APPLICATION AND USE OF FLYWHEEL IN ENGINEERING:
OVERVIEW

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Abstract: Energy-savings systems can be classified into different types: hydraulic, electric and mechanical system using flywheels. Flywheels have been used to achieve smooth operation of machines. Now days flywheels are complex constructions where energy is stored mechanically and transferred. Most engineers have used the concept of storing kinetic energy in a spinning mass to smooth their operation. The research work will confirm the percentage of energy recovered from the primary power source when compared traditional one.

Keywords: flywheel, hydrostatic drive, energy saving

I. INTRODUCTION

Several hundred year ago pure mechanical flywheel were used solely to keep Machines running smoothly from cycle to cycle, there by render possible the industrial revolution during that time several shapes and designs where implemented. The flywheel project, commenced in 1986, viable energy saving and emission reducing resource for one board public transport vehicles. The complete flywheel system based on a combination of new technologies and it termed Electro Mechanical Accumulator for energy Re-use. The purpose research and development program to develop technology that drastically reduces the cost of energy stored in and delivered from utility scale flywheels specifically for the benefit of renewable power generation. The goal to store 50% of grid capacity within 50 years. There are a number of attributes that make flywheel useful for applications where other storing units are now used.

II. FLYWHEEL

A flywheel is a rotating mechanical device that is used to store rotational energy. Flywheels have a significant moment of inertia and thus resist changes in rotational speed. The amount of energy stored in a flywheel is proportional to the square of its rotational speed. Energy is transferred to a flywheel by applying torque to it, thereby increasing its rotational speed, and hence its stored energy. Conversely, a flywheel releases stored energy by applying torque to a mechanical load, thereby decreasing its rotational.

[1] Suggested a new energy storage flywheel system Using a permanent magnetic bearing (PMB) and a super conducting magnet bearing (SMB). The permanent magnet bearing control the rotor position and superconducting magnetic bearing curb the vibration of the flywheel.

III. ENERGY STORAGE FLYWHEEL SYSTEM

In fig.1 The energy storage flywheel system using a permanent bearing (PMB) and a superconducting magnetic bearing. The permanent bearing (PMB) is set at the top part of the flywheel rotor. The superconducting magnetic bearing (SMB) is set at the bottom part of flywheel rotor. So that same magnetic pole come in contact by four permanent magnets are installed in the rotor. A flywheel is made of fiber reinforced plastics in the centre of rotor, where the flywheel measures 70mm in diameter, 10mm thickness and 0.32kg in weight with rotor weight shown table no.1

Table 1

<table>
<thead>
<tr>
<th>Specifications of the energy storage flywheel system</th>
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<tr>
<td>Storing energy</td>
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<tr>
<td>Flywheel weight(with rotor weight)</td>
</tr>
<tr>
<td>Length of rotor</td>
</tr>
<tr>
<td>Turn number of coil</td>
</tr>
<tr>
<td>Flywheel diameter</td>
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<tr>
<td>Flywheel weight</td>
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</table>
In [3] flywheels have been used to achieve smooth operation of machines. The early models where purely mechanical consisting of only a stone wheel attached to an axle. Flywheel storage systems have been used for a long time. Material and semiconductor development are offering new possibilities and applications previously impossible for flywheels. The fast rotation of flywheel rotors is suitable for direct generation of high voltage.

IV. FLYWHEEL BASICS

1. Energy storage in flywheels

The kinetic energy stored in a flywheel is proportional to the mass and to the square of its rotational speed according to Eq. (1).

\[ E_k = \frac{1}{2} I \omega^2 \]  

(1)

where \( E_k \) is kinetic energy stored in the flywheel, I is moment of inertia and \( \omega \) is the angular velocity of the flywheel. The moment of inertia for any object is a function of its shape and mass. For steel rotors the dominant shape is a solid cylinder giving the following expression for I:

\[ I_{\text{cylinder}} = \frac{1}{2} r^2 m - \frac{1}{2} r^4 \pi \rho \]  

(2)

Where \( r \) is the radius and \( l \) is the length of the cylinder, \( m \) represents the mass of the cylinder and \( \rho \) is the density of the cylinder material.

