PILOT APPLICATION OF FLYWHEELS IN RES-BASED POWER PLANTS

G. N. Prodromidis and F.A. Coutelieris

Department of Environmental & Natural Resources Management, University of Patras, Seferi 2, 30100, Agrinio, Greece, Tel: +302641074196; Fax: +30 2641074176, fcoutelieris@upatras.gr

ABSTRACT

The present study deals with the feasibility of Flywheel Energy Storage Systems (FESS) in several RES-based stand-alone electricity production systems. Energy buffering is necessary in any RES-based off-grid system, however conventional energy storage systems (batteries, hydrogen etc.) suffer from limited equipment lifetime, high initial costs, and negative environmental impact during their operation as well as after their life-cycle. This study combines the mature technology of storing kinetic energy through a flywheel, with more conventional technologies such as electrochemical batteries. Through an extensive study of existing technologies, it is proved that an off-grid project with advanced and totally "green" technologies is feasible, and of comparable cost to more conventional RES-based systems. Furthermore, this study presents general information on FESS operation in several projects.

KEYWORDS

Flywheel, Hybrid System, Energy Storage System, Renewables, Zero emissions.

1 INTRODUCTION

Over the last 20 years, the world's population has increased by approx. 1.6 billion people and is expected to rise by 1.4 billion over the next 20 years (REN21, 2011). The above trend corresponds to an analogous increment in electricity demands due to industrialization, urbanization and motorization that are strongly associated with increased energy consumption, which consequently affects the fossil fuel process. In addition, the wasteful use of fossil fuels aggravates climate change due to continuous environmental pollution. The efficiency of energy production processes as well as the optimal adjustment between the load coverage and the consumption of specific parts of a stand-alone power system is crucial to eliminate energy waste. Therefore, the use of Renewable Energy Sources (RES), which are usually characterized by efficient energy conversion cycles, is further strengthened.

An attractive option towards optimization of global electrification in terms of environmentally friendly solutions is the development of off-grid supplied electricity systems. These hybrid systems are characterized by zero pollutant emissions and the lack of excessive operation and maintenance costs. Such systems are currently established in isolated remote areas for rural electrification where connection to the national grid is difficult and expensive (Bekele and Tadesse, 2012). During the last decades, renewable technologies such as photovoltaic panels/arrays (PVs) and wind turbines became popular in projects providing electricity to several one-way, grid connected and autonomous power plants up to 10kW.

The main drawback characterizing all RES-based autonomous systems is that the environmental energy potential is quite unpredictable since it fluctuates with time and is strongly dependent on local meteorological conditions (Prodromidis and Coutelieris, 2011). Temporary energy buffering in storage systems is crucial for an uninterruptable energy supply, especially for standalone RES-based systems. Besides the well-known electrochemical batteries, numerous buffering technologies are used in mobile or medium-scale applications such as hydrogen technologies, super capacitors and compressed air pumps (Wang et al., 2013). To conclude, the development a low-cost, state-of-the-art eco-friendly device, which can be charged and discharged several times with high efficiency and has stable performance during a project's lifetime, is crucial for the total commercialization of buffering technologies based on RES. To this end, flywheels appear to provide a feasible solution, since they have numerous advantages compared to other technologies such as electrochemical batteries and hydrogen-based equipment. Their long lifespan is one of their main advantages as they can be charged and discharged at high rates for many cycles without efficiency losses. Their efficiencies are quite high (Liu and Jiang, 2007) while they can be connected either to an AC-bus, offering a huge variety of frequencies, or a DC-bus depending on the demands of the established hybrid system to cover the desirable load (Bolund et al. 2007). Drawbacks of such a solution include limited storage times as a significant percentage of commercialized flywheel stored capacity is wasted through the marvel of self-discharge. In optimum operation conditions (magnetic bearings, vacuum enclosed device, etc.), these rates are found to be in the range of 0.18 to 2.0 times stored capacity per hour (Farret and Simoes, 2006). These values are valid for very low friction losses and are significantly higher in real-life scenarios. This phenomenon can be reduced by using state-of-the-art construction materials such as carbon fibres, or by the combined use of more conventional technologies. However, this does increase the cost of such an installation dramatically, therefore the combination of different technologies prevents a more suitable solution for real-life RES-based systems.

This paper focuses on the involvement of renewable sources in off-grid systems, which constitute the starting point for the inclusion of off-grid supplied electricity into real-life projects. The current trends on designing an FESS and its implementation into an RES-based autonomous system are also discussed.

