ELECTRIC GENERATOR POWERED BY A GYROSCOPIC SYSTEM - A THEORETICAL APPROACH

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Abstract: *The development of our society now depends on electrical energy and the demand for electrical power increases yearly. Due to the vast amount of carbon dioxide released in the atmosphere by conventional power plants and the negative influence on the climate, new ways of producing electricity must be developed. A gyroscope consists of a spinning flywheel of mass m mounted in a suspension frame that allows the flywheel's axle to point in any direction. In this analysis, one end of the axle is supported by a pylon situated at a distance R from the center of mass of the spinning flywheel. In order to generate electrical energy at this low speed, the same approach should be used as in wind power electrical generators. In this case, the wind and propeller are substituted by a gyroscopic system and gravitational attraction. Based on the conservation of angular momentum, the gravitational attraction can be used to create a precession strong enough to provide the energy and torque necessary to activate an electric generator similar to those in wind power generators. Instead of recovering the energy from this kinetic energy, we can use the precession rotation created by gravitational attraction to create the necessary kinetic energy.*

Keywords: *flywheel, gyroscope, kinetic energy storage, precession*

1. INTRODUCTION

Nowadays the development of our society depends on electrical energy and the demand of electrical energy increases year by year. Due to the vast amount of carbon dioxide released in the atmosphere by conventional power plants and the negative influence on the climate, new ways of producing electricity must be developed. The renewable energy sources based mostly on wind power, solar power and hydroelectricity rely on climate and weather to work effectively [1].

For this reason, these renewable energy sources may exhibit large fluctuations in power output. In order to become reliable as primary sources of energy, energy storage is a crucial factor. Electrical Energy Storage (EES) refers to a process of converting electrical energy into a form that can be stored for converting back to electrical energy when needed [2].

These technologies open the way to producing, storing and consuming electrical energy locally. One direct result is the increased mobility based on electric energy. Along the years, several solutions for EES were developed. Because electricity is not easy to be directly stored, it can be stored in other forms and converted back to electricity when needed. EES technologies can be classified according to the form of storage into the following:

Chemical Energy Storage: *Electrochemical energy storage*: conventional batteries (lead-acid, nickel metal hydride, lithium ion), flow-cell batteries (zinc bromine and vanadium redox). *Chemical energy storage*: fuel cells, molten-carbonate fuel cells and metal-air batteries. *Thermochemical energy storage*: solar hydrogen, solar metal, solar ammonia dissociation–recombination and solar methane dissociation–recombination.

Thermal Energy Storage: *Low temperature energy storage*: aquifers cold energy storage, cryogenic energy storage. *High temperature energy storage*: steam or hot water accumulators, graphite, hot rocks and concrete.

Electrical Energy Storage: *Electrostatic energy storage*: capacitors and supercapacitors. *Magnetic/current energy storage*: superconducting magnetic energy storage.

Mechanical Energy Storage: *Kinetic energy storage*: flywheels. *Potential energy storage*: Pumped hydro storage, compressed air energy storage. [1,3]

2. MECHANICAL ENERGY STORAGE

A flywheel is a mechanical storage device which converts electrical energy to mechanical energy. The electrical energy is stored in the form of rotational kinetic energy based on the rotating mass principle. A spinning cylinder or disc is used to store rotational kinetic energy and when is needed this energy is used to regenerate electrical energy. The amount of rotational kinetic energy stored is calculated with following equation,

$$E_k = \frac{1}{2} I \omega^2 \tag{1}$$

Where I is the moment of inertia and ω is the angular velocity. The moment of inertia is a function of its shape and mass, given by equation,

$$dI = dmr^2 \tag{2}$$

$$I = \int x^2 dm_x \tag{3}$$

Where x is distance from the rotational axis to the differential mass dm_x.

According with equation 1 the most efficient way to increase the amount of stored energy is by increasing rotational speed ω.

