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Modelling Optimal Energy Storage for Wind Turbines Using Flywheels

Mohamed M. Alhneaish[1], lutfeya A. almagguz[2], Ali A. Alshommaki[3]

[1]Mohamed.alhneaish@sabu.edu.ly, [2]lutfeya.almaggus@ sabu.edu.ly, [3]ali.shommaki@tpc.ly

[1,2] Department of Mechanical Engineering, Faculty of Engineering, Sabratha University, Libya

[3] The Libyan higher technical center for training and production

***Corresponding author email: Mohamed.alhneaish@sabu.edu.ly**

ABSTRACT

The growing demand for environmentally friendly, cost-effective, and renewable energy sources has driven the advancement of electromechanical devices like flywheels. A flywheel is a device that stores electrical energy as kinetic energy, offering benefits such as high-power output and long lifespans. However, it is typically a large and costly system used in industrial applications. The Flywheel Energy Storage System (FESS) has reignited significant interest among researchers as a promising solution for storing excess AC power for future use. When utilized as a networked storage device, the flywheel plays a critical role in maintaining network stability by addressing sudden uncertainties caused by random fluctuations in wind speed. This functionality is essential for Wind Energy Conversion Systems (WECS) to perform like traditional energy sources and support the electrical grid. The effectiveness of the flywheel in stabilizing the grid and its control capabilities are strongly influenced by its size.

The primary aim of this paper is to design a flywheel that meets performance requirements while minimizing material usage in terms of both mass and volume. An optimal design process was conducted for four different materials to determine the minimum mass needed to achieve identical energy storage levels for a 5 MW wind turbine application. A genetic algorithm implemented in the MATLAB® environment was utilized to solve the nonlinear objective function and derive the optimal mass and size of the flywheel. The results demonstrated that this approach successfully identified the minimum mass and optimal size, with simulation outcomes achieving the intended goal of reducing energy fluctuations.

Keywords: Flywheel, Optimal Design, Energy Storage Systems.

1. Introduction

Wind Energy is a fast-developing source of energy since 1996. The main drawback of wind energy is its nonuniform pattern because it varies by geographic location, time in the year and time of the day. One of the widely accepted methods to overcome this problem is by coupling the wind turbine with the energy storage system .There are four storage systems; they are Compressed Air Energy Storage system (CAES), Superconducting Magnetic Energy Storage system (SMES), Flywheel Energy Storage System (FESS) and Hydrogen Energy Storage System (HESS) [1] .

Nowadays the Energy Storage Systems (ESSs) for the integration of renewable sources have become an important component of the energy system. Energy storage systems are designed to store excess energy from wind turbines that will be provided to the grid in times of energy scarcity [2]. Volatility and uncertainty in wind energy pose a major risk to system operators in the wind energy industry. Wind power coupling is used with energy storage as a means to reduce wind fluctuation and uncertainty and reduce the presence of unused energy. Unavailable energy is defined as energy that can not be absorbed or provided by ESS.

The combination of ESSs and wind turbines is an effective way to increase the rate of wind energy penetration. Several types of clean energy storage technologies have been mentioned in [1], Where it was noted that it should be used to strengthen the public network and maintain energy levels. ESS is an important part of today's wind turbine systems planning. Lithium batteries have been proposed to store wind energy and optimize the battery life in [2]. Flywheel Energy Storage Systems (FESSs) have been integrated with wind turbines in [3] to reduce the fluctuations in energy generated by random wind speed in time and space and to make wind energy replaceable as conventional energy sources. Using a multi-objective optimization method the life cycle optimization and sizing of a hybrid storage system has been dealt with in [2] . Optimization based sizing of an energy storage system is discussed in [4] and linear programming based sizing of a hybrid storage system is discussed in [5]. Dispatch and power sizing of the flywheel based on done based on the frequency components are discussed in [6].

In this research, the flywheel was identified as a potential candidate to solve the problem of fluctuation electric power. When the flywheel work as a storage device connected to the grid. Subsequently, the controllability is important because it must explain sudden uncertainty. In order to, wind energy conversion systems (WECS) can operate as a traditional source.

The ability to control FESSs and their effectiveness in network support is closely related to its size [7], Therefore, the main objectives of the design of the hinge are to achieve performance requirements with the lowest possible use of materials in terms of mass and volume. In this research, the optimal design of five materials will be carried out to find the minimum mass required for the energy storage values with the installation of a 2 MW wind turbine. Several algorithms were proposed to solve the nonlinear objective function to obtain the optimal size of FESS [8]–[10].

