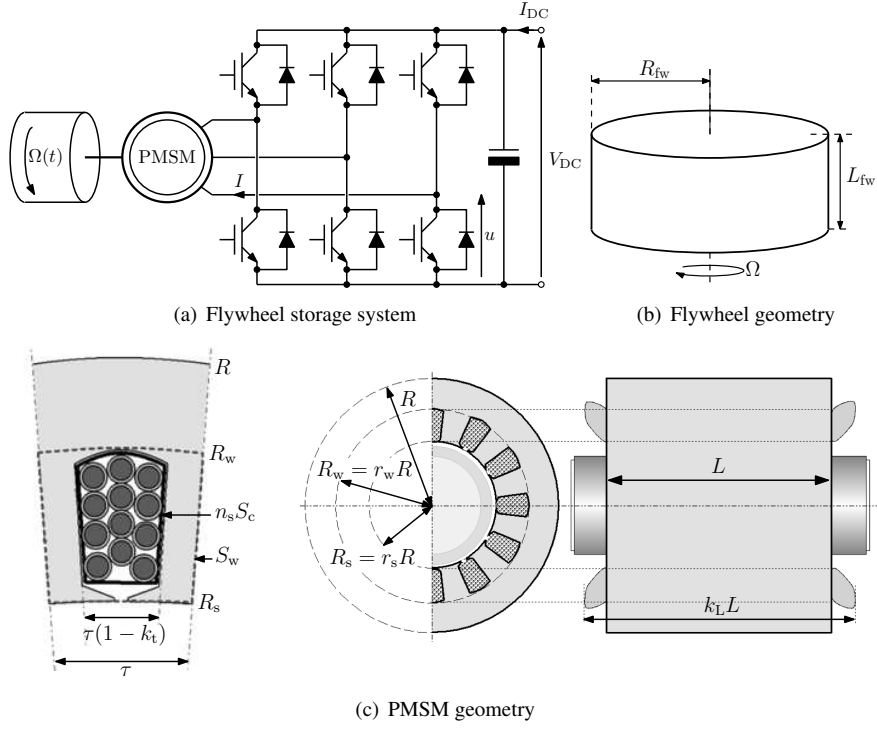


Figure 1: Structure of the studied flywheel energy storage system and its different parts.

where  $m$  is the mass (kg), and  $R_{fw}$  the outer radius, as shown in figure 1(b). The main constraint of a flywheel is the peripheral speed  $v_{p\max}$  given by:

$$v_{p\max} < \sqrt{\frac{\sigma}{K\rho}} \quad (3)$$

where  $K$  is the shape factor of the flywheel, equal to 0.6 for a plain cylinder [3], and  $\rho$  the mass density of the material (in  $kg.m^{-3}$ ). All in all, for a plain cylinder and for a given material, the geometrical parameters of a flywheel are:

$$R_{fw} = \frac{1}{\Omega_{\max}} \sqrt{\frac{\sigma}{K\rho}} \quad \text{and} \quad L_{fw} = \frac{4J}{\rho\pi R_{fw}^2} \quad (4)$$

### 2.1.2 Permanent magnet synchronous machine

In this section, the permanent magnet synchronous machine is sized from an optimized analytical approach developed in [7] and [12]. With this model the geometry of the machine is obtained taken into account mechanical and thermal constraints, core and copper losses. The optimization criterion is the specific power. This methodology is applied and generalized to arbitrary torque and speed profiles. The geometry of the machine is illustrated by figure 1(c). In this model, it is assumed that the steel parts are infinitely permeable, the study is limited to the first harmonic and the losses in permanent magnets, due to the slot effects, are neglected. At last, the thermal constraint consists on a maximal temperature increase between the winding and the external surface (assumed to be constant during a cycle). The result of this modeling is given by:

