LOW COST ENERGY STORAGE, FLYWHEEL SYSTEMS, DEVELOPED FOR INTELLIGENT BUILDING APPLICATIONS AND SENSOR FEEDING IN ISOLATED AREAS

Valentin DACHE[1], Valentin SGÂRCIU[2]

The article presents a system of energy storage in the flywheel, as an study for alternative batteries, destined to power the underwater sensors or, generally, for isolated and inaccessible areas, as well as to conventional UPS (Uninterruptible Power Supply) systems with Pb-acid batteries, for the storage of energy from renewable sources. The purpose is to evaluate/measure how such a system is suitable for energy storage over a period of hours / tens of hours and its use in tandem with different energy sources (mainly renewable) on a small scale. It is demonstrated the operation of two alternator-flyer systems, at low costs and made with accessible components that exist on the market, being determined the main characteristics and performances.

Keywords: flywheel, energy storage, renewable energy

1. Introduction

Energy storage systems (SSE) are used to facilitate a balance between energy sources and consumers. Although they are not in themselves energy sources, they can substantially improve the stability, quality of energy and reliability of an energy system. In this process, the energy from the source is usually converted to another form of energy and stored, with the possibility of being converted back to the original or another form needed by final consumers [1]. The main forms in which energy can be stored are chemical, mechanical, thermal and magnetic energy [1] [2] [3].

To ensure the performance of today's electricity grids, there is a high demand for reliable, cost-effective, long-term service and environmentally friendly energy storage systems. Flywheels provide a solution for storing energy in mechanical form, and their use dates since pottery time. Over time the flywheels have found their main application in steam engines and later in internal combustion engines, to smooth the output power during combustion cycles. Over time, the clear advantages of incorporating the flyers into the electricity production and distribution grids, such as lowering energy cost, ensuring the need for energy in emergency situations, improving the quality of electricity by

[1] Eng., University POLITEHNICA of Bucharest, Romania, e-mail: valentin.dache@gmail.com
[2] Prof., University POLITEHNICA of Bucharest, Romania, e-mail: vsgarciu@aii.pub.ro

reducing fluctuations and facilitating the implementation and exploitation of renewable energy sources have been observed. Once with technological advancement and development of more durable and cheaper materials, more efficient bearings, more efficient and reliable electronic power components, the technology of flywheel energy storage systems has advanced considerably [4] [5], as well as the new spectrum of their applications, such as in the transport industry, military applications or space satellites [6].

With storage capacities up to 500 MJ and power from kW to GW, these systems can be used in important applications of energy storage in an electrical system [6,8]. The most common application of the flywheels in electricity storage is the construction of uninterruptible power supply (UPS) and the improvement of power quality [9,10,11]. For this type of applications, the electrochemical battery is very inadequate, because daily high number of charging/discharging cycles are shortening battery life [12]. Network disruptions are efficiently managed by the flywheel, which offers an improvement over batteries given the instant response time and longer life cycle. Even with a single cycle per day, the electrochemical battery is unlikely to last even 10 years under these conditions (3650 cycles). This can only be achieved if the discharge level is low and the battery is carefully managed, both electrically and thermally. It is also necessary to specify an energy storage capacity of two to five times the capacity required to reduce the discharge level, which leads to a higher cost.

Supercapacitors have been tested for these types of applications, but with the same initial cost [3], their lifespan is relatively low (up to 12 years). For a longer use of such a system and to reduce the capacity to minimize costs, it is useful to use the system several times a day to offset daily consumption and to introduce energy surplus into the grid during rush hours.

Several flywheel storage systems reviews have been presented by several papers in the literature. A comparison of storage energy technologies is made in [13], where the improvements and problems associated with Flywheel Energy Storage Systems (FESS) are numerically and analytically demonstrated. A comparison of energy storage technologies for high power applications is performed in [14] and a FESS study for power system applications is provided in [15]. The control of high-speed FESS systems for space applications is discussed in [16]. Different FESS are briefly reviewed in [17] and an overview of previous projects is presented in [8]. In [18], the authors focus on the engine-generator (MG) evolutions for FESS, where common electric systems, used with flywheels together with their control, are reported in [19]. An examination and simulation of the FESS for an isolated wind system is presented in [9]. This analysis has a different approach from the previous one, it is functional, and, above all, it takes a very recent literature on what is a topic that is developing very quickly.

Mainly, the flywheel itself is a disc made of either steel or composite materials (carbon fiber or glass, along with different types of resins), which accumulates energy as its speed of rotation increases. The energy stored at a certain speed of rotation depends on the flywheel geometry, the density of the material used and the angular velocity:

$$E_{rot} = \frac{1}{2} I \omega^2 \quad (1)$$

$$I = \int mr dr \quad (2)$$

, where I is inertial moment (kgm^2), and ω is angular velocity (rad/s).

In operation, the flywheel suffers energy losses through various mechanisms [7], in particular by air friction and bearing friction. The rate at which energy (power) is lost due to air friction depends on the air density ρ_a, the dynamic viscosity β_a, the angular velocity ω, and the height and radius of the flywheel, h and r:

$$P_{air} = 0.04 \rho_a^{0.8} \beta_a^{0.2} (r\omega)^{2.8} (2r)^{1.8} \left(\frac{h}{2r} + 0.33\right) \quad (3)$$

The power lost from bearings friction depends on their friction coefficient, μ, mass m, radius r and angular velocity ω:

$$P_{bearings} = \mu mg * r\omega \quad (4)$$

The total energy after a time interval t of the flywheel which initially rotated with ω speed is:

$$E_{net} = \frac{1}{2} I \omega^2 - \int_0^t \left(P_{air} + P_{bearings}\right) dt \quad (5)$$

The maximum radius of the flywheel and the speed of rotation are limited by the resistance to breaking (and stretching) of the material used. Therefore, when designing a flywheel it must be taken into consideration that breaking resistance σ_t is higher than the radial loadσ_{rad} :

$$\sigma_t \geq \rho r^2 \omega^2 = \sigma_{rad} \quad (6)$$

2. Building and testing proposed system

The functional diagram of chosen electro-mechanical assembly is presented in Fig. 1. The diagram was realized in two variants, one for domestic consumption study (using alternator 1), and the second one for small systems study, that is most suitable for depth sensors power supply and beyond.