If we double the flywheel’s speed, the amount of stored energy increases by four times. Because a flywheel speeds up as it stores energy and slows down when it is discharging, to deliver the accumulated energy, results the useful energy depend on minimum and maximum of angular velocity according with the following equation [4-6],

$$E_k = \frac{1}{2} I (\omega_{max}^2 - \omega_{min}^2) \tag{4}$$

For a solid cylinder or disc-type rotating mass, the moment of inertia is given by:

$$I = \frac{1}{2} mr^2 \tag{5}$$

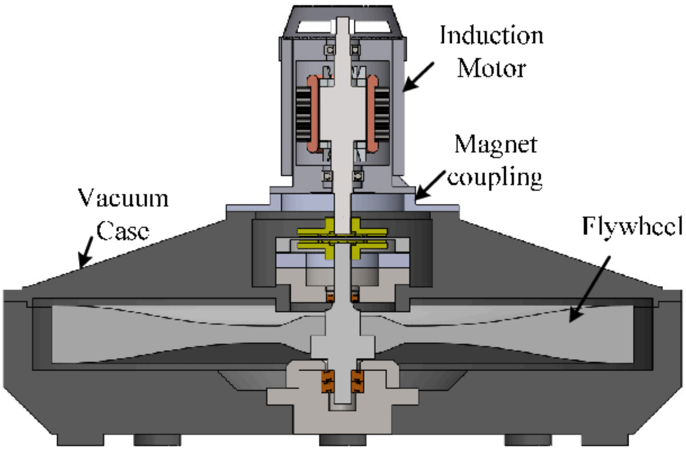

FIG. 1 Flywheel [7]

The amount of energy which can be stored in a flywheel is limited by the maximum speed at the rotor can operate because of the strength of material. In order to operate in a safety zone, the stress experienced by the rotor must remain below the strength of the rotor material. Nowadays the flywheels are used for frequency regulation, trackside energy recovery, electromagnetic aircraft launch, uninterruptible power supplies, motorsport and spacecraft.

All these applications prove the fact the flywheel can easily convert electric energy into rotational kinetic energy, store kinetic energy for long period of time without significant losses and release this energy as electrical energy when is needed. In all presented applications the time of releasing energy is relatively short between 1s to 1 hour with an efficiency between 85-95%. In this paper I am looking for a way to increase the discharging time and to keep the other advantages.

On the other hands the mechanical energy storage based on potential energy like pumped hydro has a discharge time between 6-24 hours and efficiency between 65-85%.

~~A~~ pumped hydro power energy storage consists of two water reservoirs located on different altitudes. The electricity is used to pump water from the lower altitude reservoir to the higher altitude reservoir. The electrical energy is converted into potential energy stored, and converted by a hydroelectric turbine back into electrical energy.

The quantity of stored energy depends on the volume of water in the upper reservoir and the differential height of between the two reservoirs. In this paper I am looking for a way to harvest the gravitational attraction in a more efficient way. This goal can be achieved if we combine the kinetic energy storage with gravitational attraction to obtain a new system based on gyroscope theory and torque-induced regular precession.

3. GYROSCOPE THEORY

A gyroscope consists of a spinning flywheel of mass *m* mounted in a suspension frame that allows the flywheel's axle to point in any direction. One end of the axle is supported on a pylon in point O at distance *R* from the center of mass G of the spinning flywheel.

The flywheel is spinning around Ox axis with a spin angular velocity ω_{gyr}. When the gyroscope is released the center of mass rotates around a vertical axis Oy with a precession angular velocity ω_{pr}.

This movement occur when the magnitude of the precession angular velocity is much less than the magnitude of spin angular velocity, $\omega_{pr} << \omega_{gyr}$. This assumption is collectively called the gyroscopic approximation [8,9].