2 MATERIALS & METHODS

A laboratory-scale FES system was designed and constructed by using an electric motor of 1hp that would be fed by the excess energy from RES technologies when the environmental potential fluctuates at high levels. This electric energy is transformed into kinetic energy and stored in a rotational mass. By following the reverse path it can be given back to the system via the electric motor, acting as an alternator. The power of the specific motor is determined by the power of the battery (approx. 660W) and by the rotational speed (peak at approx. 1800rpm≈188.5rad/sec). Measured without load, the angular velocity was found higher than that given by the manufacturer because the standard value of 1800 rpm corresponds to standard supply voltage under the manufacturer's standard conditions, not attained in laboratory experiments. Here after, the higher rotational velocity is the experimental velocity (approx. 2150 rpm), measured under 12 V DC continuous supply without loads on the motor.

Several problems had to be overcome during the construction of the experimental FES system, mostly concerning the solidity of the rotational parts and the stability of the whole project. Numerous small-sized parts were designed from scratch. All the apparatus is presented in Fig. 1 and described in Table 1


(a)


b.


c.

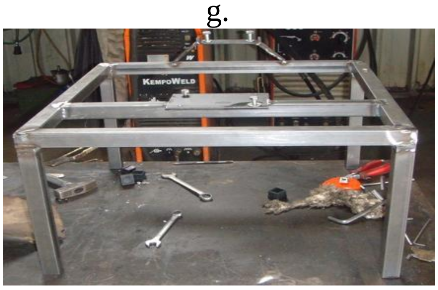

d.


e.


f.


g.


h.



i.

Figure 1: The experimental apparatus (a) and its specific parts: (b) electric motor, (c) axle, (d) electromagnetic clutch, (e) roller bearings with housing, (f) adapter for axle, (g) adapter for rotational mass, (h) steel base, (i) frame.

Table 1: Description of the parts of the established FES system.

Parts	Description	Quantity
Axle	Aluminum, 15 cm long, supports the rotational mass.	1
Bearing housing	Steel case, oil lubricated for the roller bearing at the end of the axle which is supported on the frame.	1
Adapters	Aluminum, one to adapt the clutch to the motor's axle and one to permanently connect the rotational mass with the axle.	2
Electromagnetic clutch	Mayr ROBATIC, 24V, 20W and 20 Nm. Engages the rotational mass when appropriate.	1
Roller bearing	Diameter of 0.02 m. Responsible for reducing friction losses during rotation.	2
Rotational mass	Stores the kinetic energy from the electric motor; inner radius: 0.19m, outer radius: 0.25m, mass: 1.8kg, thickness: 0.005m and 8 connecting radii included.	1
Steel base	Mounted onto the electric motor to keep the outer housing of the clutch stable for the rotation of its internals.	1
Voltage source	Fed by the grid and offers 24V to the clutch during its engagement to the system: Phoenix Contact, 100V-240V AC input, 22.5-29.5V DC output.	1

Given the 1 hp electric motor, it is easy to calculate the torque provided at maximum power, which is approx. 3.956Nm. Two layouts (solid and hollow cylinder) and two different materials (steel and aluminium) have been taken into account for the simulations (see Table 2). It was found that the best option is the hollow aluminium rotational mass, presented in detail in Fig. 2, while the differences observed between the ideal mass and the constructed one can be attributed to safety reasons (avoid damage due to vibrations). One of the fundamental differences is the number and size of the connecting radii (eight instead of the four initially designed). This design eliminates the distortion of the rotational mass during rotation due to its higher thickness. The mass of the final construction was 0.700 kg heavier than the ideal because the adapter is also included with the axle.

Table 2: Ideal vs. constructed rotational mass.

Motor info				
P_{motor} (W)	745.69			
ω (rad/sec)	188.5			
Rotational mass	**Solid steel**	**Solid aluminum**	**Hollow steel**	**Hollow aluminium**
R_{max} (m)	0.215	0.310	0.270	0.380
R_{min} (m)	-	-	0.235	0.325
m (kg)	1.940	1.390	1.600	1.070
ω_{rot} (rad/sec)	181.88	176.95	181.99	187.50
L (m)	0.0017			
Operational results				
$E_{kinetic}$ (Wh)	0.207	0.290	0.317	0.473
I (kg m^2)	0.045	0.067	0.069	0.097
n (%)	0.0278	0.0389	0.0425	0.0634

a. b.

Figure 2: The rotational mass: (a) design, (b) construction.