2. Design Requirements

Modern FESS mainly consists of a flywheel rotor, magnetic bearings, a motor/generator, a vacuum chamber, and power conversion system. The flywheel rotor is supported by magnetic bearings that provide very low frictional losses up to 98%.

Flywheel energy storage system (FESS), is a mechanical energy storage that stores energy in the form of kinetic energy in rotating mass, the motor/generator converts mechanical energy to electric form, and vice versa [11]. The flywheel rotor is the key of FESS research and development. Because the rotor work in a high speed, it must of high energy density, high mechanical strength, and dynamics properties. Therefore, current researches have focused on optimum design on geometric parameters of flywheel rotor, and stress analysis [10].

On the other hand, an important task for the flywheel design is to determine power and energy storage requirements. This task requires some information and assumptions about where the storage device will be located, and what the demands will be. Distributed energy storage throughout the electricity grid, or in people's homes, will have different requirements than storage demands at renewable generation plants (wind/solar farms) or other higher levels on the grid. An easy way to model the dynamic behavior of flywheel energy storage in a system is shown in [12], that states that the rate of change of stored energy is equal to the difference in grid power, and load demand, which also allows the designer to explore the effects of running losses on energy storage performance by doing parametric studies through the flywheel time constant.

3. Mathematical Model of Flywheel

The most distinctive characteristic of all flywheel energy storage systems is their very high power density. They can be charged at very high rates and can deliver great powers. Another advantage of flywheel energy storage devices is the absence of pollution in all forms; chemical, thermal and acoustical, provided that the system is properly designed and installed. The flywheel has a very high efficiency for short-term storage, even if the energy losses are dependent on the time during which the energy is stored. For short-term storage, the efficiency of a flywheel can be very near to 100%, which decreases to a lower value for medium- or long-time storage [8]. Operation in a vacuum is essential to reduce losses from the air drag. Also, the bearing system must be designed for high energy storage efficiency. The essential components of a Flywheel Energy Storage System (FESS) are the rotor, bearings, motor/generator, and vacuum or very low pressure chamber [13], as shown in Figure 1

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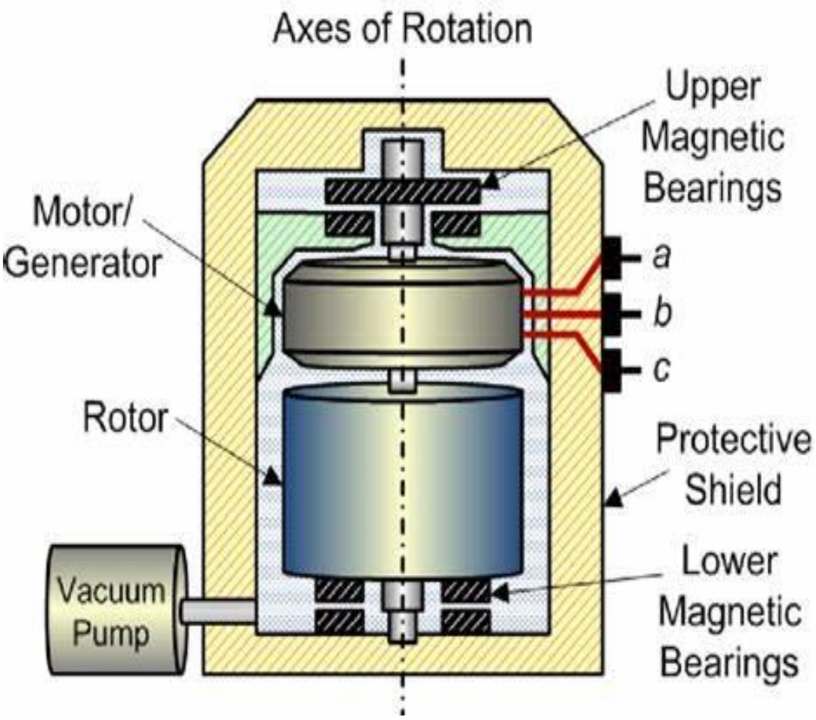

Figure 3.1: Schematic view of the flywheel's storage system

Energy is stored in a rotating mass, depending on the speed of the rotating mass and inertia. The amount of kinetic energy is stored as rotational energy. An advanced flywheel operating in high vacuum suspended on magnetic bearings can maintain a very high efficiency for long periods. Flywheels store energy in the form of kinetic energy. The amount of energy 'E' stored in a flywheel varies linearly with a moment of inertia with the square of the angular velocity 'ω' according to Eq. (3.1).

