PMSM and Inverter Sizing Compromise Applied to Flywheel for Railway Application

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Abstract– **In this paper the authors study the first step of power inverter and permanent magnets synchronous machine (PMSM) sizing, considering the application to a flywheel energy storage system. Knowing the operating characteristics of the drive defined by the application, our approach is based on determining the evolution of both machine torque and power converter current as functions of the rotational speed. It is shown that those curves strongly depend on the relative speed range of constant power and constant torque operations. The authors explain how to choose Ω_{t_1} (the rotational speed corresponding to the beginning of the constant power working) in order to obtain a good compromise between the inverter power and the PMSM torque. Finally the authors detail the influence of a real cyclic working on the design of the flywheel system.**

Keywords – **Flywheel, inverter, electrical machine, permanent magnet, railway**

I. INTRODUCTION

Today's flywheel batteries used optimized components (i.e., rotor, electrical machines and inverter), and they became serious contenders for a variety of important energy storage applications such as electrochemical batteries or ultra-capacitors [1].

The flywheel system presented in this paper is designed for railway applications, sized to provide full autonomy to the vehicle. For example, we consider the tramways having sufficient autonomy to achieve whole trips between two stations with energy braking recovery. Compared to electrochemical batteries, the specific power can be higher, nearly comparable to ultra-capacitors. Moreover, flywheel systems lifetime and reliability are better than the two previously mentioned energy storage systems [2], and it is particularly important for railway applications since the system should be able to be used more than 12 hours a day during 30 years.

As an example, a high speed composite flywheel for an advanced technology transit bus was developed and tested by university of Texas. As a result, the engine power was reduced by a factor of 25% and the acceleration time to 75 Km/h was reduced by a factor of two [3]. It's clear that these kinds of performances are very interesting; however, its components (magnetic bearings, composite material) makes it unattractive for commercial aspect. An interesting discussion on the reducing of costs is carried out in [4].

In this paper the authors propose to study the interactions between the electrical machine and the power converter designs, in order to find a compromise that will satisfy sizing and operation constraints.

II. FLYWHEEL SYSTEM PRESENTATION AND SPECIFICATIONS

A flywheel system stores energy as rotational kinetic energy by accelerating a rotor up to the maximum possible speed compatible with mechanical resistance of the rotor. The reversible conversion of kinetic energy into electric energy is obtained with an electrical machine. This type of energy storage device considered in this paper is mainly composed of the following components:

- A flywheel (i.e., a cylinder made of composite or steel);
- An electrical machine (i.e., the PMSM);
- A reversible power converter to fed the electrical machine (charge of the flywheel) or to recover electrical energy (discharge of the flywheel);
- Bearings compatible with the high rotational speed;
- Containment with partial vacuum to avoid mechanical losses and corresponding heating (which are all the most difficult to evacuate that the rotor is in partial vacuum).

The Figure 1 shows the schematic diagram of such a flywheel system and the Table 1 gives the specifications that are considered in this paper.

III. MACHINE-INVERTER SIZING COMPROMISE

The Figure 2 shows the classical operating area of a PMSM during a charge of the flywheel. The total duration of the charge, t_2, is fixed by the specifications. The first part of the charge, from 0 to t_1, is characterized by a constant torque operation, and the second part, from t_1 to t_2, deals with a constant power operation. Our goal is to study the influence of the choice of t_1, i.e. of the duration of the constant torque working versus the duration of the constant power working,

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on the sizing of the machine and the power converter. In a simple approach, it can be assumed that the machine size is imposed by the maximal torque that the motor has to provide and the inverter size is imposed by the maximal power (or current for a given voltage) that must flow in the inverter.

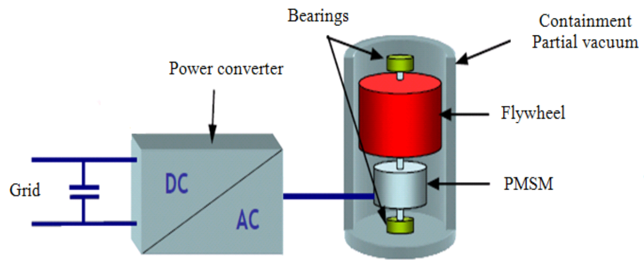

Figure 1. Block diagram of a flywheel system [5].

