REVIEW PAPER ON RAILWAY REGENERATIVE BRAKING SYSTEM USING FLYWHEEL TECHNOLOGY.

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Abstract: Energy storage is emerging as a solution to energy savings, energy management and performance improvement for power systems. From different available technologies, Fly-wheel Energy Storage Systems (F-ESS) are useful to attain energy solutions because of high energy density, large number of discharge cycles, long lifetime, future potential advancements and reduced costs for few minutes discharge time. The objective of this review paper is to use the concept of flywheels and its benefits apart from other technologies to assess how they can enhance the power system performance and achieve energy saving in some railway application, emphasizing the application of these energy storage systems for passenger and freight trains. Quantify the increase of the power quality in the railway power system and the cost advantage by incorporating FESS. This review paper will focus on how to integrate F-ESS into power systems in railway as a solution to absorbing regenerative braking energy and delivering it when a train is moving from a valley to uphill. Case studies which resemble common railway power system phenomenon are also in-cooperated to analyze amount of power wasted, amount of power that can be produced and saved using F-ESS with the aim of improving energy consumption of railway power systems.

Keywords: Flywheel, Energy storage system (F-ESS), Kinetic energy, Regenerative braking, Electrical energy, High specific energy.

Introduction

With increasing energy prices, operators began to get interested in saving electrical energy and reducing their electricity bill or electrical energy consumption. Thus, many solutions have been employed on the market and some are still being developed. Some solutions are intrusive and require replacing old equipment or installing new ones on-board. These different technologies developed were basically meant to improve the power efficiency of the devices to reduce power loses and improve the power consumption levels of the train and reduce power consumption costs. The high power of modern locomotives or trains coupled with the abundant arrival/departure frequency in key train stations result in frequent voltage drops of the local network and limited acceleration capability regardless of equipment efficiency. These results in power capacity in traction stations providing irregular power supply and converters in such stations are dimensioned to deliver more than the average power demand.
Given that nearly most electrical generation in the world is achieved from generators and about 65% of the world's power is used in motors, it is logical to consider rotational energy storage as a prime solution to energy solutions. Flywheel Energy Storage System (F-ESS) has benefits of high power density, high number of discharging cycles, long lifespan and relatively low costs. The charging of the F-ESS can be achieved in a few minutes, for instance, and totally discharged during the train acceleration. The trains and locomotives power focused on ranges between 1.5 to 6 MW. Considering that the time taken to discharge an energy storage system should be in between 1 to 10 minutes, the energy storage of F-ESS should be in between 25 to 1000 kWh. The relevance of this is that it shows how FEES can be integrated in the railway power systems by taking advantage of regenerative braking to charge it, supplying energy close to the loads, and by limiting the optimum power required from the traction stations.

Background on Energy Consumption a Rail Network

The case study assessment of railway energy consumption in the United Kingdom is a close representation of the general energy consumption patterns for any railway system. The total energy consumed by rail vehicles recorded in the United Kingdom is approximately 15 million MWh per year, and can be divided equally between electric and diesel traction [3]. Electric vehicles are subdivided into high voltage (25kV AC) intercity trains and both high and low voltage (750V DC) multiple units which operate predominantly in regional and commuter services. Electric freight locomotives relatively consume small amount of energy. Diesel passenger vehicles can be classified, in terms of energy consumption, according to the transmission and service type. The Association of Train Operating Companies (ATOC) produces yearly energy consumption data for rail vehicle in the United Kingdom. This data is for the primary fuel energy consumed which includes losses resulting from the generation and distribution of electricity.

A 2007 report by the Railways Safety and Standards Board (RSSB) provides detailed estimates of the total energy losses for United Kingdom rail vehicles [4]. The estimated power generation efficiencies for both electric and diesel traction are as follows:

Average electric power generation efficiency = 40%
Average diesel engine fuel efficiency = 32%

These estimations were made on the basis of current technology. Once the power generation losses have been taken into account, a breakdown of where the supplied electrical or mechanical energy is used in the vehicle gives an indication of where efforts to improve efficiency should be focused. [4]