The system can be mainly operated with any power source as long as it can provide a voltage of approximately 12Vdc (mini-turbines for deep ocean currents, photovoltaic panels, small wind turbines, mini-hydro power plants directly from the course river, etc.). Although it is suitable for domestic use, for simplicity and given the purpose of the project, the possibility of pushing electricity into the distribution grid was not implemented, and the energy source used is a source of laboratory voltage, detailed below.

The operating design principle is the following: while there is a surplus of energy, a part of this is temporarily stored in a small battery (from which the rotor of a synchronous machine is fed with constant current for a short time).), and the rest feeds a three-phase converter, which in turn supplies the three phases of the synchronous machine, starting the flywheel. When the power is not available, the three-phase converter is disconnected from the three phases of the machine stator with the help of three relays, and this supplies the necessary consumers through the three-phase rectifier, using the energy stored in the flywheel.

In a practical application, in the case that we are using alternator 1, the output voltage will be controlled automatically during flywheel slowing, varying the excitation current of the rotor. For the second alternator/motor, a DC-DC converter can be used to maintain the output voltage to the desired value, depending on the load consumption.

The Pb-acid battery is only required for startup system as long as the only available power source is the flywheel. This can be avoided if the remaining magnetization of the synchronous generator rotor is enough to provide an output voltage, greater than the opening voltage of the rectifier diodes; After starting the system, a small part of the generator's output power can be used to ensure the excitation of the rotor. Decoupling the relays can also be avoided if a three-phase converter is used which has no automatic braking option.

One of the advantages by using this type of system is that the maximum energy stored depends mainly on the flywheel mechanical limits and the synchronous machine, by being able to reach very high energy densities compared to other conventional systems.

2.1. System components

Most of the components and subassemblies used for measurements were specially designed and made for the purpose of the present work. For measurements the following instruments have been used: twomultimeters Mastech MS8218, digital oscilloscope Siglent SDS 1104X-E digital oscilloscope, Micsig TO1074, acquisition board Omega DAQ 2416 and non-contact speedometer Peaktech 2790. For both studied cases, AC machines were studied because of the contact wearing that would become a problem in long-term use with DC machines. For motor / generator purpose, an car alternator was used for the first case (Fig. 2). This is a three-phase synchronous machine with a maximum input / output current of 100A, a 3Ω excitation winding resistance, a stator winding of 0.0195Ω (the windings are connected to the star) and a nominal working voltage of 12V. In order to be able to control the excitation currentindependently and separately, the rotary contacts of the rotor were directly connected, without using the built-in voltage regulator. Also, the built-in rectifier diodes were disconnected to allow access to the three-phase windings of the stator, and for the rectification an external diode bridge was used.

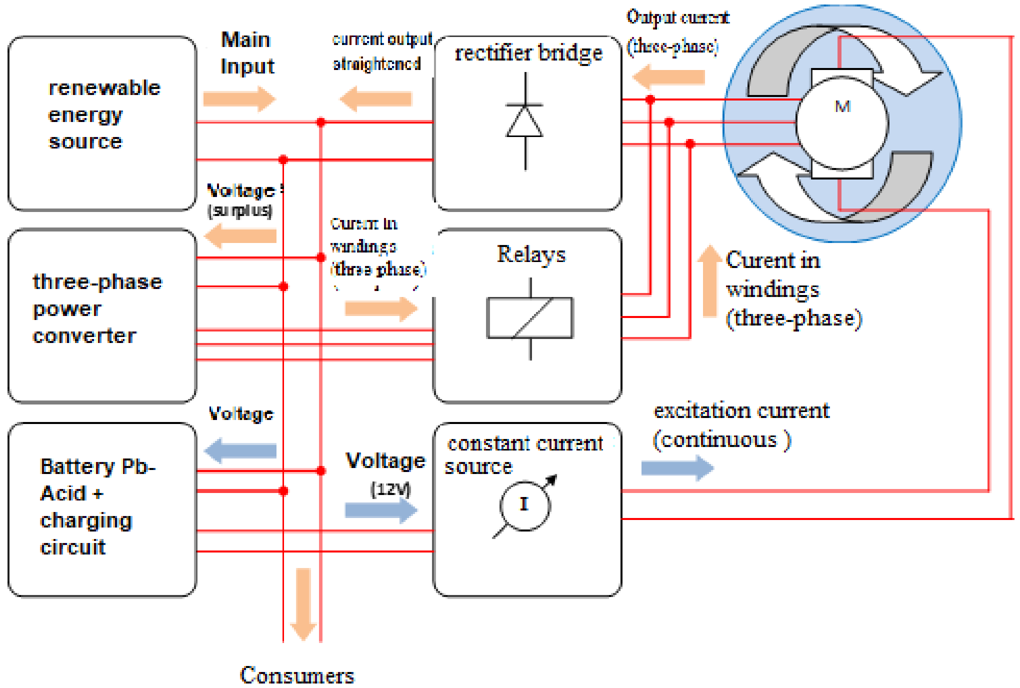

Fig. 1. Functional diagram of the flywheel energy storage system

As a flywheel, a 10 kg training weight and 30cm diameter was used. Given been intricate geometry, the steering wheel balance adjustment was performed manually, and total inertial moment was determined experimentally.