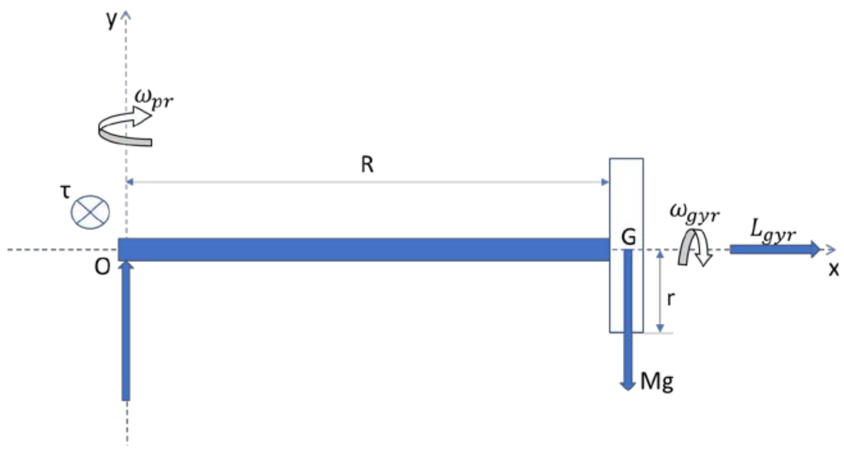

FIG.2 Gyroscope torque-induced regular precession

$$\omega_{pr} = \frac{\tau_{gyr}}{L_{gyr}} = \frac{MgR}{I_{gyr}\,\omega_{gyr}} \tag{6}$$

Where:

- M is the mass of precession equal with total mass which create the torque τ_{gyr}, $M = m + m_{aditional}$.
- m is the mass of flywheel.
- $m_{aditional}$ is used to increase the torque in order to obtain a desired precession angular velocity. For the spinning flywheel is used a disc-type rotating mass of radius r.
- L_{gyr} is angular momentum of flywheel.

Equation 6 can be written:

$$\omega_{pr} = \frac{MgR}{I_{gyr}\,\omega_{gyr}} = \frac{MgR}{\frac{1}{2}mr^2\omega_{gyr}} = \frac{2g}{\omega_{gyr}}\frac{M}{m}\frac{R}{r^2} \tag{7}$$

For my further analyses I assume all frictional forces acting on point O are friction forces from precession and all frictional forces acting on point G are friction forces from flywheel.

The kinetic energy of precession can be calculated with following equation:

$$E_{kpr} = \frac{1}{2}I_{pr}\,\omega_{pr}^2 = \frac{1}{2}MR^2\omega_{pr}^2 = \frac{2g^2}{\omega_{gyr}^2}m\frac{M^3}{m^3}\frac{R^4}{r^4} \tag{8}$$

a) Let investigate the case when the values of friction forces is zero.

The system will maintain the flywheel speed and precession movement as long as the gravitational attraction exists. From (7) result the product between precession angular velocity ω_{pr} and spin angular velocity ω_{gyr} is constant.

$$\omega_{pr}\,\omega_{gyr} = \frac{2MgR}{mr^2} \tag{9}$$

Also, the product between kinetic energy of precession E_{kpr} and kinetic energy of flywheel E_{kfly} is constant.

$$E_{kfly}\,E_{kpr} = R^4\frac{M^3g^2}{4mr^2} \tag{10}$$

In order to analyze some characteristics of a gyroscope I will use pictures from well know demonstrations with gyroscope available on YouTube. I used this unconventional approach to offer the possibility to verify more rapidly my affirmations.

First, the precession rotation of a gyroscope creates centrifugal forces acting in the same way like in other rotation.

FIG.3 Centrifugal forces during precession

In one of his demonstration Professor Eric Laithwaite hang a gyroscope using a rope [10]. In the left side of fig. 3 picture inside the arrow is the position of rope without gyroscope. In the right side of picture, the rope with gyroscope create an angle relative with initial position. In presented video we can observe the gyroscope start from vertical position and without external forces create an angle with vertical. This angle is created by centrifugal forces created during precession rotation.

b) Let investigate the case when the friction forces of precession are zero and the friction forces of flywheel are non-zero.

Due to the friction the flywheel spin ω_{gyr} value decrease. According with (7) the precession angular velocity value should increase and the value of kinetic energy of precession should increase. The angle between precession axe Oy and flywheel rotation axe Ox should remain the same.