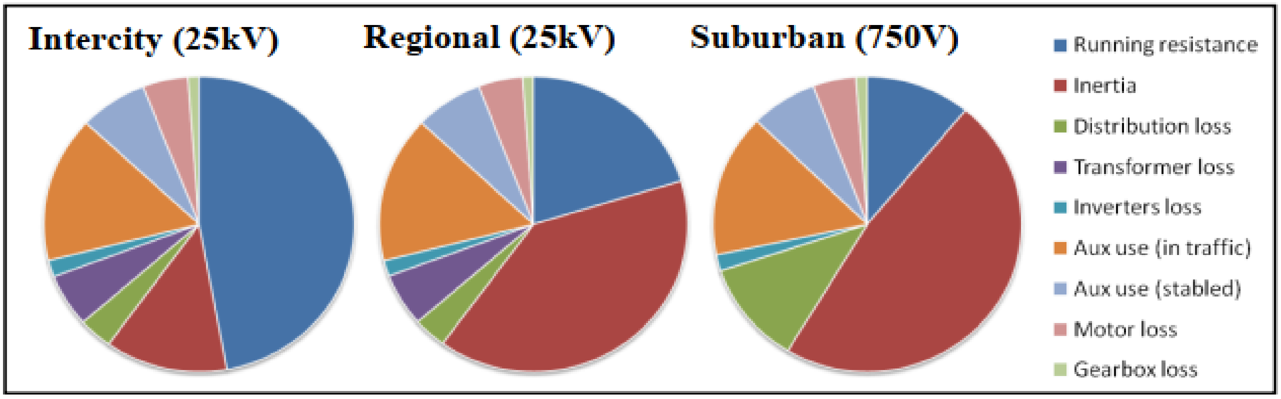


Figure 1: Analysis of energy loss

The above data reflect the percentage proportion of inertia losses in relation to other losses. The inertia losses shown in the figure above are therefore likely to be higher than current levels, although factors such as power and efficiency limitations in the electrical power-train limit the proportion of braking energy that can be regenerated. Moreover, 'line receptivity' also limits regeneration in DC systems, which results in regenerated electrical energy being dissipated in a bank of resistors if there is insufficient power demand from other vehicles in the same section of track.
This issue can be solved by using inverting equipment at the DC substation however this technology is not used in the UK railways and most railway systems. [4][5] Therefore a solution can be achieved (along with a range of other potential benefits) by implementing hybrid power-train systems in rail vehicles. The potential of hybrid technology to reduce fuel consumption and emissions has been given as one of the reasons for pursuing widespread electrification of the UK network [6]. Hybridization is therefore one of the paramount measures which have been identified as suitable for reducing the energy consumption of the UK railways.

Assumption made:

- The tractive resistance of the flywheel used is negligible or the small does not affect much the tractive effort required.
- Motor used is light in weight and small size.
- The speed of the motor is proportional to the speed of the train.

Regenerative Braking System

A train in motion when braking has a lot of energy which could otherwise be wasted to the surrounding environment in form of heat and noise, an overview of kinetic energy is given by the formula:

$$KE = \frac{1}{2}MV^2$$

Where: KE is the kinetic energy, M is the mass of the train and V is the velocity or the speed of the train.
To have a clear concept of a Regenerative energy system and its impact on the train energy performance, we look into a simplest basic train illustration:
As a case study; let's consider a 20Tonne train moving at 120km/h. Now, on braking the train to a speed of 10 km/h the amount of energy spent is around 121kJ using the equation given above. This energy typically could just be lost into the environment inform of heat and sound if there is no proper mechanism to tap this energy. However as suggested in our review paper ,a design is made so as to convert the energy from braking into useful electrical energy which can be used to power some auxiliary functions i.e.

- Providing acceleration boost, in required situations (hence some of the peak power requirements are being handled by RBS).
- Idling requirements: during idling the engine can be switched off and the energy stored in RBS can used to restart the train and the engine. [13]
- Supplemental propulsion unit for peak/ non-peak power requirements [14].

Suppose that the efficiency of the brake is 25% of this energy, there would still be an amount of 11.85 kJ (25% of 47.8kJ) of energy available at each braking instance, which represents the amount of energy that can be utilized. This energy is roughly, neglecting all losses, enough to accelerate a vehicle from 0 km/h to around 32 km/h (using the equation). The stored energy using RBS can be reutilized for different purposes, either to help improve performance or fuel efficiency, in either case assisting in Load Sharing. Load sharing or Load averaging can be defined as sharing of the power requirements of the vehicle between a primary and secondary propulsion or energy storage unit [11, 12].

In this whole process, RBS can also essentially function as a brake system. But due to heavy torque demands at emergency braking situations RBS alone would not be sufficient; therefore it needs to be a supplementary system to existing proven friction braking.

An RBS mainly consists of two parts:

- The Transmission
- The Energy Storage system (ESS).

Depending on the design arrangement of the RBS, the transmission is supposed to transmit energy from the wheels (or drive train) to/ the ESS and vice-versa. The ESS can store the kinetic energy in different forms depending on its type [8]. The RBS and its various types can be classified on the basis of the type of transmission and the type of energy storage system (ESS). The choice for the transmission is usually dependent and subsequent on the type of ESS selected.

Parts and Operation of an RBS

Selection of Energy Storage System:

The main factors when selecting an on-board energy storage device include the size of the storage device both physical size and the storage capacity and safety issues (especially on passenger trains). Storage devices can be used on-board railway cars for three main purposes: energy consumption reduction, peak power reduction and catenaries-free operation i.e the train running without using power from overhead supply for some distance. These trains need storage devices capable of not only providing a high peak power, but also high energy capacity.