$$E = \frac{1}{2}.I.\omega^2 \tag{3.1}$$

$$I = m.r^2 \tag{3.2}$$

where I is the moment of inertia, m is the mass of flywheel and r is the mean radius of the disc. Substituting equation (3.2) with equation (3.1) we get:

$$E = \frac{1}{2}.m.r^2.\omega^2$$

(3.3)

Also, the energy stored can be expressed in terms of peripheral velocity v = r. ω, as:

$$E = \frac{1}{2}.m.v^2 \tag{3.4}$$

The maximum energy density can be categorized into a few basic types [3.6] and [3.7], this allows the kinetic energy stored in a flywheel to be expressed as:

$$E_{\mathrm{K}} = K.V.\sigma \tag{3.5}$$

where E_{K} is maximum energy density in the flywheel, V is material volume of flywheel σ is maximum stress in the flywheel, and K is the shape factor.

The maximum energy density with respect to volume and mass respectively is:

$$e_{\mathrm{v}} = K.\sigma_{\mathrm{a}} \tag{3.6}$$

$$e_{\mathrm{m}} = K.(\sigma_{\mathrm{a}}/\rho) \tag{3.7}$$

where e_{v} is energy per unit volume , e_{m} energy per unit mass, σ_{a} is allowable material stress in the flywheel, ρ is mass density and K depends on the geometry and material properties of the rotor, is usually called the flywheel shape factor of 1 or less [14], [15]. Not all the stored energy can be used during discharging [9]. The useful energy per the mass unit can be given as follows:

$$e_{\mathrm{m}} = (1 - s^2).K.(\sigma_a/\rho)$$

(3.8)

where s is the ratio of minimum to maximum operating speed, usually s = 0.2.

4. Flywheel Rotor’s Materials

In general, the choice of the optimal material of the flywheel depends on the design requirements and an assortment of constraints. For a given rotor volume, the material with the highest ultimate strength will store the most energy. When calculating the energy density, radial stress and tangential hoop stress must be taken into account. Flywheel rotors are usually made of either an isotropic material or anisotropic material. For isotropic materials, such as metals, the hoop stress is dominant [16]. Anisotropic materials, like fiber-reinforced composites, have higher tensile strengths than metals [17]. When higher specific energy is desired, metallic rotors are made from merging steel and titanium. Metallic rotors are often made of moderate-strength steel because of its low cost and manufacturability. Researchers in [3], [17], [18] had presented the summary of a comparison between composite and metals materials used in flywheels. Flywheel energy storage systems are usually categorized as either low-speed or high-speed, which ranging 1800-7700 rpm for low-speed and 8000 to 36700 for high-speed flywheels [19]. Low-speed flywheels typically utilize metal rotor and are characterized by low energy density. The most common application for low-speed flywheels is to act as a power quality device to provide ride-through of interruptions up to 15 s long or to bridge the shift from one power source to another. Examples of leading commercial manufactures of low-speed flywheels are Piller and Active Power. Examples of commercial manufacturers of high-speed flywheel systems are Beacon Power and Vycon Energy.

5. Optimization of Flywheel Design

The major objective of flywheel design is to achieve the anticipated performance requirements with lowest possible material used. Many researchers used tools such as the finite element method and the optimization tools to design flywheels [7], [20]–[22]. Therefore, the objective of this work is to design the flywheel to get the required inertia with safe allowable stresses. The efficiency of a flywheel is determined by the amount of energy it can store per unit weight. In this study, four materials were compared for the same value of energy storage. The objective is to find the rotor inertia and its angular velocity. The specifications of the Beacon Power flywheel are adopted, which include a 2 kW/5 kW-h class FESS with the operating speed range of 8,000 to 16,000 rpm, with 85% round trip efficiency, and a composite flywheel rotor.