The second synchronous machine used is a brushless motor type U7-V2.0 KV420 (manufactured by T-Motor, Germany), with permanent magnets, with a maximum current of 40A, a stator winding resistance of 0.0165Ω (the windings are connected in a wye configuration), a maximum working voltage of 25V, a maximum power of 1180W and a speed ratio of 420 rpm/volt (Fig. 3)

The flywheel, with a mass of approximately 1kg, was adapted to the purpose of a steel flange. The balancing was done manually, and the adjustment with the alternator shaft was made using an ABS adapter.

The rectifier bridge was built using six high-power IXYS DSEI120-06A with the following characteristics:

- Maximum reverse voltage: 600V
- Nominal current: 126A
- Maximum current (pulse): 540A
- Recovery time: 35ns
- Direct polarization voltage drop: 1.12V

- Maximum dissipated power: 357W

For connectivity were used six screw connectors (3 phases, 1 null, 2 DC outputs), with the possibility to connect cables with the maximum section of 16mm2, at a nominal current of 67A, the main limitation factor is the power released in cable contact resistance at conjunction. The bridge made is displayed in Fig. 4.

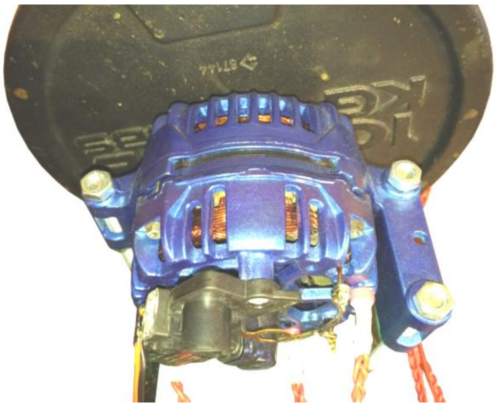

Fig. 2. First alternator and flywheel

In a practical application, to avoid efficiency losses and increase, the bridge can easily be made by using six MOSFET transistors and synchronous rectification or Schottky diodes if relatively low output powers are required. In this case, a diode bridge was chosen due to load three-phase balance complexity, at operating voltages up to 14V.Losses in the system at high currents can become significant.

Fig. 3. Second alternator and flywheel

The three-phase converter used it is built from of a motor speed controller without brushless, model Fly Pro, and a servomechanism testing module that allows manual speed variation, with the following features:

- Nominal working current: 60A
- Supply voltage: 8.4 – 25.2 V
- Modulation frequency: 8kHz

The manual rotation speed variation was used for all experimental determinations. To determinate flywheel acceleration, it was tried to maintain a constant acceleration. In order to disconnect the generator windings from the three-phase converter during measurement, it have used three relays, supplied separately, (common used use in cars), type HFV7 / 012-HT, with the following specification:

- Control voltage: 12V (7.2V – 18V)
- Coil resistance: 90Ω
- Contact configuration: SPST-NO
- Maximum contact current: 70A
- Contact material: AgSnO2
- Maximum contact voltage: 50V

Fig. 4. The rectifier bridge

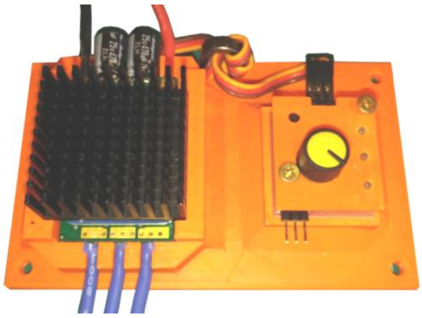
Fig. 5. The 3-phase converter

The power supply used for both alternators is a MeanWell RSP-320 switching voltage source that supplies 13.6V (adjustable) voltage at 24A maximum current. To provide the excitation current of alternator 1, a separate current source was used, and the required power was not included in the efficiency calculations.

2.2. Experimental results

Due to the complex geometry of the flywheel assembly, different densities and inaccessible dimensions, the inertial moment of entire assembly (for each alternator) could not be calculated, and it was determined experimentally. For this purpose, a known body of mass was used, used in falling over a certain distance to accelerate the flywheel up to a certain maximum speed, with the help of a negligible mass wire wrapped around its circumference. The maximum speed of the flywheel was measured with a non-contact Peaktech 2790 speedometer. For better accuracy of results, the experiment was repeated 10 times, averaging the maximum speeds thus measured.

Table 1

Experimental results for determining the moment of inertia

Measure	*Symbol and formula*	*Unit*	*Result*	
			A1	**A2**
Body mass -measured	*m*	*kg*	0.55	0.525
Falling Height - measured	*h*	*m*	1	1
Gravitational acceleration - calculated based on location	*g*	m/s^2	9.806	9.806
Flywheel circumference - measured	*L*	*m*	0.93	0.435
Maximum flywheel speed - measured	*V*	*rpm* *rad/s*	81.6 8.54	361 37.8
Initial potential energy	*Ep = mgh*	*J*	5.393	5.14
The final speed of the body	$Vp = \frac{V(rpm)}{60} * L$	*m/s*	1.26	2.61
The final speed of the body	*Vc =Vp*	*m/s*	1.26	2.61
Maximum kinetic energy of the body	$Ecc = \frac{m * Vc^2}{2}$	*J*	0.436	1.788
Maximum kinetic energy of the flywheel	*Ecv = Ep - Ecc*	*J*	4.95	3.352
Inertial moment ofensemble	$I = \frac{2Ecv}{V(\frac{rad}{s})^2}$	$kg * m^2$	**0.1355**	**0.00574**

The system energy input presented is the potential energy of the body that falls on the distance h, energy that will be found in the kinetic energy of the flywheel and the kinetic energy of the body at the end of the distance h. Due to the low angular speed of the flywheel, the losses due to friction with air and bearings were neglected. Knowing the dependence between stored energy base on angular velocity and inertial moment, the energy was determined from the calculation, the resulting value being used in all subsequent calculations. In determinate the performance of each system, these were tested one at a time, on two speed ranges: 500-1800rpm for alternator 1, and 1000-5500rpm for alternator 2. To determine the efficiency of the alternators during acceleration, their speed was gradually increased, manually, during which the instantaneous current was continuously measured and recorded using Siglent SDS 1104X-E oscilloscope, at 50μs intervals. The data obtained were processed to obtain the average current and the RMS current. Due to the rapid acceleration, the mechanical losses were substantially lower than in the case of generator operation. The results for both alternators are summarized in Table 2.