Types of ESS for RBS application

Electrochemical Battery:

In an electrochemical battery, the energy is stored in the form of chemical energy and released in the form of electrical energy. Electrochemical batteries have been one of the most preferred forms of energy storage systems adopted across a wide range of applications due to their compactness and cost. They are commonly used in modern automobiles to power accessories and for startup of the internal combustion engine. Recently, in the search of alternative means of propulsion there has been extensive research and development in battery technology as a good form of ESS for automobiles. Fervently, it resulted in the advent of the 'battery electric vehicle' (BEV) and the hybrid electric vehicle (HEV), which has gained popularity in the industry [9]. These vehicles use electric motor/generator pairs to propel themselves and to recapture braking energy (electric RBS) with a battery power source. The regenerative braking system uses a generator at the wheels or drive train to convert the rotational energy into electrical energy which is stored in the battery, and when necessary the electric motor utilizes the same energy to impart momentum to the vehicle. The electric battery however has had its application demerits which include inherent losses that accompany the energy transformations resulting in low transfer efficiency [15]. Other demerits include low specific power (power per unit weight of storage system), lack of required service life span and a low storage efficiency which diminishes which each charge/discharge cycle. These demerits contribute to a limited range for battery BEVs and HEV applications and have become fairly more successful as they use an internal combustion engine, with its relatively high specific energy and power, to supplement the battery. There has been ongoing research into other electrochemical batteries like Li-ion and NiMH etc., for better performance for these applications. [9]

Ultra Capacitor Storage

Ultra capacitors have the capacity to store considerable electrical energy at low voltage [9]. A capacitor operates by storing electrical energy in the form of positive and negative charges. These unlike charges are separated and stored in two parallel insulated plates. The capacity to store energy is directly proportional to the permittivity of the insulator/dielectric, the area of the plates and inversely proportional to the distance between the plates. There is ongoing research in this area to find ways to make use of Ultra capacitors as well as combining both Ultra capacitors and battery in order to improve the efficiency. [9]

Hydraulic and Pneumatic Energy storage

In hydraulic and pneumatic ESS, energy is stored by compressing a fluid and storing it in an accumulator, which is mechanically or pneumatically operated. Hence, during regenerative braking, utilizing a hydrostatic transmission consisting of a pump–motor, energy is captured and stored in the accumulator and the compressed fluid is subsequently used to run the hydraulic motor to run the vehicle. This method has been a well-researched technology and has been implemented in various concept vehicles which are currently in the market. The downsides to Hydraulic/pneumatic ESS are that they very heavy with low energy density and have excessive noise problems associated with them. [16]

Kinetic Energy Storage System or Flywheel Energy Storage

This concept captures and stores the mechanical or rotational kinetic energy of the wheels in the same form, in a heavy rotating mass or the "flywheel". If a mechanical variation is used for transmission there won't be any losses associated with the energy transformations as energy is being transmitted in mechanical form throughout. But in many cases with flywheels for energy storage, and a non-mechanical transmission, energy transformations and consequently the associated losses exist for example an electrical transmission is used in the flywheel battery (FWB) designed by University of Texas at Austin, Center of Electro Mechanics (UT CEM) [12]; therefore flywheels are used for their high specific energy (depending on the material of the flywheel), high specific power, , long service life, high tolerance to charge discharge cycles and low cost. Due to these advantages, flywheels are being used for Energy storage in various applications some of which are:

1. Uninterrupted Power Supply (UPS) systems [10, 17].
2. Grid energy systems like the Beacon Flywheel Power Storage Plant in Stephentown, New York [18].
3. Standalone/Auxiliary propulsion unit and for regenerative braking in transportation.

Flywheels store rotational kinetic energy according to the equation given below:

$$Ek,rot = {}^{1}\!/_{2}\, I\omega^{2}$$

Where, ***Ek,rot*** : rotational kinetic energy*,* ***I*** : the rotational inertia of the flywheel about the rotating axis *and* $\boldsymbol{\omega}$: the angular velocity of the flywheel

The equation implies that the maximum amount of energy that can be stored in a flywheel system can be increased by either increasing the design maximum angular velocity (ωmax) of the flywheel or the inertia (I) of the flywheel or both. However due to safety and stability concerns associated with flywheel shattering and gyroscopic effects respectively, in automobile research applications, low speed low inertia flywheels have been preferred over high speed flywheels. Recently, these tradeoffs are being resolved with the advent of new materials with high specific strength, which include composite materials and design of safer high speed flywheels with high energy storage capabilities which has become a possibility. However windage losses and bearing losses are the major concern when using flywheels for energy storage. [19]

Energy Storage System Comparison

Several types of energy storage devices are used in power systems and their application depends on the advantages they can provide. The aim of this section is to compare flywheels with other technologies in an extensive classification. Since this review paper is targeting to incorporate/retrofit the railway power system with an energy storage system close to the loads, compressed air, superconducting magnetic and pumped hydro technologies are ruled out from the comparison since these are strongly dependent on the geographical situation. A list of technologies suitable for energy storage in the railway application is represented below:

- Flywheel
- Lithium-Ion batteries, Lead-Acid batteries and Nickel-cadmium batteries
- Super capacitors

The specific application of this study will restrict the usage of some storage devices since the main interest is to supply energy as close as possible to the train, and this one is moving, short depth of discharge due to application usage, which is less than 10 minutes (based on acceleration and braking times).
Technologies with low energy cost and low power are desirable for railway applications. However, each technology has a relation of power and energy per kg as seen. Thus, fixing the power capacity, an estimation of the associated cost can be found.