$$V_{PMSM} = \sqrt{2} \frac{\Gamma_{em(rms)}}{h \Delta T_{\max}} \times \frac{L/R}{1 + L/R} \times \sqrt{\frac{\rho_{co} k_L}{k_f}} \times \sqrt{\frac{k_{ad} (k_{ec} p \Omega_{(rms)}^2 + k_h \Omega_{(avg)})}{p}} \times \sqrt{\frac{1 + r_w}{(1 - r_w)(r_w^2 - r_s^2)} + \frac{p^2}{k_t r_s^2}} \quad (5)$$

where  $V_{PMSM}$  is the outer volume of the machine,  $p$  the pole pair number,  $h$  the heat transfer coefficient,  $\Delta T_{\max}$  the temperature rising,  $\Gamma_{em(rms)}$  the effective torque,  $\Omega_{(rms)}$  and  $\Omega_{(avg)}$  respectively the effective and average angular speed. Then, to optimize the specific power of the machine, the volume given by (5) must be minimized through the geometrical parameters  $r_w$ ,  $r_s$  and the number of pole pairs  $p$ . In [7], it is demonstrated that the optimal design for an Si.Fe stator core and for speed above 3000 rpm is obtained with the next parameter set  $p = 1$ ;  $r_s = 0.44$ ;  $r_w = 0.73$ . From the volume equation (5) and for a given ratio  $\tau_{rl} = L/R$ , all the mechanical and electrical parameters of the machine can be computed. The length  $L$  and the external radius  $R$  are given by

$$R = \left( \frac{V_{PMSM}}{\pi \tau_{rl}} \right)^{1/3} \quad \text{and} \quad L = \tau_{rl} R \quad (6)$$

The maximal peripheral speed must also be calculated and compared to those given by the tensile strength limit of the material:

$$V_{pm(max)} = \left( \frac{V_{PMSM} \Omega_{(max)}^3 r_s^2}{\pi \tau_{rl}} \right)^{1/3} < v_{pm(lim)} \quad (7)$$

The equations (5) and (6) permit to calculate the electrical parameters and the quantity of magnet, iron and copper of the machine. The electrical model of the machine take into account the induced electromotive force  $E(t)$  (in V), the terminal resistor of the winding  $R_{co}$  (in  $\Omega$ ) and the cyclic inductance  $L_{cyc}$  (in H). The terminal resistor  $R_{co}$  and the cyclic inductance can be obtained from the geometrical parameters of the machine:

$$R_{co} = \frac{144}{3\pi} \frac{\rho_{co} k_L \tau_L R}{k_f} \frac{p^2 n^2}{R_w^2 - R_s^2} \quad \text{and} \quad L_{cyc} = \frac{6\pi \mu_0 n^2 R_s L}{e + e_{mag}} \quad (8)$$

with  $n$  the turns number,  $\mu_0$  the vacuum permeability,  $e$  the mechanical airgap and  $e_{mag}$  the height of the magnets.

Now, let us define the mass of the machine. It is deduced from the mass of iron, copper and magnet, more detailed in the full paper :

$$m_{iron} = \rho_{iron} (V_r + V_y + V_t) \quad (9)$$

$$m_{co} = \rho_{co} k_w \pi (1 - k_t) (R_w^2 - R_s^2) k_l L \quad (10)$$

$$m_{mag} = p \rho_{mag} \theta_{mag} e_{mag} (2 R_s - 2 e - e_{mag}) L \quad (11)$$

with  $\rho_{iron}$ ,  $\rho_{mag}$  and  $\rho_{co}$  the mass density of iron, magnet and copper,  $k_w$  the slot fill factor,  $\theta_{mag}$  the magnet pole arc and  $e_{mag}$  the magnet thickness.