Table 2

Experimental results for determining the drive efficiency for the two alternators

	Alternator 1	**Alternator 2**	Unit
Power supply voltage	*13.62*	*13.62*	*V*
Acceleration time	*19.07*	*18.35*	*s*
Measured current (medium)	*10.24*	*3.98*	*A*
Measured current (RMS)	*10.90*	*4.16*	*A*
Winding resistance	*0.041*	*0.071*	Ω, *L-L*
Today drive energy	*2660.67*	*993.94*	*J*
Copper losses	*4.82*	*1.23*	*J*
Winding losses, air, bearings, driver, recovery circuit	*434.40*	*72.45*	*J*
Calculated mechanical energy	*500-1800 rpm*	*1000-5500 rpm*	
	2221.45	*920.26*	*J*
Drive efficiency	***83.49***	***92.59***	***%***

It can be observed that alternator 2 have an higher efficiency, mainly due to lower copper losses, more efficient bearings and optimized geometry, although the final speed was substantially higher.

a) Experimental results for Alternator 1

In order to determine the energy losses of the system in the absence of the load current, a series of experimental determinations were carried out, in which the flywheel was brought at a speed of 1800 rpm, after which it was left free up to 500 rpm without any consumer logged in. During the flywheel slowdown, its speed was measured every 10 seconds.

The determinations were made first without any excitation current, and then with excitation currents up to 1A, from 0.2 to 0.2A, according to Fig. 6. In the absence of the excitation current and neglecting the remaining rotor magnetization rotor, the only losses are the mechanical ones: friction of the flywheel with the air, mechanical work of the internal fan incorporated in the generator, friction in the bearings and friction of the brushes on the rotor.

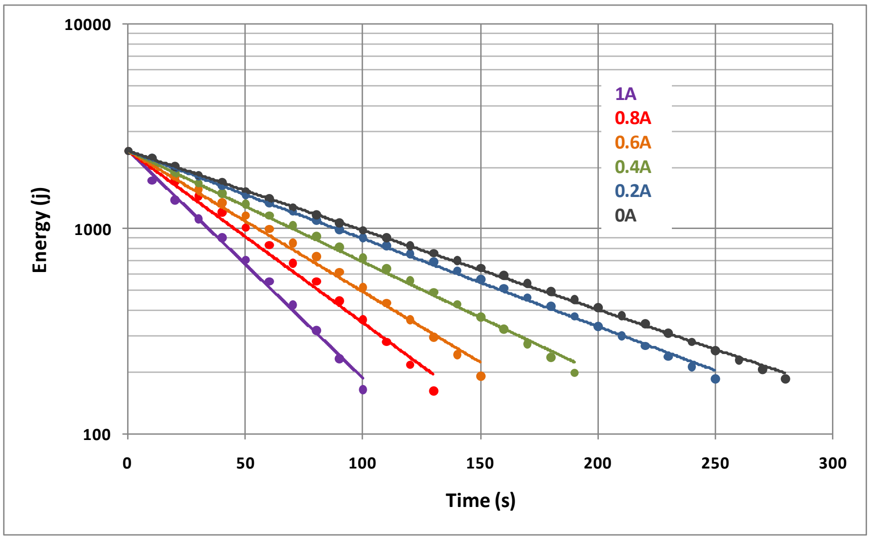

Fig. 6. Flywheel energy variation over time, without load in deceleration and different current excitation

When the rotor it is excited, to the mechanical losses, the hysteresis losses in the core and the losses through Eddy currents are added; copper losses are not taken into account, since no load is present (Fig. 7).

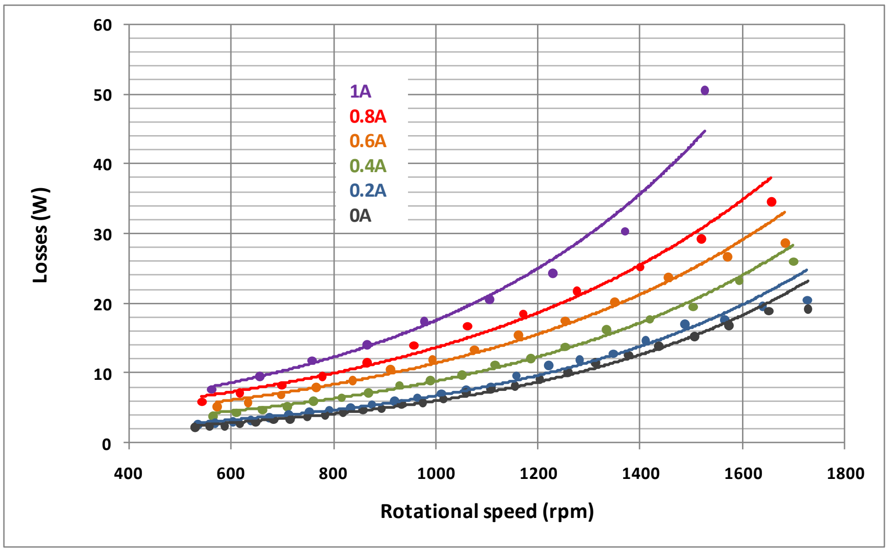

Fig. 7. Power lost at different rotations without load in deceleration and different current excitation

For each intermediate point determined experimentally, the total losses (W) were determined. As can be seen from the figure, the electrical losses are significant, greater than the mechanical ones, which suggests a first possible improvement that can be brought to the system, in order to extend the operating time to several hours. This would consist of the use of a generator with a high performancetole pack, to avoid Eddy currents as much as possible. A second improvement would be either placing the assembly in a vacuum chamber or optimizing the flywheel surface in such a way as to minimize friction with the air. A final improvement is the elimination of fan built into the generator.