Table 1: Average energy cost and power cost for different technologies

Energy cost (US$/KWh)	**Power cost(US$/KW)**	
Super capacitor	10000	200
Flywheel	4000	300
Pb-Acid battery	500	500
NiCd battery	1000	1000
Li-ion battery	1000	2200

From table the values must be adjusted to match the application in railway system implementation. For a 10 minutes discharge, Pb-Acid battery will have an excess of energy 3 times the requested to meet power requirements, then the energy cost it is 3 times more expensive. Similarly the adjusted power cost for super capacitors will be 25 times bigger since to meet the energy requirements it will have an excess of power. Adjusted values are represented in bold type in table 4. The corrected cost for a ten minutes discharge (0.167h) is calculated as below. The reason why the cost is calculated over KW is because it is the unit used for flywheel suppliers:

Table 2: Adjust average energy cost and power cost for a 10 minute discharge

Energy cost (US$/KWh)	Power cost(US$/KW)	Corrected cost(US$/KW)	
Supercapacitor	10000	**5000**	6670
Flywheel	4000	300	968
Pb-Acid battery	**1500**	500	750,5
NiCd battery	1000	1000	1167
Li-ion battery	1000	2200	2367

In the same way, for one minute discharge (0.0167h) the adjusted values are represented in red in table 5 and the corrected cost is shown in equation 2:

Table 3: Adjusted Average Energy Cost and Power Cost for a 1 minutes discharge

Energy cost (US$/KWh)	Power cost(US$/KW)	Corrected cost(US$/KW)	
Supercapacitor	10000	**500**	660
Flywheel	4000	300	364
Pb-Acid battery	**15000**	500	740
NiCd battery	**3500**	1000	1056
Li-ion battery	**10000**	2200	2360

These figures just provide an approximation of reality. Detailed information depends on manufacturing processes, number of units built and installation costs. The trend is showing that flywheels have the cheapest corrected cost in a range from 1 to 10 minutes; it is therefore logical to look into flywheels in terms of technology cost. In order to place F-ESS in a better position than Lead-Acid battery or super-capacitors, other operation features must be raised: F-ESS present stable voltage and power level independent of the depth of discharge, state of charge and temperature for a longer life cycle compared with their competitors. To know the energy stored it is only needed the rotational speed of the rotating mass, while energy stored by batteries and super-capacitors are more difficult to predict. Power electronics are the responsible to set the limitation on the output and input power of the motor/generator responsible to spin the flywheel, while electrochemistry is the limiting factor for batteries and super capacitors. The trend shows a future advances in the control of the motors and an increase of power density will be seen in the following years [7]

Implemented Flywheels or Prototypes

The University of Texas at Austin has made great efforts to progress in F-ESS, in such a way that it has become one of the most important places in researching this technology in the United States during the past years. Some of achievements include a comparison of rated power and discharge time for various storage technologies. According to their researches flywheels are considered to be pulse power devices that compete well with super capacitors or high power lithium ion batteries. However, CEM has also developed flywheels which can provide longer term energy storage needs.

In rail application, flywheel energy storage system is used for recovery of braking energy rapid acceleration and speed maintenance on grades. A study of the spin commissioning and drop tests for this flywheel was done but however, no physical implementation has been found [22]. Somewhere around the point number 3, approximately 130kWh 2MW could be of major interest for railway application in trains. The trains in application consideration will be fully electric, a slightly bigger capacity and discharge time may be required. A single unit or a multiple unit implementation is therefore a cost-related decision.

Rated power for passenger and freight trains approximately ranges from 1 to 6MW and the discharge time required will be around 1 to 10 minutes. Energy stored in the flywheel concept is defined as a consequence of fixing the maximum output power and discharge time, which are values around 100 to 1000 KWh for this application.

Table 4: Flywheel Prototype and Flywheel Implemented

Power (kW)	Energy (kWh)	Year (Generation)	Others	
Keihin Electric Express Railway at Zushi	2000	25	1988 (First)	Implemented
Launch Point	50.000	5000	2008 (Third)	Prototype
ATZ and MM 2	250	12.5	Second	Prototype
Kinetic Energy System ACE2	350	56	2003 (Second)	Prototype
Kinetic Energy System SA2VE	5600	889	2006 (Second)	Prototype

In some other places like in London underground, it has been used a 300kW flywheel, with no details on energy, then it upgrades top 1MW. Investment was recovered in 5 years.

OVERVIEW FLYWHEEL REGENARATIVE ENEGRY DESIGN MODEL

In regenerative braking process, the traction motor acts as a generator and restores part of the kinetic energy into electrical energy. To utilize this energy, a mechanism to feed back the energy to the grid of to store it in the storage systems should be put in place. During this process of feeding back the energy to the grid or storing it, the RBS simply functions as a braking system for the train. But due to heavy torque demands at emergency braking situations RBS alone would not be sufficient; hence it needs a supplementary system like disc bake or friction braking in the train thus reducing the cost of operation and thus increased revenue for the train company.
The design model will look into the following components in depth:

- A generator/Motor
- Energy storage devices to store the energy
- Interface and synchronization of these components (Transmission): The transmission is responsible for transmission of energy from the wheels to the ESS and vice versa.