### 2.1.3 Power converter

In this section, the design and sizing of the power electronic converter is presented. It is used to control power flows between the FESS and the loads. The structure of this power converter is three-phases IGBT bridge, as shown in figure 1(a). The loads are connected to the DC side, as well as the power supply used to recharge the flywheel. The PMSM is connected to the AC side of this converter. The used convention for the machine is a positive power during the recharge of the flywheel, i.e. a negative power during its discharge. The topology of such a device consists in two IGBT and two parallel diodes per branch and the control is assumed to be a classical . During a period  $T$  of pulse-width modulation (PWM), the transistors  $T_{1,3,5}$  operate throughout the time  $aT$ , where  $a$  is the duty cycle. On the contrary, transistors  $T_{2,4,6}$  will operate during the time  $(1 - a)T$ . After several calculations, the mean value of the losses in the power convert are given by:

$$P_{igbt} = 3 I_m \left( \frac{V_{ce0}}{\pi} + \frac{R_c I_m}{4} \right) + \frac{V_m I_m}{V_{DC}} \cos(\phi_{v/i}) \left( \frac{V_{ce0}}{8} + \frac{R_c I_m}{3\pi} \right) \quad (12)$$

$$P_d = 3 I_m \left( \frac{V_{d0}}{\pi} + \frac{R_d I_m}{4} \right) - \frac{V_m I_m}{V_{DC}} \cos(\phi_{v/i}) \left( \frac{V_{d0}}{8} + \frac{R_d I_m}{3\pi} \right) \quad (13)$$

$$P_{sw} = \frac{3}{\pi} f_{sw} \frac{k_{esw}}{V_{ce \max}} I_m V_{DC} \quad (14)$$

where  $f_{sw}$  is the switching frequency,  $V_m$  the output phase voltage,  $I_m$  the line current,  $P_{igbt}$ ,  $P_d$  respectively the conduction losses in IGBTs and diodes, and  $P_{sw}$  the switching losses.  $V_{ce0}$ ,  $R_c$ ,  $V_{d0}$ ,  $R_d$  and  $k_{esw}$  are parameters of the power converter devices, obtained from manufacturer documents. Next equations summarizes the scale law results for a set of IGBT and diode parameters:

$$V_{ce0} = V_{d0} = 0.5 + 0.02 \sqrt{V_{ce(\max)}} \quad R_c = \frac{1.1}{I_{cn}} \quad R_d = \frac{0.8}{I_{cn}} \quad k_{esw} = 7 \cdot 10^{-12} V_{ce(\max)} \quad (15)$$

## 3 Economical models

Here, the economical models are presented. They include the acquisition and operating cost through the raw materials, lifetime and energy cost. Acquisition costs of the flywheel and the PMSM is based on the raw material quantity of steel, copper and magnet. From [15], the Kevlar epoxy, E-Glass epoxy and maraging-C300 materials are the cheapest in the point of view of energy cost and volume. So, in applications with space constraints, these material are well suited for the flywheel design [1, 5, 15]. For PMSM ferromagnetic core and winding, commonly used materials are respectively the Fe-Si alloy and copper. Examples of cost values for these raw materials are given by table 1. These values are obtained or deduced from manufacturer's datas and literature [16, 17, 18]. For

Table 1: Row material costs and manufacturer .

Symbol	Description	System part	Value
$C_{fw}$	Maraging-C300		32.6 €/kg
	E-Glass/epoxy	flywheel	23.5 €/kg
	Kelvar/epoxy		72.0 €/kg
$C_{FeSi}$	Fe-Si alloy	PMSM core	3.0 €/kg
$C_{Cu}$	Copper	PMSM winding	6.0 €/kg
$C_{mag}$	Magnet	PMSM magnet	140.0 €/kg

the power converter, most work suggests cost based on the rated power. In [19, 20, 21, 22, 23, 24], the studied structures are dedicated to single phase inverter for grid connection of PV systems. They are well suited for the cost estimation of inverters with a rated power