For each current excitation value, the total power lost approximate expression was determined, and the results are presented in Table 3. By making the difference between the total losses with excitation current and those without current, the electrical and mechanical losses can be differentiated. Mechanical loses base on speed value and the excitation current (Table 4).

Table 3

Lost power as a function of excitation current for alternator 1

Excitation Current (A)	Power lost (W)
1	2.947*exp(0.00178*V)
0.8	2.884*exp (0.00156*V)
0.6	2.384*exp (0.001565*V)
0.4	1.654*exp (0.001677*V)
0.2	1.132*exp (0.00179*V)
0	0.942*exp (0.00186*V)

Table 4

Mechanical and electrical losses for different rotational speeds

Rotation (rpm)	Mechanical lost (W)	Electrical Lost (W)
1800	26.8	45.8
1700	22.2	38.5
1600	18.5	32.4
1500	15.3	27.2
1400	12.7	22.9
1300	10.6	19.2
1200	8.8	16.2
1100	7.3	13.6
1000	6.1	11.4
900	5.0	9.6
800	4.2	8.1
700	3.5	6.8
600	2.9	5.7
500	2.4	4.8

In order to maintain the flywheel at a certain rotation speed, the system requires a certain power input, which compensates for the total losses in that moment. By determining the currents and the voltages at the source after the flywheel was previously brought to a certain constant speed, lost compensation power needed was found, which include also the losses in the three-phase converter, Ammeter and connection wires (Fig. 8). From the voltage measured at the source terminals, to eliminate the errors due to the ripples, the voltage drop value on the used ammeter shunt was excluded (100mV / A, an ammeter with 10A at the scale ending point).

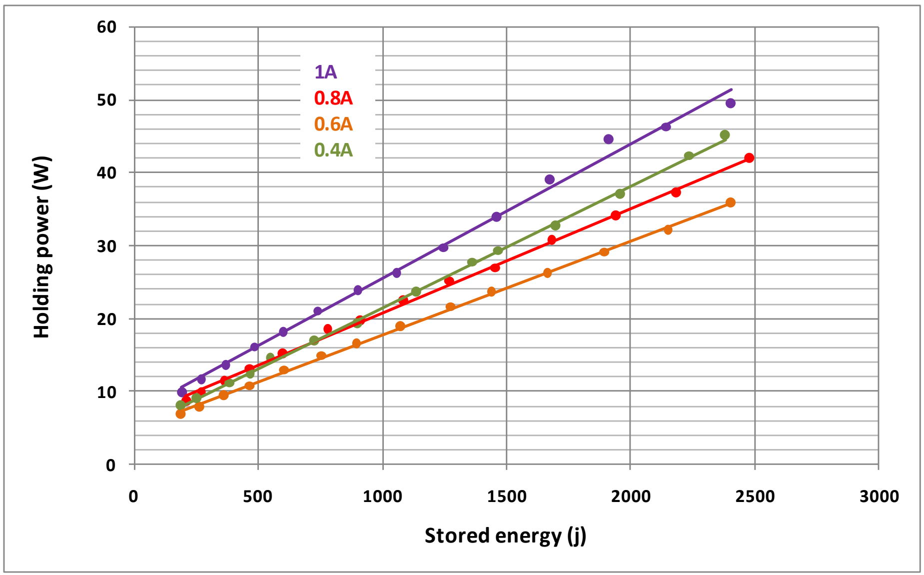

Fig. 8. Holding power as a function of the stored kinetic energy

As the excitation current decreases, the losses also decrease, which leads to a reduction of the holding power - the input power necessary for maintaining a constant rotational speed given all the losses at that particular moment, until the excitation current becomes insufficient for an efficient rotor drive (the copper and core losses increase for a given amount of torque, which eventually becomes insufficient for overcoming the friction losses), a threshold above which the losses begin to increase, a tendency which is manifested on the entire range of rotational speeds. Fig. 9 and Table 5:

Table 5

Maintaining power for different rotational speeds and excitation currents

Rotational speed (rpm)	Maintaining power(W)			
	1A	0.8A	0.6A	0.4A
500	10.4	9.1	7.2	7.9
1100	23.6	19.3	16.3	19.9
1500	37.9	30.3	26.2	32.9
1700	46.7	37.1	37.1	40.9

Fig. 9 shows extended data) show this behavior and suggest that in this configuration, an excitation current of about 0.6A leads to the highest efficiency (a lower or higher current would increase either ohmic losses or losses through Eddy currents).