FLYWHEEL BASED REGENERATIVE BRAKING SYSTEMS

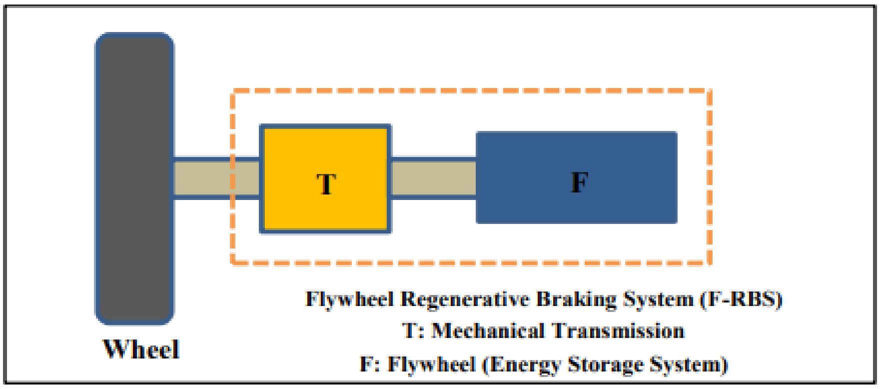


Figure 2: Basic Flywheel Regeneration Model

Flywheel energy storage has fast charge and discharge speed, and it is capable of discharge huge power in a very short time. So it has become a wise choice to solve power quality problems.

Flywheel as compared to ESS has more advantages and is suitable for the use by trains, basically stores kinetic energy or rotational energy as component of angular velocity and moment of inertia.

They are used for their ability to:

1. Smoothen out rotations and Provide continuous energy.
2. Have high energy storage capacity and release at a very high rate if and when needed.

Using flywheels provides the advantage of a high power (storing and releasing both) ESS, compared to conventional batteries. Due to which, Flywheel Energy Storage (FES) systems are being used to replace electrochemical batteries in the field of power supply for Uninterrupted Power Supply (UPS) systems, grid power storage requirements and pulse power requirements.

The stored energy in a flywheel is given by the equation:

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

or

$$E = \frac{1}{2} (kMr^2)\omega^2$$

Where,

- I stands for Fly wheel's Moment of Inertia
- ω stands for Rotating Velocity. It is measured as radians per second.
- M stands for Flywheel's Mass
- R stands for Flywheel's Radius, and
- K stands for Inertial constant

Therefore, to recover or add energy to or from the flywheel the inertia I or the angular velocity ω needs to be varied. This means, the flywheel exerts a torque only if its angular momentum is varied and vice versa for torque on the flywheel, in any case the angular momentum i.e, the mathematical product of moment of inertia (I) times the angular velocity(ω) needs to be varied, implying either or both of I and ω need to be varied. Hence in case of flywheel energy storage the transmission needs to have an ability to vary either of the two quantities. A continuously variable transmission (CVT) is one of the most common forms of variation mechanisms, which varies the ω (angular speed). Any CVT should have a wide ratio range to accommodate and match both the speeds at each end (flywheel and wheel), and needs to continuously variable across the range to initiate energy transfer. The CVT needs to needs to match up speeds by switching to required gear ratio (Mechanical: gears, variable diameter pulley, toroidal surfaces;
Electrical: motor/generator, hydrostatic: pump/motor etc.). Once both the sources (flywheel and the wheel) are connected and at equilibrium, the ratio needs to be varied i.e., in this scenario from ratio = 10:1 to 5:1 or 20:1, continuously to vary the speeds so as to initiate an energy transfer or a momentum exchange.

DESIGN OBJECTIVE

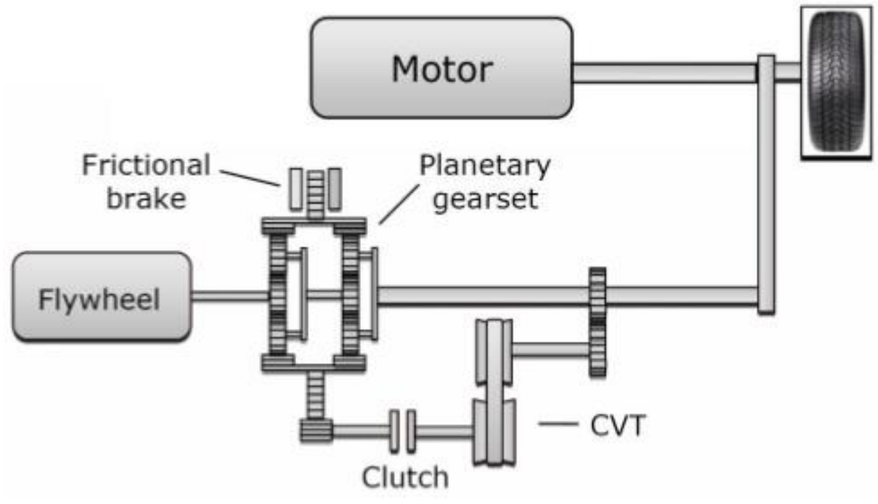


Figure 3: Simple design Integration of flywheel concept

The main design objective of this model is to create a regenerative braking system model which stores the kinetic energy during braking to energy form that may be stored in ESS devices or in a flywheel. Such a system will benefit the train by: Saving the wasteful braking energy and reusing that energy as an additional source to power the train, although temporarily, thus saving engine's power and consequently reducing net fuel consumption.