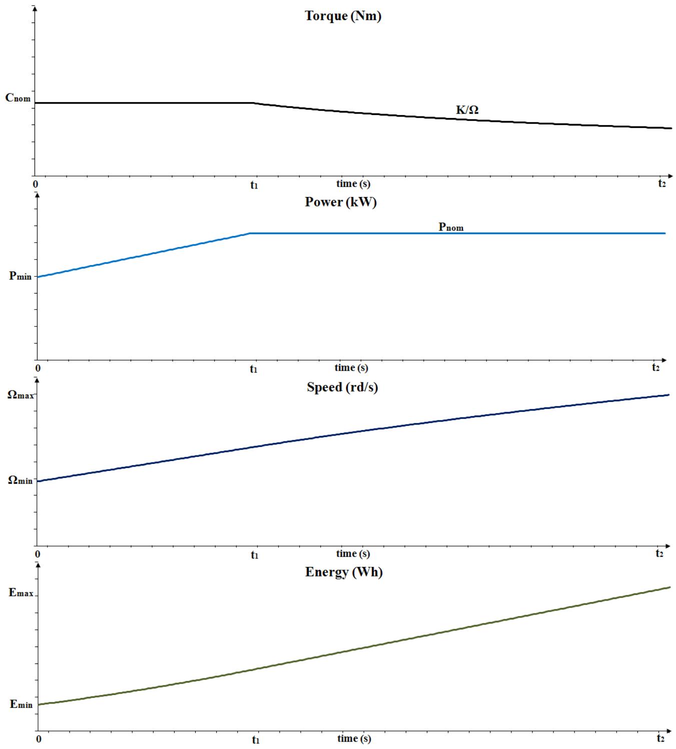

Figure 2. Torque, Power, Speed and Energy of Flywheel (Operating area).

TABLE 1. SPECIFICATIONS OF THE CONSIDERED FLYWHEEL SYSTEM

Maximum energy [kWh]	2
Minimum energy [kWh]	0.5
Duration of one charge [s]	20
Grid Voltage [V]	750

According to figure 2, the followings design parameters are defined:

- P_{nom} : the maximum converted power;
- P_{min} : the minimum converted power;
- C_{nom} : the maximum motor torque;
- t_1 :the time when maximal power is reached $(0 < t_1 < t_2)$;
- t_2 : the total duration of the charge.

It is also important to note that, in the proposed study, the beginning of flux weakening does not correspond necessarily to t_1. This value is imposed by the DC voltage at the input of the inverter, and the beginning of flux weakening depends on whether the maximum voltage is reached [6] before or after the time t_1.

The torque, speed and power evolutions during the two phases (see in figure 2) are characterized by the following equations:

- For $0 < t < t_1$, the angular speed Ω has a linear evolution : $\Omega = \Omega_{min}$ at $t = 0$ and $\Omega = \Omega_{t_1}$ at $t = t_1$. The motor torque is then defined by:

$$C = J \cdot \frac{d\Omega}{dt} = J \cdot \frac{\left(\Omega_{t_1} - \Omega_{min}\right)}{t_1} \qquad (1)$$

with J the flywheel moment of inertia (kg.m²).

- For $t_1 < t < t_2$, we have $\Omega = \Omega_{t_1}$ at $t = t_1$ and $\Omega = \Omega_{max}$ at $t = t_2$. The motor torque is then defined by:

$$C = \frac{K}{\Omega} \text{ with } K = \frac{1}{2} \cdot J \cdot \frac{\left(\Omega_{max}{}^2 - \Omega_{t_1}{}^2\right)}{t_2 - t_1} \qquad (2)$$