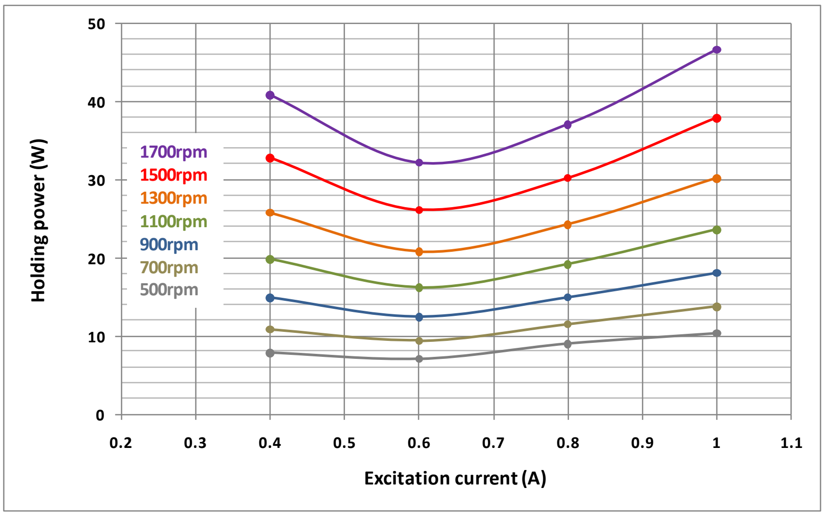

Fig. 9. Holding power as a function of excitation current for different rotational speeds

To test generator operation, in load, the flywheel was brought to certain rotational speeds, after which the three-phase converter was disconnected, and the generator was used to charge current in load resistances of known values, between 5 and 30Ω, previously determined. At each 10second interval the voltage at the load terminals and the speed of rotation were measured. Based on these results, summarized in Table 6 at 1800rpm speed, the characteristics of Fig. 10 were plotted.

Table 6

Maintaining power for different rotational speeds and excitation currents

Load resistance (Ω)	5	10	15	20	25	30
Excitation Current (A)	**Load power (W)**					
1	17.04	9.25	6.31	4.72	3.84	3.31
0.8	11.47	5.98	4.18	3.18	2.55	2.14
0.6	6.46	3.28	2.32	1.77	1.43	1.2

Using determined power and knowing energy variation in time (power) as a function of flywheel speed, the efficiency of the machine as a generator was determined for each value of the load resistance (Fig. 11), as the fraction of the mechanical energy stored in the flywheel which is actually dissipated by the load. The figure shows the significant power increase with the decrease of the load resistance due to the fact that at load resistances significantly higher than the internal resistance the generator behaves mainly as a voltage source (and the load power varies with the square of the current), as well as the fact that the flywheel slows down faster, which means that overall, the electrical and mechanical losses are smaller during the total slowing time.

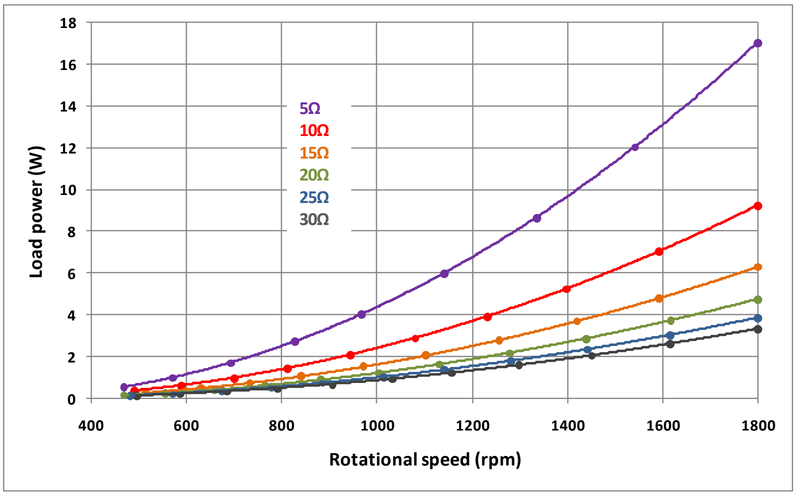

Fig. 10. Power in charge at 1A current excitation

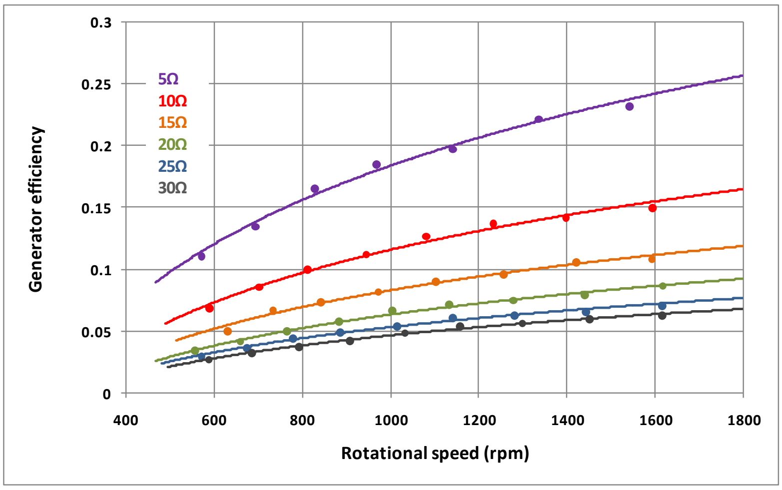

Fig. 11. Generator efficiency, depending on speed, at different load resistors, for an excitation current of 1A

b) Experimental results for Alternator 2

Being built with permanent magnets, alternator 2 does not allow control of the magnetic field of the rotor. The variation of the energy stored in the flywheel over time, without load resistance, is shown in Fig. 12. The high efficiency of the alternator itself suggests that most of the power lost to maintain the flywheel at a certain speed (Fig. 13) are by rubbing with air, and gives a first indication of the main way in which the efficiency of the system can be increased, namely by placing the whole assembly in vacuum.