The other shape is a hollow circular cylinder. M.O.I of hollow circular cylinder is

\[ I = \frac{1}{2} m (r_o^2 + r_i^2) = \frac{1}{4} \pi \rho \left( r_o^4 - r_i^4 \right) \]  

(3)

2. Magnetic bearings

Mechanical bearings used in the past cannot, due to the high friction and short life, be adapted to modern high-speed flywheels. Instead a permanent or electro permanent magnetic bearing system is utilized. Electro permanent magnetic bearings do not have any contact with the shaft, has no moving parts, experience little wear and require no lubrication. It consists of permanent magnets, which support the weight of the flywheel by repelling forces, and electromagnets are used to stabilize the flywheel, although it requires a complex guiding system. An easier way to stabilize is to use mechanical bearings at the end of the flywheel axle, possible since the permanent magnet levitates the flywheel and, thus, reduce the friction. The best performing bearing is the high-temperature superconducting (HTS) magnetic bearing, which can situate the flywheel automatically without need of electricity or positioning control system. However, HTS magnets require cryogenic cooling by liquid nitrogen.

Flywheel rotor design [3] is the key of researching and developing flywheel energy storage system. The geometric parameters of flywheel rotor were affected by much restricted condition. It was applied to determine flywheel rotor parameters of 600Wh.

V. MAXIMUM OUTER RADIUS

The primary components of a flywheel rotor are metal shaft, flywheel, magnetic bearing rotor and thrust disk. There are two basic classes of flywheel. The first class of flywheels uses steel main structure material. Second class of flywheel uses a metallic hub and composite rim made up of an composite material such as carbon-fiber.

1. STRESS ANALYSIS

Shows that the metallic hub (or steel flywheel) can be divided into spoke and metal rim. They become of uniform thickness rotating disk. The stress at a point in the disk is three stress states: the radial stress \( \sigma_r \), tangential stress \( \sigma_\theta \) and axial stress \( \sigma_z \) because the surface of the disk is a free surface in the \( z \) direction, \( \sigma_z = 0 \). For an isotropic material the radial and tangential stress are expressed.

\[ \sigma_r = \frac{3+\mu}{b} \rho \omega^2 \left( R^2 + r^2 - \frac{r_i^2}{R} - r_i^2 \right) \]  

(4)

\[ \sigma_\theta = \frac{3+\mu}{b} \rho \omega^2 \left( R^2 + r^2 + \frac{r_i^2}{R} - \frac{1+3\mu}{3+\mu} r_i^2 \right) \]  

(5)

Where \( r \) and \( R \) are the inner and outer radius of the disk, \( \mu \) is the poisson’s ratio, \( \rho \) is the material density, \( \omega \) is the angular velocity and \( r_i \) is radius of the i.th point.

2. Maximum outer radius calculate

The maximum radial stress is at \( r_i = \sqrt{Rr} \) in Eq.(4). the maximum tangential stress is at \( r_i = r \), the maximum stress is obtained.

\[ \sigma_{r_{\text{max}}} = \frac{3+\mu}{b} \rho \omega^2 (R - r_i)^2 \]  

(6)

\[ \sigma_{\theta_{\text{max}}} = \frac{3+\mu}{4} \rho \omega^2 \left( R^2 + \frac{1+\mu}{3+\mu} r_i^2 \right) \]  

(7)

Comparing tangential stress \( \sigma_{\theta_{\text{max}}} \) with maximum radial stress \( \sigma_{r_{\text{max}}} \) at \( r_i = \sqrt{Rr} \) point

\[ \sigma_{\theta i} - \sigma_{r_{\text{max}}} = \frac{3+\mu}{8} \rho \omega^2 \left( R^2 + r_i^2 + \frac{1+3\mu}{3+\mu} Rr \right) - \frac{3+\mu}{8} \rho \omega^2 (R - r_i)^2 \]  

(8)

Geometric parameters of flywheel rotor

The important function of flywheel rotor store kinetic energy, it must have the enough polar moment of inertia. In addition, it also meet the demand, such as mass, dynamics behavior.

3. The polar moment of inertia of flywheel

The energy stored by a FESS is calculated

\[ \Delta E = \frac{1}{2} I (\omega_{\text{max}}^2 - \omega_{\text{min}}^2) \eta \]  

(9)
where $\Delta E$ is the energy stored by the flywheel, $\omega_{\text{max}}$ and $\omega_{\text{min}}$ are the maximum and minimum operation speed of the flywheel, and $J$ is the moment of inertia of the flywheel, i.e.

$$J = \frac{2\Delta E}{(\omega_{\text{max}}^2 - \omega_{\text{min}}^2)\eta} \quad (10)$$

A 5kwh superconduction flywheel energy storage system has advantages in terms of high electrical energy density, environmental affinity and long life. However, the superconductor flywheel energy storage system has disadvantage that electromagnetic damper is needed because superconducting bearing do not have enough damping coefficient. The purpose of this experiment is to develop a method of damping the vibration of the superconductor flywheel energy storage system. A piezoelectric actuator was attached to a superconducting bearing system for feasibility test in order to make it as a damper of the SFES.