3 THEORETICAL AND EXPERIMENTAL RESULTS & DISCUSSION

In the present study, the efficiency is calculated by dividing the mean energy stored in a specific time interval by the energy consumed by the electric motor in the same period. This magnitude depends on the time-scale of the whole process since, in a flywheel system, the duration of the rotational motion of the cylindrical mass is a crucial parameter for the estimation of the system's efficiency. For the optimal case of Table 2, the value of 0.0634% corresponds to a one-hour time-scale while the flywheel can be rotated for less than one minute. This very low percentage can be increased by changing the rotational time taken into account to calculate the efficiency of an FES system. By decreasing the time step of charging, the energy consumed by the electric motor can be directly comparable to that given back to system through the reverse path by the rotation of the mass.

Table 3: Experimental measurements.

t (sec)	ω(rad/sec)	E_{FES} (kWh)	Mean E_{FES} (kWh)	$E_{consumed}$ (kWh) $\left[=\frac{745.69}{3600}t\right]$	n (%) $\left[\frac{\text{Mean } E_{FES}}{E_{consumed}}\right]$
1	199.77	0.000357		0.000207	
2	194.05	0.000337	0.000347	0.000414	83.78
3	186.97	0.000313	0.000336	0.000622	54.02
4	179.49	0.000288	0.000324	0.000829	39.09
5	172.11	0.000265	0.000312	0.001036	30.13
6	164.94	0.000244	0.000301	0.001243	24.19
7	158.26	0.000224	0.000290	0.001450	19.98
8	151.86	0.000207	0.000279	0.001658	16.86
9	145.75	0.000190	0.000270	0.001865	14.45
10	140.58	0.000177	0.000260	0.002072	12.56
11	136.01	0.000166	0.000252	0.002279	11.04
12	131.20	0.000154	0.000244	0.002487	9.79
13	126.52	0.000143	0.000236	0.002694	8.75

The experimental process demonstrates that an FES system is capable of being rotated for a couple of seconds and then it stops due to friction losses because the apparatus is not vacuum-enclosed. In addition, the whole rotation of the axle is based on typical roller bearings with high friction losses compared to electromagnetic bearings. The efficiencies ranged between 83.78% and 8.75% and the operational time fluctuated from 2 to 13 sec (Table 3), although the flywheel can be rotated for 40 sec due to the moment of inertia. The analysis is meaningless for such long time periods because the angular velocity of the flywheel decreases under 126.5 rad/sec for t>13 sec, thus the motor can return voltages lower than 12V. The time-dependent efficiency (last column in Table 3), could be improved by the use of an electric motor of higher angular velocity consuming the same amount of energy.

4 CONCLUSIONS

In this study, an FES system was simulated under different scenarios, and one of which (laboratory-scale) was implemented to validate the theoretical analysis. This process revealed the outstanding characteristics of flywheels during their operation. More precisely, two different materials and shapes were simulated for the rotational mass. It is proved that a hollow aluminium cylindrical mass is the preferable option since it can give better energy storage results. This mass shape was included into the experimental apparatus, designed and built to validate the theoretical results. As efficiency decreases rapidly with time due to friction losses, such an FES system can rival competitive storage technologies widely available on the market, but only for applications that use a storage energy bank to support a system for a very short-time during its operation or to cover a peak load for a limited time during a single day such as UPSs.

5 REFERENCES

Bekele, G., Tadesse, G. (2012). Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. *Applied Energy*, 97, 5-15.

Bolund, B., Bernhoff, H., Leijon, M. (2007). Flywheel energy and power storage systems. *Renewable and Sustainable Energy Reviews*, 11, 235-258.

Farret, F.A., Simoes, M.G. (2006). *Integration of Alternative Sources of Energy*. New York: John Wiley & Sons.

Liu, H., Jiang, J. (2007). Flywheel energy storage-An upswing technology for energy sustainability. *Energy and Buildings*, 39, 599-604.

Prodromidis, G.N., Coutelieris, F.A. (2011). A comparative feasibility study of stand-alone and grid connected RES-based systems in several Greek Islands. *Renewable Energy*, 36, 1957-63.

REN21 Steering Committee (2011). *Renewables 2011 Global Status Report*. www.REN21.net

Wang, Y., Ronilaya, F., Chen, X., Roskilly, A.P. (2013). Modelling and simulation of a distributed power generation system with energy storage to meet dynamic household electricity demand. *Applied Thermal Engineering*, 50, 523-535.