- By using (1) and (2), the rotational speed Ω_{t_1} (at the instant $t = t_1$) corresponding to the beginning of the constant power working is defined by:

$$a \cdot \Omega_{t_1}{}^2 + b \cdot \Omega_{t_1} + c = 0 \;\Rightarrow \Omega_{t_1} = -\frac{\left(b + \sqrt{\Delta}\right)}{2 \cdot a} \qquad (3)$$

(indeed only the positive solution is considered),

With: $\Delta = b^2 - 4 \cdot a \cdot c$, $a = -\frac{(2 \cdot t_2 - t_1)}{2 \cdot (t_2 - t_1) \cdot t_1}$,

$b = \frac{\Omega_{min}}{t_1}$ and $c = -\frac{\Omega_{max}}{2 \cdot (t_2 - t_1)}$

With the previous equations, we can plot the evolutions of torque, speed and power profiles of the electrical machine as a function of t_1. Moreover, by assuming a given efficiency η of the machine and using a PWM control, the output power of the inverter P_E at the instant t_1 and its current I_E are given by the following equations [7]:

$$U_M = \frac{\sqrt{3}}{2} \cdot \alpha \cdot U_{bus} \;\; and \;\; V_M = \frac{U_M}{\sqrt{3}} = \frac{U_{bus}}{2}$$

$$I_E = \frac{2}{\sqrt{3}} \cdot \frac{P_E}{U_{bus}.\cos(\varphi)}, \text{ with } P_E = \frac{P_M}{\eta} \tag{4}$$

where U_{bus} is the grid voltage given in the Table 1, U_M is phase voltage, V_M is the simple voltage, α is the duty cycle (assumed to be equal to 1), $cos(\varphi)$ is the power factor and $P_M = C \cdot \Omega_{t_1}$ is the mechanical power depending on the torque and the speed which were characterized by (1) (defining the operating area of Figure 2).

Using (4), the evolution of the inverter current versus t_1 can be determined. Thus, the sizing results are shown in Figure 5. The plotted curves are obtained as follows:

- It is clear that the optimal case concerning the design of the motor is obtained when no flux weakening operation occurs throughout the whole charging time of the flywheel. This case corresponds to a constant torque operation and $t_1 = t_2$; for this case, evolutions of torque, power and speed are plotted in Figure 3. Then, Figure 5 shows the normalized torque increase, relatively to the optimal value of torque obtained without flux weakening by using the following equation:

$$C(\%) = \frac{[\Delta t_1^2 \cdot \Omega_{max}^2 - (X \cdot t_1 \cdot \Delta t_2)^2] \cdot t_2 \cdot \Omega_{max} 100}{2 \cdot t_1 \cdot \Delta t_2 \cdot \Delta t_1^2 \cdot (\Omega_{max}^2 - \Omega_{max} \cdot \Omega_{min}) \cdot X} - 100 \tag{5}$$

Where: $X = \left(\frac{\Omega_{min}}{t_1} + \sqrt{\left(\frac{\Omega_{min}}{t_1}\right)^2 + \frac{\Omega_{max}^2 .(2.t_2 - t_1)}{(t_2 - t_1)^2 \cdot t_1}} \right)$

$$\Delta t_1 = 2 \cdot t_2 - t_1 \qquad and \qquad \Delta t_2 = t_2 - t_1$$

- The same analysis is applied to the current inverter. The optimal case is obtained for constant power operation and $t_1 = 0$; for this case, evolutions of torque, power and speed are plotted in Figure 4. Then, the evolution of the normalized current, relatively to the optimal value, is given by the following equation:

$$I(\%) = \frac{[\Delta t_1^2 \cdot \Omega_{max}^2 - (X \cdot t_1 \cdot \Delta t_2)^2] \cdot t_2 100}{\Delta t_2 \cdot \Delta t_1^2 \cdot (\Omega_{max}^2 - \Omega_{min}^2)} - 100 \tag{6}$$

The curves of $C(\%)$ and $I(\%)$ are plotted for $0 \le t_1 \le t_2$ in Figure 5.
It can be observed in this Figure that, when the begin of the constant power working occurs in the first half of the time $(0 < t_1 < t_2/2)$, a torque decrease (up to 40 %) can be reached, while the current inverter can increase up to 30 % in the second part of the time $(t_2/2 < t_1 < t_2)$. Using the results shown in Figure 5, a compromise between machine and inverter sizing can be proposed around the intersection point of the two curves $C(\%)$ and $I(\%)$ or by calculating the