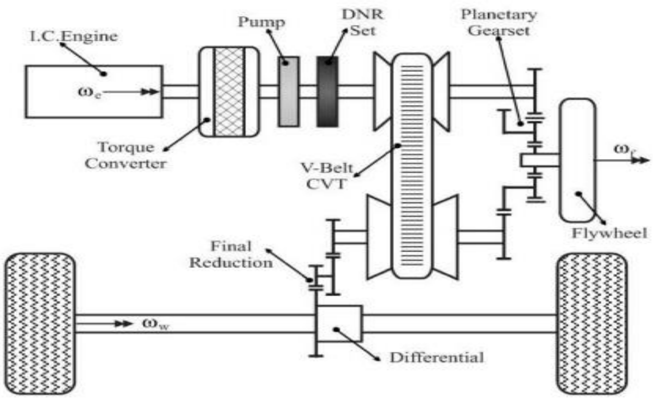
The objectives of design model are to develop a system that:

- Has high energy density and power density – Enough to capture the available braking energy and store the energy needed to accelerate the train.
- Has high storage and transfer efficiency.
- Conceptually and otherwise, simple and minimalistic in design.
- Safe in operation.
- Lightweight
- Cost effective.
- Easy to implement and operate.

Considering the merits i.e its high specific energy, compactness and operational/implementation simplicity and the demerits of the ESS system, it is found to be ideal and suitable for storage of regenerative energy. However, it was found lacking in storage/recharging efficiency and the transmission losses associated with energy conversion from mechanical energy to electrical energy. So, on an exploratory basis, a flywheel having a mechanical transmission was selected with the aim of overcoming these particular shortcomings of an Electrical regenerative braking system. With a flywheel ESS, high specific power can be achieved and depending on the design, high specific energy can be obtained as well. Additionally, flywheels have excellent recharge efficiencies and very long cycle lives. On coupling this with a mechanical transmission the conversion losses are eliminated as the mechanical braking energy is transmitted and stored in the same form. The other advantages being the system can be cost effective (depending on the design) and simple to recreate. The problems associated with flywheel systems are high weight addition and safety issues. Therefore most of the design goals are met with a Flywheel based Mechanical System. The Flywheel regenerative concept consists of a low/high speed flywheel with a mechanical transmission and this arrangement is to be directly connected to the wheel axle/spindle.

Flywheel Rotor Requirements

Due to the advancements in the technology, flywheels have become more complex and advanced. Nowadays, sophisticated Flywheels contain the kinetic energy in a high speed moving rotating drum which acts as rotor of a generator, when additional energy remains unconsumed, and then it is used to boost the rotary drum's speed. At instances where energy is required, then this drum drives the generator. These super flywheel rotors are made up of very strong: density ratio such as fiber materials from carbon. The rotor usually spins at an average speed of 100000 RPM thus requiring materials that are very strong which can withstand high exertion of centrifugal force. These rotors are mounted in a vacuum cavity to minimize the losses due to air friction. This friction loss can further be nullified using magnetic levitation bearings.



Mechanical Transmission

Figure 4: Mechanical Transmission using CVT

Overall Configuration

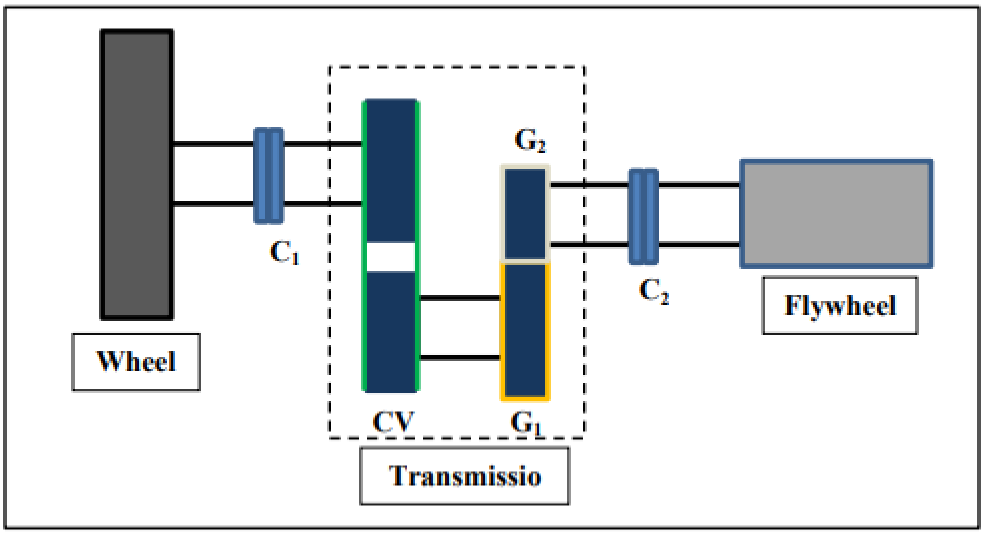


Figure 5: Overall Configuration C: Clutch; G: Gear CV G1 T

The overall construction of the system is presented. The Flywheel RBS consists of Low Speed Flywheel connected to a flywheel fixed gearing which is connected to the primary pulley of Rubber Belt VDP CVT through a clutch arrangement. The Secondary pulley is connected to the wheel through another clutch. The purpose of the flywheel fixed gearing is to provide an overall wide gear ratio range between the flywheel and wheel. The efficiency of energy transmission is given by:

$$n \text{ overall} = ncvt \times ngear$$

- where, n overall : Overall gear ratio at the wheel including that of CVT and flywheel
- n cvt : Gear ratio of the CVT
- n gear : Gear ratio of the fixed flywheel gearing

Note: In the coming sections, the design calculations for the flywheel regenerative braking are presented, and the regenerative Flywheel braking system is designed with the aim that the total inertial load of the train will be distributed equally between the axles of the wheels.