5.1 Design and Optimization Process of Flywheel Rotors

The energy stored by a flywheel is the function of its mass, radius and angular velocity. The angular velocity is limited because of the maximum stress produced inside the flywheel rotor. The stress at a point in the disc is composed of three stress states, the radial stress σ_r, tangential stress σ_θ, and axial stress σ_z. Because the surface of the disc is a free surface in the z direction, $\sigma_z = 0$. In this case the maximum stress in the non-pierced disc or (solid disc) [8] , $\sigma_{max} = \sigma_r = \sigma_\theta$ and can expressed as follows :

$$\sigma_{max} = \rho\omega^2 r^2 \left(\frac{3+v}{8}\right) \qquad (5.1)$$

where v is the poison's ratio. Subsequently, for safe operation, the flywheel has to be operated at the speed which will not produce a maximum stress greater than the allowable stress of the material, therefore we consider a factor of safety into account. Through optimization, the minimum mass can be found for different materials for the same energy storage capacity. The corresponding angular velocity and radius can be obtained, with using the genetic algorithm optimization. The four materials were selected and used for design of flywheel, and their properties are given in [23]. The objective function and constraints are same for all the four materials with different values of density ρ, and allowable stress, $\sigma_{all} = {}^{\sigma_{max}}/_{S}$, where S is the factor of safety equals to 1.5. Therefore, the objective function can be written as follows:

$$\text{minimize} \quad m = 2E/r^2.\omega^2 \qquad (5.\ 2)$$

with upper and lower bounds limit the angular velocity and radius in meters as follows:

$$\omega_{min} \le \omega \le \omega_{max} \qquad (5.\ 3\text{-a})$$

$$r_{min} \le r \le r_{max} \qquad (5.\ 3\text{-b})$$

Additionally, the flywheel design is subjected to the following nonlinear constraint,

$$\left\{\omega^2 \le \sigma_{all}/\rho r^2 \left(\frac{3+v}{8}\right)\right\} \qquad (5.4)$$

6. SIMULATION AND RESULTS

As previously mentioned, the main goal of solving this optimization problem is to find optimal value of the mass, radius and angular velocity. The comparison results are summarized in Table 6.1, which shows the materials and the minimum mass, angular velocity. The comparison results are summarized in Table 6.1, which shows the materials and the minimum mass, angular velocity, mean radius and height obtained for given values of energy storage.

Table 6.1: Rotor material comparison

Material	Energy Storage (W-h)	Mass (Kg)	Radius (cm)	Height (cm)	Angular Velocity (rpm)
Composites **E-glass Fiber** ***(40% epoxy)***	2000	70.9	43.9	6.16	10208.5
	4000	130.9	45.3	10.68	9880.4
	5000	163.6	46.1	12.9	9721.2
	6000	196.3	47	14.88	9527.2
Titanium **Ti-5Al-2.5Sn**	2000	168.3	38.9	7.9	7180.63
	4000	336.67	40.3	14.7	6923.77
	5000	420.8	40.6	18.13	6877.57
	6000	505	42.1	20.24	6631.52
Aluminum **Alloy 1100**	2000	270.7	41.7	18.28	5281.48
	4000	541.4	41.7	36.57	5281.44
	5000	676.8	41.7	45.71	5281.43
	6000	812.18	41.7	54.86	5281.43
Steel **A36 ASTM**	2000	174.8	38.8	4.7	7071.14
	4000	349.7	40.2	8.2	6817
	5000	437.14	41.6	10.24	6588.11
	6000	524.57	42	12.1	6522.88

As noted from the table above, the amount of energy stored increases with increased rotor mass and radius, and decreased angular velocity. Among four materials, E-glass Fiber composites can be used in modern flywheels to store energy with minimum mass. It can be also used in high-speed applications, as the values of angular velocities obtained are higher than that of other materials. The results in Table 6.1 agrees with Beacon-Power specifications for commercial flywheels.

Using the proposed control in [24], the flywheel was integrated with a 5 MW wind turbine, to evaluate its response under volatile wind speed profiles, with average wind speeds equal to 10.4 and 12.5 m/s, respectively. Both wind speed profiles have a time span of 250 second.

The comparison results show the effectiveness of the wind turbine with FESS in smoothing the wind power supplied to the grid.

Figure 6.1. shows comparison between the responses of wind turbine with FESS and wind turbine without FESS under a variable wind speed profile with an average wind speed equals 10.4 m/s. The results show reduction in grid power gradients is further illustrated

and a significant reduction 31.1% in the Tower fore-after bending moment TFAM has been achieved by using WTFESS of as compared to wind turbine without FESS with a slight loss in energy capture up to 0.336%.