of 1 to 5 kW. There is, however, few studies on three-phase IGBT converters. In [25, 8], the authors deal with three phase AC-DC-AC converter for wind turbine, more expensive than a simple IGBT inverter. Additional datas are obtained from quotes of manufacturers, on three-phase IGBT inverters, including current sensors and DC-bus capacitor. These cost datas permit to approximate The power converter cost (in €) by:

$$C_{\text{conv}} = 35 \sqrt{P_{\text{conv}}} \quad \text{with} \quad P_{\text{conv}} = \frac{3}{4} V_{\text{ce}(\text{max})} I_{\text{c}(\text{max})} \quad (16)$$

where  $P_{\text{conv}}$  is the maximal output power of a three-phase IGBT converter, obtained from rated voltage ( $V_{\text{ce}(\text{max})}$ ) and current ( $I_{\text{c}(\text{max})}$ ) of the IGBT.

To be accurate, a techno-economic optimization on an electrical energy storage system must take into account the operating costs. The target application is a small electric ship, which carries short distances (round trip between two shores). Today, this ship exists and is only supplied with supercapacitors [11, 9, 10]. In this work, we compare this technological choice with a flywheel storage system, used as the only source of energy. The operating costs for such an application, must take into account the maintenance, the lifetime and the consumed electrical energy. In this work, the lifetime of the flywheel storage system is assumed to be 20 years. Because the maintenance few depends on the system sizing, it is not integrated in the optimization. However, the losses take a great part in the final cost of such a system. They are taken into account assuming a cost of 0.1 €/kWh.

## 4 Optimization results

The optimization of the flywheel storage system is applied to the electrical ship *Ar Vag Tredan*, operating currently with ultracapacitors. The two objectives are the optimization of the total acquisition and operating cost for a duration of 20 years, and the volume of the storage system. Three materials for the flywheel (see Table 1) are tested and compared on the basis of these two criteria. The optimization variables are the maximum angular speed ( $\Omega_{\text{max}}$ ) and the the inertia ( $J$ ) of the flywheel, the number of turns of the PMSM ( $n$ ). The rated current and voltage of the power converter are selected in a list of classical values (for IGBT devices). Results are given as Pareto front on Figure 2. This result shows that each material used for the flywheel design permits to achieve a best set cost-volume.

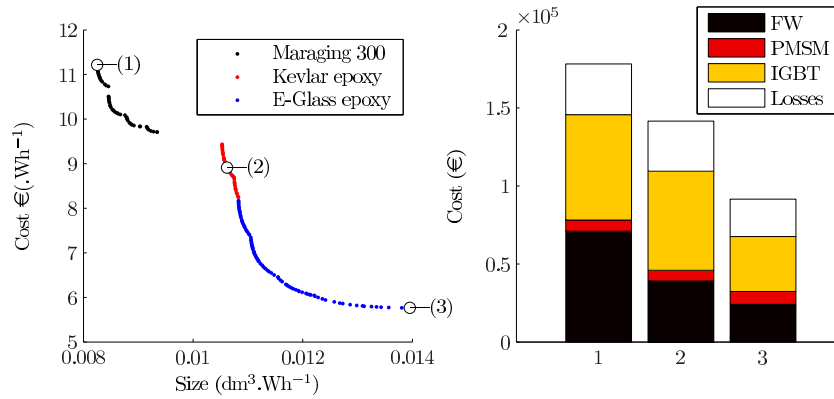


Figure 2: Optimization results.

The Maraging material is expensive, but reduces the size of the storage system. In contrast, the E-glass is a low-cost material, but constrained to a larger size for the flywheel. More details on the optimization results will be given in the final paper.

## 5 Conclusion

This work present a methodology for the sizing of a flywheel storage system. Each subsystem is described with technical and economical models. The optimization is done for a set of three different flywheel materials and are compared on cost and size criteria, using the load profil of an ultracapacitor electrical ship. This work will show that a flywheel storage system is competitive with other technologies such as ultracapacitors or batteries. In the final paper, these economical and technical comparisons will be more detailed.

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