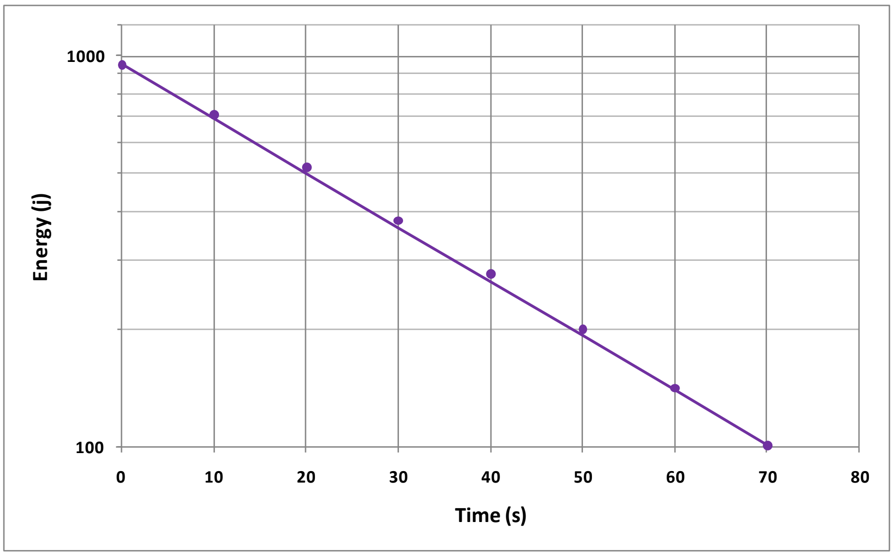

Fig. 12.The variation of the energy stored in the flywheel over time, without load resistance

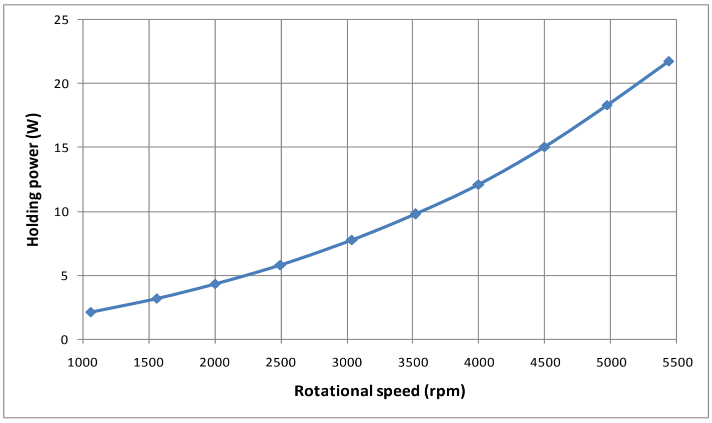

Fig. 13. Maintaining power as a function of rotational speed

The determinations in generator mode were made by bringing the flywheel to the speed of 5500 rpm, and then by cutting current in increased load resistances of 5, 10, 15 and 20 Ω, up to the speed of 1000rpm. The results are illustrated in Fig. 14. The main factor which is limiting the speed of the Flywheel was, same as alternator 1, it’s to allow safe operation with reduced vibration base on limited balance possibilities. Generation efficiency (Fig. 15) is significantly higher than Alternator 1, a difference mainly due to much smaller electrical losses. Air friction remains the main loss mechanism, mainly due to the shape of the flywheel and the longitudinal holes.

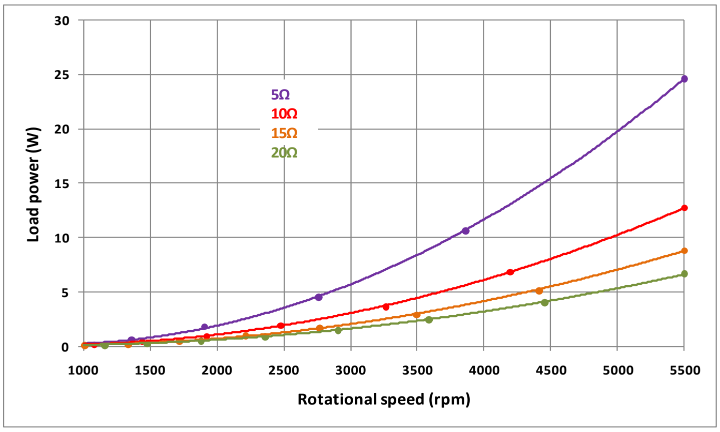

Fig. 14. Load power as a function of rotational speed for different loads

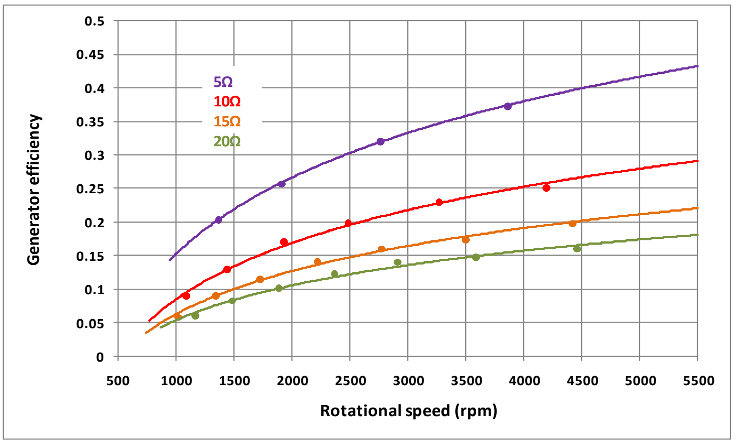

Fig. 15. Alternator 2 efficiency as a function of rotational speed for different loads

3. Conclusion

The operation of two alternator-flywheel systems has been demonstrated, and also the main features and performances being determined with low costs and handmade accessible components,

After determinations, the main limitation of the systems proposed for study can be observed:

- the power to maintain the steering wheel at a certain speed is relatively high, under the given conditions, the main reason being air friction;

- the efficiency of the systems is reduced, mainly when using high load resistances, where the duration of discharging energy from the flywheel is sufficiently large to allow a substantial and undesirable increase of all losses.