Noting the capabilities of FESS to charge and discharge energy" State of charge" SOC. Additionally, an improvement in fluctuation in power up to 85% as show in Figure 6.2 for the wind turbine with FESS as compared to without FESS, also

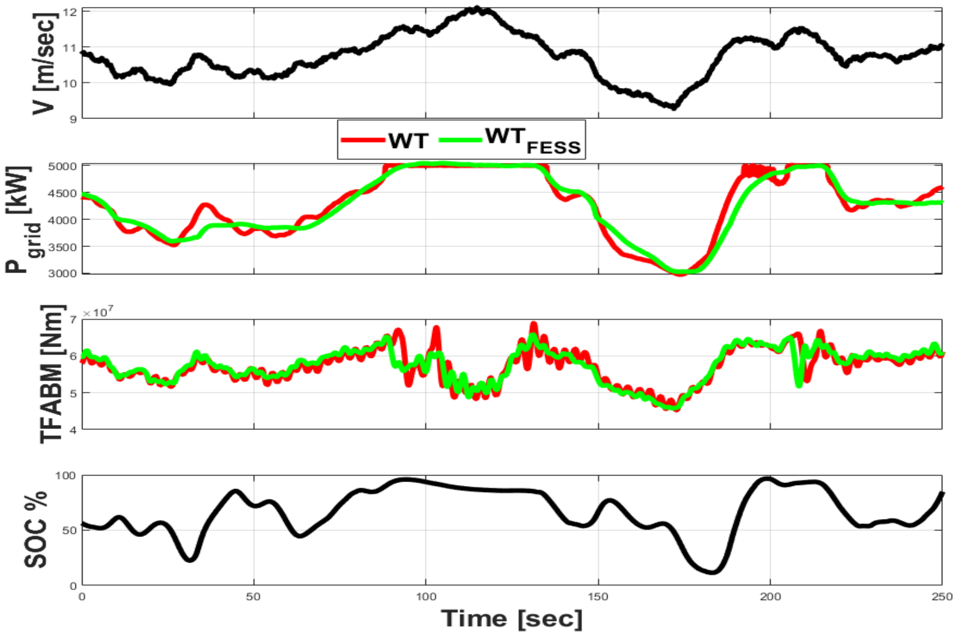

Figure 6.1. A comparison between the responses of the wind turbine without and with FESS for a wind profile with an average 10.4 m/s.

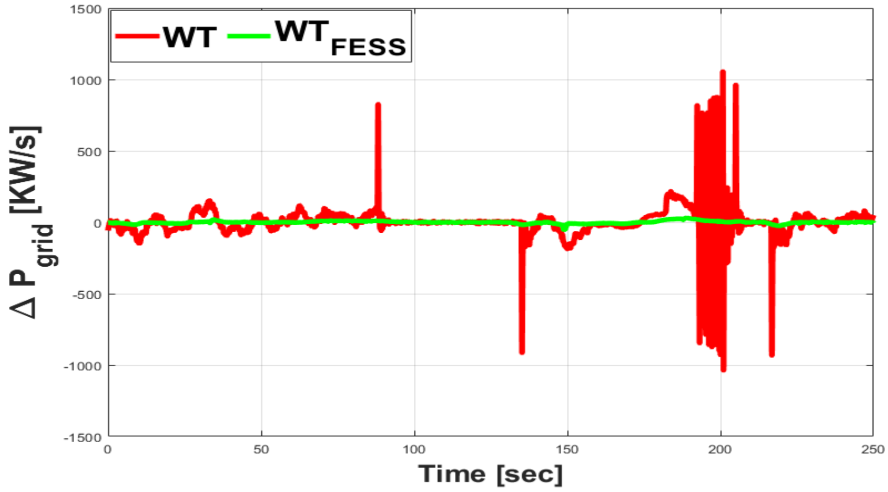

Figure 6.2. fluctuation of power with volatile wind profile with an average 10.4 m/s

Figure 6.3 shows another comparison between the responses of wind turbine with FESS and without FESS under a variable wind speed profile with an average wind speed equals 12.5 m/s. The results in shown an improvement in both fluctuation in power up to 91% and TFAM DEL up to 33.89% for the wind turbine coupled with FESS as compared to that without FESS. The reduction in grid power gradients is further illustrated as shown in Fig 6.4, with a slight loss in energy capture up to 0.123%.