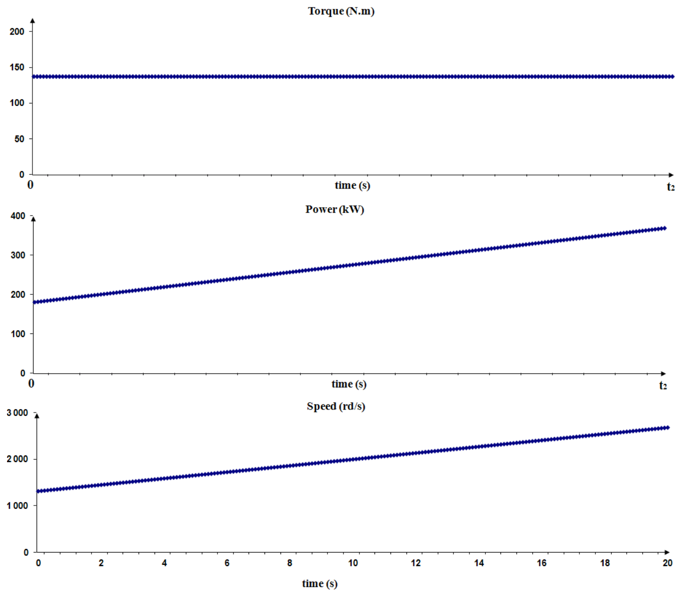

Figure 3. Evolution of :Torque, Power and Speed when $t_1 = t_2$

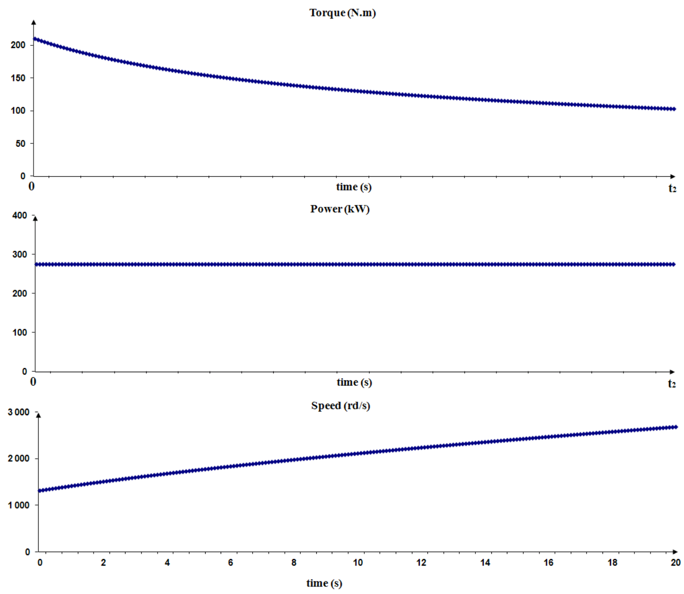

Figure 4. Evolution of :Torque, Power and Speed when $t_1 = 0$

minimum of the sum $C(\%)$ + $I(\%)$, which corresponds to a time of constant power working beginning equal to the middle of the wished flywheel charge duration: $t_1 = t_2/2$.

$$\frac{d\left(C(\%) + I(\%)\right)}{dt_1} = 0 \qquad t_{compromise} = t_2/2$$

IV. INFLUENCE OF CYCLIC OPERATION ON THE FLYWHEEL DESIGN

As mentioned in the introduction, the use of flywheel and more generally energy storage systems in urban railway applications such as tramway for example, has very stringent constraints due to cyclic operations. In this context, Figure 6 shows an example of flywheel operating modes considering real cyclic solicitations. The SOC (State Of Charge) is calculated as follows:

- the flywheel is assumed to be completely charged at the beginning of the operation (*SOC = 1*);
- then, considering the power imposed by the load (traction motors), the energy, the SOC, the speed and the torque are calculated by using the mathematical model presented in the previous part.