Both assemblies have been proven to be functional using low cost, affordable, high efficiency components. From the analysis of power losses it is confirmed that air friction is the main loss mechanism. Eliminating these losses allows both a more efficient operation and an increase of the working speed up to the operating limit of the alternators used. Therefore, the systems thus proposed can be improved by vacuum enclosures uses or by larger flywheels without increasing air friction.

A possible extrapolation of the results obtained for alternator 1 shows that by emptying the assembly, using quality sheets in the alternator and eliminating the classic diode bridge, the losses can be reduced by approximately 88%. In this context, adding more identical flywheels on the same shaft to total a mass of 100kg and increasing the speed to over 5000 rotations per minute, the total free slowing time, without load and without excitation current, can be extended to over 10 hours, and the holding power at less than 3W. The application is therefore suitable for domestic use for day-to-night energy storage, with substantially reduced costs and a much longer service life compared to electrochemical battery systems. In practice the system can be easily oversized, with minimal costs, the maximum energy can easily exceed the capacity of generation of renewable energy systems on a small scale.

The results obtained for alternator 2 suggest that, using the same improvements mentioned above, the application can be extended to supply sensors in isolated, inaccessible areas, allowing both the storage of energy for durations of the order of hours, and the possibility of using energy in short pulses at very high currents, in the order of tens of Amps.

R E F E R E N C E S

[1] Mustafa E. Amiryar and Keith R. Pullen - A Review of Flywheel Energy Storage System Technologies and Their Applications - Appl. Sci. 2017, 7, 286; doi:10.3390/app7030286

[2] Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. - Progress in electrical energy storage system: A critical review - Prog. Nat. Sci. 2009, 19, 291–312.

[3] Medina, P.; Bizuayehu, A.W.; Catalao, J.P.S.; Rodrigues, E.M.G.; Contreras, J. - Electrical Energy Storage Systems: Technologies' State-of-the-Art, Techno-economic Benefits and Applications Analysis - Proceedings of the 47th Hawaii International Conference on System Sciences, Waikoloa, HI, USA, 6–9 January 2014; pp. 2295–2304

[4] Vafakhah, B.; Masiala, M.; Salmon, J.; Knight, A. - Emulation of flywheel energy storage systems with a PMDC machine - Proceedings of the 18th IEEE International Conference on Electric Machines, Vilamoura, Algarve, Portugal, 6–9 September 2008; pp. 1–6.

[5] Liu, H.; Jiang, J. - Flywheel energy storage - An upswing technology for energy sustainability - Energy Build - 2007, 39, 599–604.

[6] Hebner, R.; Beno, J.; Walls, A. - Flywheel batteries come around again - IEEE Spectr. 2002, 39, 46–51
[7] Prodromidis, G., and Coutelieris, F. - Experimental and Theoretical Investigation of Flywheel -Based Energy Storage in Off-Grid Power Plants Using Renewables - Journal of Energy Engineering, 142(1)
[8] Bolund, B.; Bernhoff, H.; Leijon, M. - Flywheel energy and power storage systems - Renew. Sustain. Energy Rev. 2007, 11, 235–258
[9] Sebastián, R.; Alzola, R.P. - Flywheel energy storage systems: Review and simulation for an isolated wind power system. - Renew. Sustain. Energy Rev. 2012, 16, 6803–6813.
[10] Emadi, A.; Nasiri, A.; Bekiarov, S.B. - Uninterruptable Power Supplies and Active Filters - Illinois Institute of Technology: Chicago, IL, USA; CRC Press: Washington, DC, USA, 2005
[11] DOE/EE. Flywheel Energy Storage. - An Alternative to Batteries for Uninterruptible Power Sypply Systems - U.S Department of Energy (DOE), Energy Efficiency and Renewable Energy: Washington, DC, USA, 2003.
[12] Bender, D. - Flywheels - Sandia Report; Sandia National Laboratories: Albuquerque, ME, USA, 2015
[13] Sabihuddin, S.; Kiprakis, A.; Mueller, M. - A Numerical and Graphical Review of Energy Storage Technologies. - Energies 2014, 8, 172–216
[14] Farhadi, M.; Member, S.; Mohammed, O. - Energy Storage Technologies for High-Power Applications. - IEEE Trans. Ind. Appl. 2016, 52, 1953–1961
[15] Daoud, M.I.; Abdel-Khalik, A.S.; Massoud, A.; Ahmed, S.; Abbasy, N.H. - On The Development of Flywheel Storage Systems for Power System Applications: A Survey. - Proceedings of the 20th International Conference on Electrical Machines (ICEM), Marseille, France, 2–5 September 2012; pp. 2119–2125
[16] Kenny, B.H.; Kascak, P.E.; Jansen, R.; Dever, T. - Control of a High Speed Flywheel System for Energy Storage in Space Applications. - IEEE Trans. Ind. Appl. 2005, 41, 1029–1038
[17] Pena-Alzola, R.; Sebastián, R.; Quesada, J.; Colmenar, - A. Review of Flywheel based Energy Storage Systems. - Proceedings of the 2011 International Conference on Power Engineering, Energy and Electrical Drives, Malaga, Spain, 11–13 May 2011.
[18] Yu, Y.; Wang, Y.; Sun, F. - The Latest Development of the Motor/Generator for the Flywheel Energy Storage System. - Proceedings of the 2011 International Conference on Mechatronic Science, Electric Engineering and Computer (MEC), Jilin, China, 19–22 August 2011; pp. 1228–1232.
[19] Awadallah, M.A.; Venkatesh, B. - Energy Storage in Flywheels: An Overview - Le stockage dénergie dans les volants: Apercu. Can. J. Electr. Comput. Eng. 2015, 38, 183–193