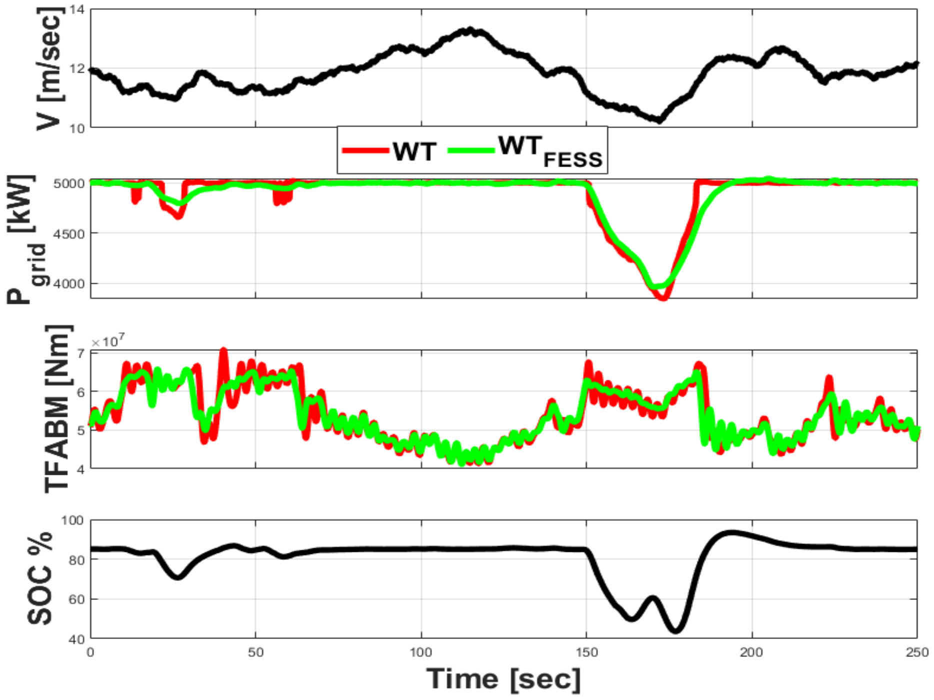

Figure 6.3. A comparison between the responses of the wind turbine without and with FESS for a wind profile with an average 12.5 m/s.

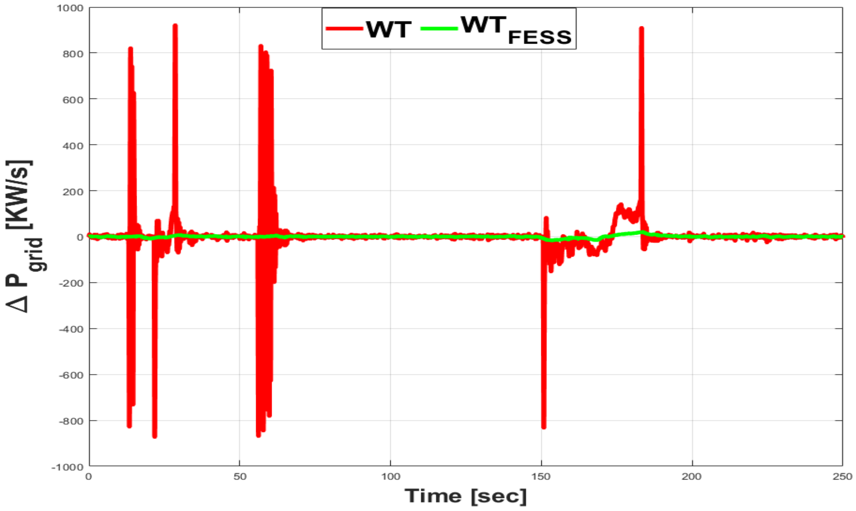

Figure 6.4. fluctuation of power with volatile wind profile with an average 12.5 m/s

7. Conclusion

Different flywheel sizes have been evaluated for optimal sizing, aiming to achieve the minimum mass along with corresponding values for radius and angular velocity. Based on the genetic algorithm methodology, it was observed that aluminum flywheels have a higher mass and lower angular speeds. Steel and titanium fall into a similar performance category. Among the four materials analyzed, E-glass fiber composites are the most suitable for flywheels due to their lower mass and ability to operate at higher angular velocities, making them ideal for high-speed applications. Additionally, the results obtained for various sizes of the Flywheel Energy Storage System (FESS) were relatively similar in terms of minimizing the power gradient. Therefore, the smallest FESS size can be utilized to significantly reduce the overall cost of the wind energy system.

The results of this research can be implemented to improve the performance of systems used in commercial and industrial wind turbines, as well as standalone renewable energy systems. Selecting the optimal size and suitable materials for flywheels contributes to reducing costs and enhancing the overall efficiency of the system.

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