Theory of Operation

The Regenerative Flywheel braking system would operate in three modes: Regenerative-Braking, Acceleration-Boost and Neutral. The three modes are described below:

1. Charge mode /Regenerative-Braking: In this mode, the train energy is captured in the flywheel and the train is slowed down in the process. First, the CVT ratio is controlled so as to set the overall ratio to match the ratio between the wheel and the flywheel in their original states. After matching the speeds aided by the CVT, the clutches are activated to connect both the wheel and flywheel to the CVT. After the connection is established, the CVT ratio is changed continuously from the original high gear ratio to lower ratios so as to initiate the required energy flow from the wheel to the Flywheel. If the need for more braking arises beyond the limits of the CVT, the braking will be switched immediately to the default brakes of the train. During the charging mode, the VSC that interfaces the shipboard power system operates as a rectifier whereas the other acts as an inverter; the transferred energy accelerates the flywheel to the rated optimum speed. During this process, the flywheel stores energy inform of kinetic energy. Energy flows from the shipboard power system through the induction machine which acts as an energy converter to the flywheel.
2. Discharge mode /Acceleration-Boost: In this mode the energy stored in the flywheel is used for accelerating the train temporarily. In this state, the clutches are activated to establish connection and the CVT ratio is switched continuously from low to high so as to initiate an energy transfer from the flywheel to the wheel. Once the flywheel energy is reduced to a certain limit or the need for the acceleration ends, the clutches are deactivated to disconnect the system on both ends.
3. Stand-by mode/ Neutral: In the neutral mode, the system is disengaged with both the flywheel and the wheel through the clutches. The flywheel and the wheel rotate at their own speeds without any connection. This can be the case either when there is no need for Acceleration-Boost or regenerative assisted braking or when automatic disengagement when the flywheel to wheel speed ratio is less or more than the extremes of the f-RBS's transmission ratio. The control of actuator mechanism in the CVT and the clutches control the operation of the system and its modes.

Energy Available for Braking:

Actual available energy during braking is given by:
Actual Available Energy= (Kinetic energy –Losses)
The losses entails (rolling, bearing, aerodynamic etc.). The actual available braking for any braking instance can be obtained by getting the change in translational train's kinetic energy plus the change in rotating kinetic energy of the whole train (including that of wheels, etc.) minus the losses due to aerodynamic drag and rolling resistance. And for the total energy for the lap, it is the summation of the individual parts over the entire lap.

Flywheel design

The flywheel is the energy storage component of the regenerative braking system. In applications with frequent power requirements, flywheel as an ESS is an attractive alternative, with negligible losses in cycle and storage efficiency over time. According to the equation of the stored kinetic in a rotating flywheel, given by the equation:

$$EK_{rot} = ½ I\omega^2$$

Where:

- I stands for Fly wheel's Moment of Inertia
- ω stands for Rotating Velocity. It is measured as radians per second.
- K stands for Inertial constant

Flywheel designs are classified on the basis of angular velocities of operation and moment of inertia characteristics. On this basis, flywheel designs can be Low speed or High speed with Low or high moment of inertia. With the needs of the application, low speed or high speed flywheels are employed. Both the low speed as well as high speed flywheel design with different geometries may be utilized for the same stored energy requirement. Common materials like metals are usually employed for making low speed flywheels as they are heavy and are economical , although they do tend to have safety concerns of shattering at high speeds,. As for high speed flywheels, composite materials tend to be used, as they have high specific tensile strengths, consequently higher specific energies and also better failure characteristics at higher speeds.

The choice of material

The specific tensile strengths for different metals are calculated to determine the material with better specific energy capability. The material physical property data is obtained using Solid Works software.

Structural Analysis of the flywheel:

To understand the safe operation mode of the flywheel i.e. safety and failure characteristics of a high speed rotating flywheel with extremely high speed of about 8000Rpm, with very high torque while charging or discharging ,the flywheel structural analysis is carried out given by the equation:

$$\sigma_t = \rho\omega^2(\frac{3+\vartheta}{8})(r_i{}^2 + r_o{}^2 + \frac{r_i{}^2 r_o{}^2}{r^2} - \frac{1+3\vartheta}{3+\vartheta}r^2)$$

Where:
ωmax - maximum angular velocity at which the maximum tangential stress equals
σmax – is calculated for the Flywheel .
From the kinetic energy equation, it can be concluded that in order to maximize energy storage of a certain flywheel, either the inertia (I) or the operating angular velocity (ω) needs to be increased. Here, the inertia of any geometry is given by

$$E_{K,max} = kV\sigma_{max}$$

For any ω of flywheel the tangential stress peaks at r = ri , so if at a certain ω, σt at ri is greater than ultimate tensile stress for the material then the flywheel will fail and this would be give ω = ωmax - the maximum angular velocity of rotating disc at or after which the disc may fail . And, ωmax will determine maximum energy that can be stored without failing (EK,max) for the flywheel with a given I