**VI. RESULT AND DISCUSSION**

In the experiment most important point before using the piezoelectric actuator is to make sure that the vibration of the permanent magnet can be damped by the high-temperature superconductor bulk moving up and down on lower vibration exciter toward the permanent magnet. The permanent magnet vibration is similar to the vibration of the superconductor flywheel energy storage system rotor and the high-temperature superconductor bulk is similar to the superconductor flywheel energy storage system.

1. Damping in superconducting system.

The vibration of mechanical system is reduce due to damping effect. In the non-contact magnetic bearing system friction is not consider. It means that friction forces do not exit in the non-contact magnetic bearing system. The damper harmonic oscillators satisfy the second-order differential equation.

$$\frac{d^2x}{dt^2} + 2\zeta\omega_0\frac{dx}{dt} + \omega_0^2x = 0 \quad (10)$$

$$\omega_0 = \sqrt{\frac{k}{m}} \quad (11)$$

$$\zeta = \frac{c}{2m\omega_0} \quad (12)$$

Where $\omega_0$ is undamped angular frequency of the oscillator, $\zeta$ is a damping ratio, $k$ is the spring constant, $m$ is the mass, and $x$ is displacement of the mass.

In the superconducting levitation system, the damping function is considered to be the combination of the mass–spring–damper configuration, as shown fig.3. The damping force $F_d$ and the oscillatory force $F_o$ in are described as

$$F_d = -c\nu = -c\frac{dx}{dt} \quad (13)$$

$$F_o = -kx \quad (14)$$

Where $C$ is the damping coefficient and $\nu$ is the acceleration.
Application And Use Of Flywheel In Engineering: Overview

Fig.5. Effect of the phase difference on PM displacement: (a) displacement of the PM is different with phase differences of $0^\circ$ and $180^\circ$, i.e., the PM and HTS bulk moved in the same direction ($0^\circ$) or in the opposite direction ($180^\circ$) and (b) displacement of the PM is different with phase differences of $90^\circ$, $120^\circ$, $150^\circ$, and $180^\circ$.

The high speed spinning mass [5] to kinetic energy by a flywheel energy store system. The energy is input and output a dual-direction motor/generator. The flywheel works within a vacuum chamber by maintain its high efficiency. Without mechanical friction active magnetic bearing utilize magnetic force to support rotors rotating shaft. Experiment has been undertaken. The flywheel has steadily past through its flexible critical speed and reached to the rotating speed of 28500RPM. Maximum tip speed is 450m/s. Maximum electrical discharge power reaches 40W. Discharge duration is 100 minutes.

VII. MAIN CONSTRUCTION AND BASIC PRINCIPLES

It uses composite material for a high rotsting speed purpose. So that storage density is obtained.

Fig.6 Rotor of flywheel constructed by composite materials

Model for the rotor-bearing system is shown in bellow with dynamical

\[ m\ddot{x} = F_{x1} + F_{x2} \]  \( \text{(15)} \)

\[ m\ddot{y} = F_{y1} + F_{y2} \]  \( \text{(16)} \)

\[ J_d\ddot{\alpha} + \Omega/\rho\ddot{\beta} = -aF_{y1} + bF_{y2} \]  \( \text{(17)} \)

\[ J_d\ddot{\beta} - \Omega/\rho\ddot{\alpha} = aF_{x1} - bF_{x2} \]  \( \text{(18)} \)

\[ m\ddot{z} = F_z \]  \( \text{(19)} \)

Where $F_{x1}$ and $F_{y1}$ are the forces by top active magnetic bearings, $F_{x2}$ and $F_{y2}$ are the forces by bottom active magnetic bearings, $F_z$ is the force by the axial active magnetic bearing, $m$ is the mass of the rotor, $J_d$ and $J_p$ are the rotating inertia, $\Omega$ is the angular speed of the rotor $x,y,z$ and $\alpha, \beta$ are the displacement.
VIII. CHARGE AND DISCHARGE EXPERIMENT

The final test to evaluate the system is the charge and discharge experiment.