Because the kinetic energy of flywheel was decreased due to friction the kinetic energy of precession cannot increase because no energy was added to the system.

In order to maintain the same value of kinetic energy of precession the angle α should be created as in the fig. 4. This angle can be clockwise as in fig. 4 or counterclockwise, above Ox axe. The kinetic energy of precession around point O before flywheel loses spin can be calculated with (8).

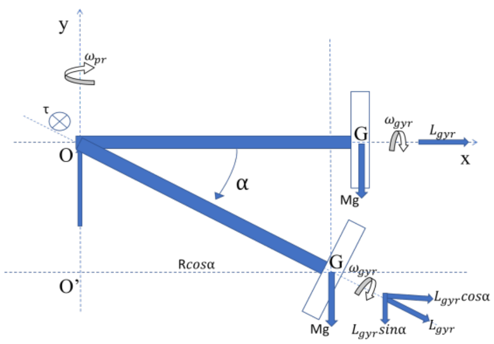

FIG.4 The angle α

The kinetic energy of precession around point O’ after flywheel loses spin is:

$$E_{kpr\,1} = \frac{1}{2} I_{pr}\, \omega_{pr\,1}^2 = \frac{1}{2} M R^2 cos^2 \alpha \omega_{pr\,1}^2 \tag{11}$$

Because the value of kinetic energy of precession must be the same $E_{kpr} = E_{kpr\,1}$, result:

$$cos\alpha = \frac{\omega_{pr}}{\omega_{pr\,1}} \tag{12}$$

The precession angular velocity ω_{pr1} around point O’ should be calculated with:

$$\omega_{pr\,1} = \frac{MgRcos\alpha}{L_{gyr}\, cos\alpha} = \frac{MgR}{\frac{1}{2} m r^2 \omega_{gyr\,1}} = \frac{2g}{\omega_{gyr\,1}} \frac{M}{m} \frac{R}{r^2} \tag{13}$$

The precession angular velocity does not depend by angle α. In this case (10) become:

$$E_{kfly}\, E_{kpr} = R^4 \frac{M^3 g^2}{m r^2} cos^4 \alpha \tag{14}$$

These theoretical results are proved by the following experiments.

In other demonstration the gyroscope has an upward movement during prece ssion [11]. In the left side of picture from fig. 5 the gyroscope start precession from an angle α between rotation axe of flywheel and horizontal axe. This angle increase in time as is showed in the right side of picture. During precession, a force appear to push the gyroscope to vertical position.

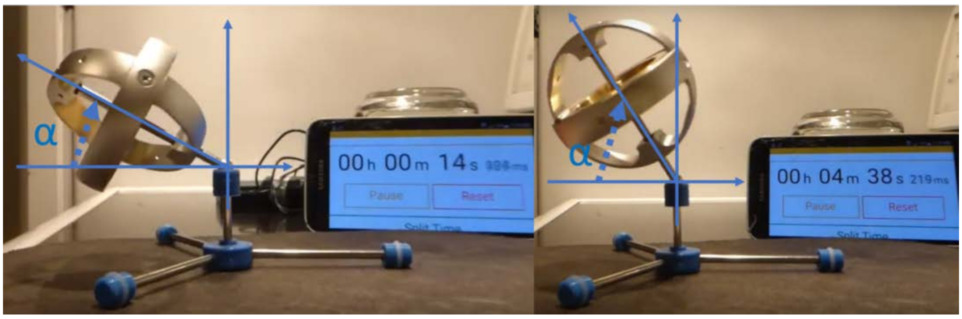

FIG.5 Upward movement during precession

In the following demonstration the gyroscope has a downward movement during precession [12]. In the left side of picture from fig. 6 rotation axe of flywheel is almost horizontal. In the right side of picture, the rotation axe of flywheel creates an angle with horizontal. During precession, a force should push the gyroscope down and is not the weight of gyroscope. In fact, in both demonstrations the system just conserves the energy and decreases the angle between axe of rotation of gyroscope and vertical axe. Let call this angle α. When the $\alpha=90^0$ results cosα=0 and the precession angular velocity $\omega_{pr} = 0$ (no precession).