In this analysis, the authors have considered the optimal compromise sizing time: $t_1 = t_2/2$. For each trip between two stations, the flywheel achieves the three generic operating modes presented in the Figure 6:

- **Mode I**: The electrical machine operates in generator mode to supply power for traction motors resulting in a decrease of speed and flywheel SOC;
- **Mode II**: Due to a recovery braking, the machine operates in motor mode to accelerate the flywheel resulting in an increase of the speed and the flywheel SOC;
- **Mode III**: The transportation system is in station and the flywheel can be recharged at its maximum state of charge.

In this study, the authors propose a comprehensive analysis of a real solicitation cycle. The Figure 7 shows the using rate of the flywheel in terms of torque machine (Machine sollicitations) and stored energy (Flywheel sollicitations). We can notice that during almost 70 % of the time, the torque of the machine is less than 50 % of its maximum torque, and 30 % during that time the machine is applied for only 10 % of its maximum torque. Since the working at maximal torque is not frequent, it seems to be possible to optimize the machines. A first solution is to keep the machine design and to minimize the cooling system. A second solution is to reduce the weight of the machine (which is certainly the key factor for the considered application) and to keep the cooling system.

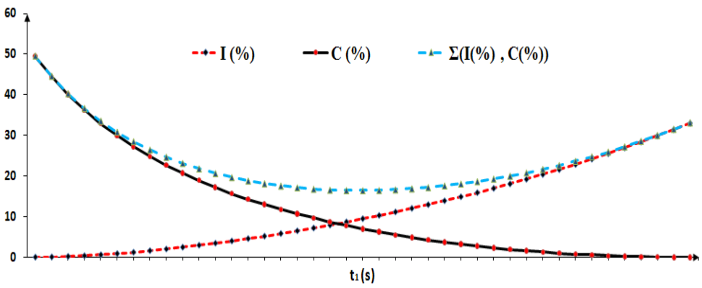

Figure 5. Curve sizing compromise Machine-Inverter.

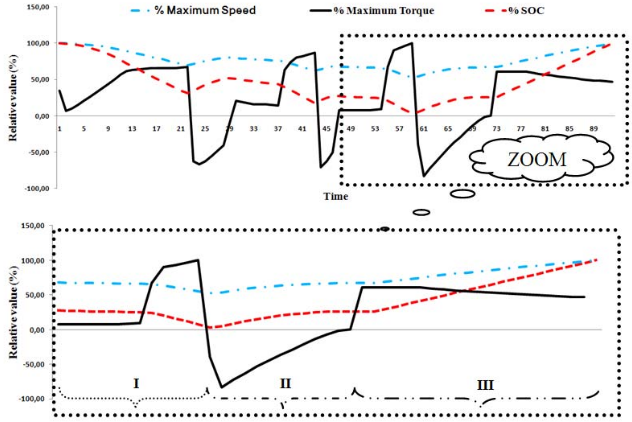

Figure 6. Cyclically operating under real stress.

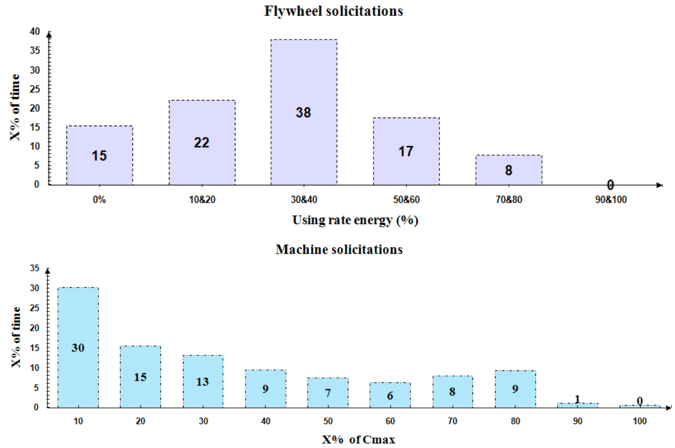

Figure 7. Real solicitations cycle analysis.