The energy storage efficiency of the preliminary experiment is summarized in Table 2.

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<table>
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<tbody>
<tr>
<td>vacuum</td>
<td>8 pa</td>
</tr>
<tr>
<td>Rotating speed at discharge</td>
<td>405RPS</td>
</tr>
<tr>
<td>Mean discharge</td>
<td>40w</td>
</tr>
<tr>
<td>Discharge duration</td>
<td>100 min</td>
</tr>
<tr>
<td>Energy stored</td>
<td>160whr</td>
</tr>
</tbody>
</table>

Table 2

A doubly fed variable speed wind induction generator [6] connected to the grid associated to a flywheel energy storage system (FESS) is investigated. The dynamic behaviour of a wind generator, including the models of the wind turbine (aerodynamic), the doubly fed induction generator (DFIG), a ac/ac direct converter, the converter control (algorithm of VENTURINI) and the power control of this system, is studied.

IX. MODELLING OF THE WIND GENERATOR

1. Modeling of the wind turbine and gearbox

The aerodynamic power, which is converted by a wind turbine, $P_t$ is dependent on the power coefficient $C_p$. It is given by

$$P_t = \frac{1}{2}C_p(\lambda)\rho\pi R^2V^3$$

(20)

Where $\rho$ is the air density, $R$ is the blade length and $V$ the wind velocity.

The turbine torque is the ratio of the output power to the shaft speed $\Omega_t$, $T_{aer} = \frac{P_t}{\Omega_t}$

The turbine is normally coupled to the generator shaft through a gearbox whose gear ratio $G$ is chosen in order to set the generator shaft speed within a desired speed range. Neglecting the transmission losses, the torque.
speed of the wind turbine, referred to the generator side of the gearbox, are given by

\[ T_g = \frac{T_{mech}}{2} \quad \text{and} \quad \Omega_e = \frac{\Omega_{mech}}{2}, \]  

(21)

Where \( T_g \) is the driving torque of the generator and \( \omega_{mech} \) is the generator shaft speed.

A wind turbine can only convert just a certain percentage of the captured wind power. This percentage is represented by \( \text{Cp}(\lambda) \) which is function of the wind speed, the turbine speed and the pitch angle of specific wind turbine blades. Although this equation seems simple, \( \text{Cp} \) is dependent on the ratio \( \lambda \) between the turbine angular velocity \( \Omega_e \) and the wind speed \( V \). This ratio is called the tip speed ratio:

\[ \lambda = \frac{\Omega_e}{V}. \]

The relation between \( \lambda \), and \( \Omega_e \) is show in Fig.12

Fig. 12. Power coefficient for the wind turbine model

If the wind speed is measured and the mechanical characteristics of the wind turbine are known, it is possible to deduce in real-time the optimal mechanical power which can be generated using the MPPT. The optimal mechanical power can be expressed as

\[ P_{mech,opt} = \frac{C_p \cdot \max \cdot \rho \cdot r^2 \cdot \Omega_e \cdot \Omega_{mech}}{\lambda^2 \cdot C_p \cdot \max \cdot r^2 \cdot \Omega_e^3} \]  

(22)

The electro-mechanical battery [7] which transforms electrical energy in to mechanical energy and mechanical energy in to electrical energy by using superconductor flywheel energy storage system. concluded that there were some external damping mechanisms. Finally, the 35 kWh SFES was test operated up to 4000 rpm. After passing two predicted critical speeds, the amplitude of vibration decreased and reached a stable rotation state.

Horizontal axle-type flywheel energy storage system [8] was manufactured using high-Tc superconductor bearings. The system running in a vacuum chamber mainly consists of a composite flywheel rotor, superconductor bearings, a motor/generator and its controller.

It is proposed [9] an HTS bulk bearing flywheel energy system (FWES) with rotor shaft stabilization system using feed-back control of the armature currents of the motor-generator. In the proposed system the rotor shift has a pivot bearing at one end of the shaft and an HTS bulk.

Flywheel energy storage (FES) can have energy fed in the rotational mass of a flywheel [10], store it as kinetic energy, and release out upon demand. It is a significant and attractive manner for energy futures ‘sustainable’. The key factors of FES technology, such as flywheel material, geometry, length and its support system were described, which directly influence the amount of energy storage and flywheel specific energy.

REFERENCE