Mathematical Modeling of Train with flywheel-Regenerative Braking System (f-RBS)
In this section, a basic mathematical model of the operation of a train with the flywheel regenerative is presented. The energy exchange between the wheel and the flywheel through the CVT/Transmission is modeled. In the derivation, the train is modeled as a wheel with an equivalent mass and moment of inertia of the whole train (including its rotating parts like all the wheels, driveshaft etc.). Consider a rotating flywheel with a moment of inertia (If), connected to a rotating wheel through a CVT,

$$E_f(t) + E_v(t) = C(constant)$$

$$\frac{1}{2}I_f\omega_f(t)^2 + \frac{1}{2}I_v\omega_v(t)^2 = C$$

$$I_v = mR_\omega{}^2 + I_{eq}$$

$$N(t) = \frac{\omega f(t)}{\omega v(t)}$$

$$\frac{1}{2}\omega_V(t)^2 \times \left(N(t)^2 I_f + I_v\right) = C$$

$$\omega_V(t) = \sqrt{\frac{2C}{(N(t)^2 I_f + I_v)}}$$

Where,

- Ef(t) : Flywheel’s Kinetic energy with respect to time t
- Ev(t) : Vehicle’s Kinetic energy with respect to time t

- m : Mass of the vehicle
- ωv(t) : Angular velocity of the vehicle/wheel with respect to time
- ωf(t) : Angular velocity of the flywheel with respect to time
- Rw : Radius of the wheel
- N(t) : Gear ratio with respect to time
- Iv : Equivalent moment of inertia of the whole vehicle

Using Equations above, the amount of energy transfer and the direction of energy transfer when the gear ratio between a rotating flywheel and wheel is forced to change, can be determined. For example, if the train, was travelling at 45 mph, and the flywheel of the regenerative Flywheel braking system is connected to is rotating at 3025 RPM, (gear ratio (N) = 4:1) then the energy transfer if the gear ratio was switched from 4:1 to a higher or lower gear is determined by the equations above.

Power of the system can also be included in the calculations to determine the time of energy transfer. In the calculations, it is considered that regenerative Flywheel braking system is acting on all wheels so the total inertial load of the train is distributed among the flywheels, i.e., the flywheel moment of inertia in the equation is equal to that of total number of flywheels.

TESTING

The implementation of the above design approach can be modeled and results of how the real system would behave by using either mathematical model as shown above or by using a simulation software i.e. Matlab. Virtual testing is among the computational methods developed recently to bridge the gap between the two approaches.

It is the process of testing any principle/product using Computer-aided tools by developing virtual prototypes and testing in conditions which can closely mimic actual conditions with close to realistic assumptions. This method of testing combines both the merits of the mathematical models and the computational tools which offers high levels of flexibility as the magnitudes of the parameters can be adjusted accordingly and the behavior of the system observed with changes in the parametric components. For most engineering problems, the real life physics can be simulated using Virtual testing, so most of the results of experimental testing can be generated with help of virtual testing. Due to its flexible and economical nature, it is a useful initial testing or supplemental tool to experimental testing.

Future Scope

Regenerative Flywheel braking system concept is a wide scope and has a lot of green areas which can be exploited further to increase its efficiency and to make its usability more preferential:

1. Integration of Computer aided control i.e use of SCADA to automate its operation i.e the CVT connection and disengagement.
2. Utilization of composite materials and carbon fiber as opposed to metals for high speed requirements, light weight and increased safety.
3. Vacuum and Containment Design for the flywheel for reduction of wind-age losses.
4. Bearing and clutch selection to reduce friction losses.
5. Use of Gear systems opposed to CVT can ensure more transmission efficiency.
6. Train standpoint as to how inclusion of two rotating/counter-rotating flywheels from two regenerative Flywheel braking systems can affect the dynamics of the moving train.
7. A more comprehensive failure and fatigue analysis for safety of the system
8. Control system design for the regenerative Flywheel braking system operation in conjunction with the train.
9. Cooling system design if required.
10. Physical/Experimental testing on a Rig and train.

CONCLUSION:

With the need of efficient and cost effective power source to power the traction power and the auxiliary functions of the train i.e lighting system and even fridges for freight trains transporting perishable goods, Flywheel regenerative braking system can be a very good concept to generate those energy requirements and stored in Energy storage devices thus cutting down the cost of overall energy requirement this therefore optimizes the revenue for the train operating company. This form of energy generation can be considered as green energy as it is tapped from the kinetic motion of the train as is braking, and this concept therefore is very important in reducing the energy consumption not only for the electric train but also for the diesel powered train thus in a given percentage particularly for the diesel powered trains it supplements its total energy requirements thus reducing fossil fuel emissions to the environment and thus reducing the global warming and general effects of climate change. This model can be made even more efficient by integrating with other renewable energy sources like solar panels to reduce to cost of train power demand.

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