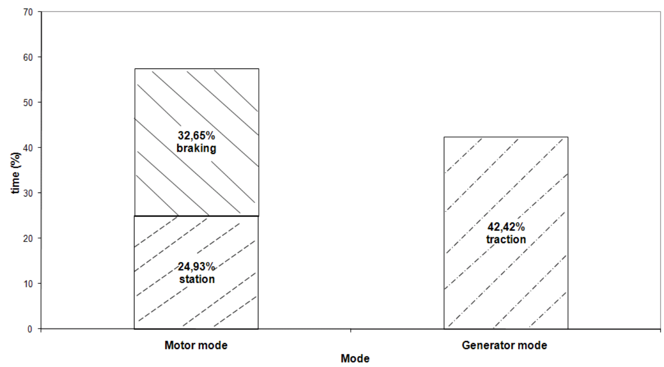

Figure 8. Operating mode of the machine

Moreover, the curve of Figure 7 (Flywheel sollicitation), presenting the using rate energy of the system during one real urban mission, shows that, during 15 % of the time, the flywheel doesn't work (0 % of using rate energy). This non-working corresponds to a phase where the tramway is in station and does not have to be recharged: thanks to braking energy recovery, the system is at its maximum energy stored (Emax=2 kWh) when arriving in station and therefore it didn't need to be recharged.

To consolidate these conclusions, figure 8 shows clearly the proportion of the different operating modes of the machine during the considered trip. This shows that the machine operates in motor mode 57.6% of the time against 42.4% in generator mode. Moreover, considering the motor mode, the working time in recovery braking represents over 32% of the time. However, during this phase, the power is not high and, as a consequence, it does not correspond to a high energy recovery.

V. CONCLUSION

In this paper we have proposed to find a sizing compromise between machine and power converter for the design of a flywheel system for urban railway applications. Indeed, a constant power working during the whole range of speed leads to an over-sizing of the motor (high maximal torque), and a constant torque working leads to an over-sizing of the power converter (high maximal power). Then, using a simplified approach, it has been shown that a good compromise corresponds to a constant torque working during the first half of the speed range and a constant power working during the second half of the speed range.

However, this first order optimal sizing has to be improved by taking into account a real working cycle. The using rate of the flywheel firstly, and the torque and energy constraints secondly, have been considered for a given cycle. With such an analysis, it has been shown that the optimal Machine/Converter sizing point can be different of the one obtained with simplified calculation. In other words, the optimal design of the complete system needs to take into account the real road profile.

REFERENCES

[1] R. Hebner, J. Beno, A. Walls, "Flywheel Batteries come around again", IEEE Spectrum, April 2002.

[2] F.N. Werfel, U. Floegel–Delor, T. Riedel , R. Rothfeld, D. Wippich, B. Goebel, G. Reiner, and N. Wehlau, "A Compact HTS 5 kWh/250 kW Flywheel Energy Storage System", IEEE Trans. Appl. Supercond. vol.17, No.2 (2007)2138-214.

[3] M.M. Flynn, J.J. Zierer, and R.C. Thompson, "Performance Testing of aVehicular Flywheel Energy System", 2005 *SAE World Conference*, Detroit Mi. April 11-14, 2005.

[4] C.S Hearn, M.M. Flynn, M.C. Lewis, R.C. Thompson, B.T. Murphy, R.G. Longoria, "Low Cost Flywheel Energy Storage for a Fuel Cell Powered Transit Bus", Vehicle Power and Propulsion Conference, Sept 9-12, 2007. VPPC 2007. IEEE

[5] http://www.femto-st.fr/f/d/fiche_projet_SEVIT_VITFER.pdf

[6] A.M. EL-Refaie, D.W. Novotny, T.M. Jahns, "A Simple Model for Flux Weakening in Surface PM Synchronous Machines using Back-to-Back Thyristors", IEEE Power Electronics Letters, Vol. 2, NO. 2, June 2004.

[7] B. MULTON, "Self-driven synchronous machine", ENS Cachan, 2004.