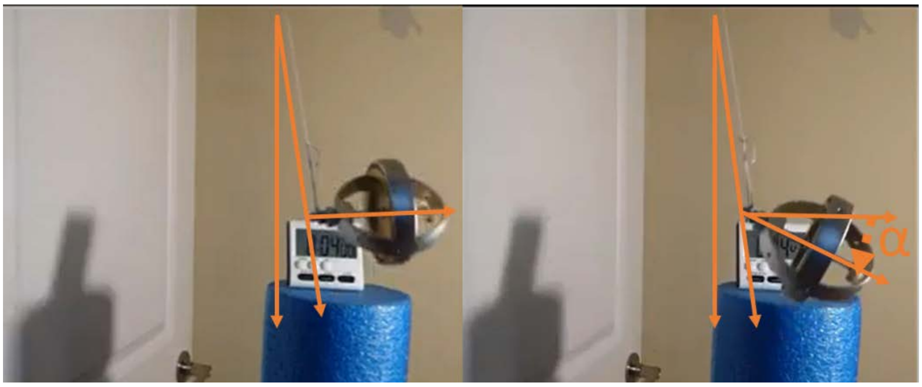

FIG.6 Downward movement during precession

Let assume the flywheel spin is maintained constant and the precession angular velocity is increased with external energy. The kinetic energy of precession adjust his value by changing the angle α.

In fig. 7 is presented this behavior of gyroscope [10]. This time in the right side of the picture the rotation axe of flywheel create an angle with horizontal axe. In the left side of the picture an external energy is added by Professor Eric Laithwaite. As a result, the angle between the rotation axe of flywheel and horizontal axe increase from below horizontal axe to above horizontal axe.

FIG.7 Precession with external energy

From these three experiments we can observe the gyroscopic system conserve the entire energy by changing the value of angle α. Results, if the kinetic energy of precession is decreased the system will conserve the entire energy by changing the value of angle α.

In a Table 1 I give some values to gyroscope in order to match the values of gyroscope from fig. 7 based only with visual approximation to find the ratio between different parameters.

Table 1. Gyroscope parameters

Parameter	Symbol	Value	SI unit
Mass of flywheel	m	10	kg
Mass of precession	M	10	kg
Flywheel radius	r	0.2	m
Precession radius	R	1	m
Flywheel angular velocity	ω_{gyr}	500	rad/s

Based on these parameters and (6) the precession angular velocity is ω_{pr}=0.98 rad/s. The result obey the gyroscopic approximation 0.98<<500. The kinetic energy of precession is E_{kpr}=4.8 J. If we compare this value with the value of the kinetic energy of flywheel E_{kfly}=25,000 J we obtain a ratio of E_{kfly}/E_{kpr}=5,199.55. This low value of kinetic energy of precession can easily create a false impression of non-existence of kinetic energy of precession. Despite the fact the dimensions of our gyroscope are not the same as in this experiment the value of kinetic energy of precession is incredibly low. For this reason, compared with the mass of flywheel 10 kg which is hard to rise with one hand, it is quite easy to increase the precession angular velocity and to rise the flywheel when is spinning using only two fingers.

c) Let investigate the case when the friction forces of precession are non-zero and the friction forces of flywheel are zero or the spin of flywheel is kept constant.

The friction forces create a lose energy which decrease the value of kinetic energy of precession. Let assume the friction forces are dumping forces and the kinetic energy of precession decrease because of these forces. If we reduce the friction forces close to zero, we can use this energy to rotate the shaft of an electric generator as utile energy.

In order to conserve the energy, the system will increase the angle α. If the value of utile energy is to high the angle α increase up to 90 degrease and the precession disappear and E_{kpr}=0. For our application I decided the angle α will increase up to 60 degrease only. The equation 14 becomes:

$$E_{kfly}\,(E_{kpr} - E_{util}) = R^4\frac{M^3g^2}{mr^2}cos^4\alpha \tag{15}$$

$$E_{util} = 180.346\left(\frac{M}{m}\right)^3\left(\frac{R}{r}\right)^4\frac{m}{\omega_{fly}^2} \tag{16}$$

4. ELECTRIC GENERATOR POWERED BY A GYROSCOPIC SYSTEM – DIMENSIONAL ANALYSES

Based on the same assumption used in a flywheel it is possible to recover the kinetic energy of precession back to electrical energy. Because of gyroscopic approximation, the precession angular velocity has a low magnitude. For this analysis we consider ω_{gyr}/ω_{pr}=2500.

In order to generate electrical energy at this low speed we should use the same approach as in wind power electric generator [13]. In this case the wind and propeller are substituted by gyroscopic system and gravitational attraction.

The precession speed can be increased by a gearbox up to a speed requested by electrical generator to work. In this way we can store the electrical energy in mechanical energy as kinetic energy of gyroscope flywheel and to harvest the gravitational attraction to produce electrical energy. This system can work as long as gyroscopic approximation is maintained.

Because the angular momentum is conserved, the spin of flywheel decrease only because of friction forces, so we only need a small amount of energy to keep the gyroscopic flywheel rotate at certain angular velocity.

Basically, this system transforms gravitational attraction into electrical energy. In this section we will calculate the dimensions of a gyroscopic system able to power an electric generator with the parameters presented in Table 2:

Table 2. Electric generator parameters

Parameter	Symbol	Value	SI unit
Power	P_{gen}	20000	W
Efficiency	η_{gen}	0.95	-
Speed	n_{gen}	250	RPM
Torque	τ_{gen}	800	Nm

This generator is mechanically connected with a gearbox. The parameters of the gearbox are presented in Table 3:

Table 3. Gearbox parameters

Parameter	Symbol	Value	SI unit
Output Power	P_{out}	21,052.63	W
Input Power	P_{in}	23,391.81	W
Efficiency	η	0.9	-
Output Speed	n_{out}	256	RPM
Input Speed	n_{in}	16	RPM
Output Torque	τ_{out}	800	Nm
Input Torque	τ_{in}	14,222.22	Nm

The required energy from gyroscopic system is:

$$E_{kin} = P_{in}t = 23{,}391.81 \cdot 1 = 23{,}391.81\,J \tag{17}$$

In order to maintain the precession rotation, the value of α is limited to 60^0. The value of utile energy should be the same as in (17).

I solved (16) based on the gyroscopic approximation ω_{gyr}/ω_{pr}=2500 for the following values: r=0.4 m; R=3 m and M=20*m. From (16) results the value of m=100 kg.

With (7) I calculated the spin angular velocity of flywheel ω_{gyr}=4,279.65 rad/s; n_{gyr}=40,870.63 RPM and angular velocity of precession ω_{pr}=1.72 rad/s; n_{pr}=16.42 RPM.

The kinetic energy created by precession is:

$$E_{kpr} = \frac{1}{2}MR^2\omega_{pr}^2 = 26{,}586.9\,J \tag{18}$$

From this we use the kinetic energy applied at the input of the gearbox E_{util}=23,678.236 J. As a result, the angle α increases from 0 to 60 degrees.

The value of torque produced by precession can be calculated with (19). The value is 14,497.84 Nm higher than required value 14,222.22 Nm:

$$\tau_{pr} = \frac{P_{util}}{\omega_{pr}} \tag{19}$$

The flywheel under gravitational attraction creates precession rotation as long as gyroscopic approximations are maintained. The kinetic energy and torque is strong enough to power a gearbox which increase the rotation up to the value required by electric generator.

The electric generator produces electricity as long as precession exists. Because the value of angular momentum of flywheel does not change because of precession the rotation will be maintained as long as frictions forces are compensate or canceled. A part of the electric energy produced can be used to maintain the value of spin angular velocity ω_{gyr}.

The system do not create electric energy from nothing but harvest the gravitational attraction in a much efficient way than actual potential energy storage systems. The main advantage of this system is the ability to produce a certain amount of electric energy without a limit of time.

CONCLUSIONS

Based on the conservation of angular momentum we can use the gravitational attraction to create precession rotation strong enough to provide the energy and torque necessary to activate an electric generator similar like in wind power generator.

The electric energy stored as kinetic energy in gyroscopic flywheel is E_{kfly}=146,523,000 J. and the ratio between E_{kfly}/E_{kpr}=5,511.098.

Instead to recover the energy from flywheel kinetic energy we can use the precession created by gravitational attraction to create necessary kinetic energy. The system is working as long as gyroscopic approximation is maintained and this time can be exceptionally long.

In this paper I didn't analyzed if this solution is efficient from an economic point of view, my intention was to prove if it possible to use a gyroscopic system to produce electrical energy and what are the dimensions of a gyroscopic system able to produce a certain amount of electrical energy. The optimization of dimensions of gyroscopic system based on desired output will be the subject of my future work.

REFERENCES

[1] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, Overview of current and future energy storage technologies for electric power applications, *Renewable and Sustainable Energy Reviews*, Volume 13, Issues 6–7, 2009, Pages 1513-1522, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2008.09.028;

[2] H. Chen, T. Ngoc Cong, W. Yang, C. Tan, Y. Li, Y. Ding, Progress in electrical energy storage system: A critical review, *Progress in Natural Science*, Volume 19, Issue 3, 2009, Pages 291-312, ISSN 1002-0071, https://doi.org/10.1016/j.pnsc.2008.07.014;

[3] E. O. Ogunniyi and H. Pienaar, Overview of battery energy storage system advancement for renewable (photovoltaic) energy applications, *2017 International Conference on the Domestic Use of Energy (DUE)*, pp. 233-239. https://doi.org/10.23919/DUE.2017.7931849;

[4] A. Tawfiq, The Flywheel Energy Storage System: A Conceptual Study, Design, and Applications in Modern Power Systems. *International Journal of Electrical Energy*. 2014, 10.12720/ijoee.2.2.146-153;

[5] M. Hedlund, J. Lundin, J. De Santiago, J. Abrahamsson, H. Bernhoff, Flywheel Energy Storage for Automotive Applications. *Energies*, Issue 8, ISSN 10636-10663, 2015. doi:10.3390/en81010636;

[6] A. Mustafa & K. Pullen, A Review of Flywheel Energy Storage System Technologies and Their Applications. *Applied Sciences*. 7. 286. 10.3390/app7030286. 2017;

[7] J. Itoh, T. Nagano, K. Tanaka, K. Orikawa and N. Yamada, Development of flywheel energy storage system with multiple parallel drives, *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Pittsburgh, PA, 2014, pp. 4568-4575.doi: 10.1109/ECCE.2014.6954026;

[8] U. Ryspek, Properties of Inertial Torques Acting on Gyroscopes. *Robot Autom Eng J*. 2018; 2(4): 555593. DOI: 10.19080/RAEJ.2018.02.555593;

[9] H. Eckardt, The Gyroscope Fully Understood: Complete Gyroscopic Motion with External Torque, *atomic precision*, 2018, https://www.upitec.org/UFT/UFT_396.pdf;

[10] Christmas Lecture given by Eric Laithwaite at Royal Institution in 1974 about gyroscope behavior. Available: https://www.youtube.com/watch?v=0L2YAU-jmcE&t=2187s;

[11] Gyroscopes precess upwards on Low Friction & Rotating Surfaces, Available: https://www.youtube.com/watch?v=mPCZbJHWZB0&list=FLKZUrRcD4As6XLZG-lo3jmw&index=8;

[12] Gyroscopes on a String, Available: https://www.youtube.com/watch?v=_Opx_rkrDK4&list=FLKZUrRcD4As6XLZG-lo3jmw&index=1;

[13] J. G. Slootweg, H. Polinder and W. L. Kling, Representing wind turbine electrical generating systems in fundamental frequency simulations, in *IEEE Transactions on Energy Conversion*, vol. 18, no. 4, pp. 516-524, Dec. 2003. doi: 10.1109/TEC.2003.816593.