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Regenerative Braking in Mass Transit

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SUMMARY

When a vehicle brakes using conventional braking, energy is created as heat by friction in the brake linings; however, all that energy is ordinarily lost and wasted. Regenerative braking is an energy recovery mechanism which slows down a vehicle or object by converting its kinetic energy into typically electric energy. The converted energy can alternatively be utilized immediately, stored until needed in energy storage systems, or transmitted elsewhere such as back into an electric grid. With regenerative braking, excess kinetic energy in these systems can be recaptured and found greatly advantageous to the applicators, leading to substantial energy savings.

Energy storage devices allow regenerative energy to be used efficiently; howbeit, regenerative braking can only be achievable with the use of a brake controller to manage it. Without the controller, the regenerative braking system is unable to determine the beginning, ending, or duration of break activation. In addition to improving the overall efficiency of locomotive transportation, regeneration also has the benefit of greatly lengthening the life of the braking system as its components do not deteriorate as rapidly. There are numerous advantages to the implementation of regenerative braking that explains the increased attraction to the technology worldwide.

KEYWORDS

Regenerative Braking, Brake Controller, Energy Storage Systems

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1. INTRODUCTION

Our need to diminish usage of fossil fuels to reduce the climate change effects has resulted in an increased interest in regenerative braking technology. Half a century ago, electric locomotives began replacing steam engines and the revolutionary advance of dynamic (regenerative) braking came about making transportation more safe and efficient [1]. First used in trolley buses and electric trains, the feature was found in the electric locomotives as a way to reduce wear and tear on wheels and brakes shoes, along with enhancing train-control [2]. The main difference between regular dynamic braking and regenerative braking technology is that the regenerative aspect does not waste the dissipated heat, but instead returns the generated power to the overhead or trackside distribution system that electric locomotives operate through [3]. Dynamic braking is termed regenerative once the recaptured energy is recovered by the supply line; however, it also lowers energy consumption as a whole [1]. Railways are the backbone of a sustainable transport system and in order to continue improving energy efficiency and savings and reduce their climate change contributions, investment in technological innovations must continue [4].

A key characteristic to consider in implementing regenerative braking is the type of rail lines. There are both AC and DC locomotives in use. With the change from direct current to three-phase asynchronous traction motors, potential benefit swung in favor of AC electrification. AC locomotives are more compatible with the regenerative braking technology and will in turn allow a higher profit from the technology applications for the future points mentioned, for example, urban train systems [5]. Also, the type of route can influence how useful regenerative braking is. The ideal type of travel that maximizes its capabilities is stop and go travel where there is fast acceleration and abrupt stopping [6].

Throughout this paper, research will be provided along with an explanation of how regenerative braking works, most beneficial situations for regenerative braking, and requirements of the technology. Proceeding, the break controller's importance is put into perspective and benefits and challenges of regenerative braking are laid out. Information on energy storage systems available and current implementations worldwide will follow and finally close with a conclusion rounding up the main focus on regenerative braking.

2. THEORY

Generating movement for a vehicle generally requires a large input of energy and every time the brake is activated, all of the built up energy is converted to heat. When in motion, energy flows from the electric power supply to the motors, providing kinetic energy and turning the wheel in order to move. Once the brakes are initiated, the process proceeds in reverse and electric circuits cut the power to the motors [6]. In a regenerative braking system, kinetic energy and momentum make the wheels turn the motors. Therefore, the motors act like generators as they produce electricity rather than consuming it [7]. Consequently, the energy flows to batteries on-board to charge or to the electric power supply from the motor-generators.

In the case of locomotives, the regenerative energy can be fed back into the distribution grid for supplying stationary loads at train stations or used to charge railway car-mounted storage containers, which can additionally supply stationary loads or be transported elsewhere for supplying remote loads. Regenerative braking is substantially more beneficial the more frequently a train stops. Hence, the braking technique is especially valuable for commuter trains and subways [6]. The kinetic energy recoverable from regenerative braking is calculated as in (1). However, the equation must be reduced by frictional and efficiency losses in the system. Also, in the situation where a mobile vehicle comes to a complete stop, the initial kinetic energy is calculated as in (2) which can be easily rearranged to solve for the energy lost.

$$KE = 0.5mV^2 \tag{1}$$

$$Initial\ Kinetic\ Energy = \Delta Stored\ Enegy + Energy\ Lost \tag{2}$$

where *KE* is kinetic energy, *m* is the mass, and *V* is the velocity. When regenerative braking technology is applied to full stop service commuter trains and to very dense suburban trains, substantial CO_2 emission reductions will transpire. Employment of regenerative braking on commuter trains will reduce emissions by approximately 8-17% and network trains will reduce emissions by approximately 30% [8].

3. REGENERATIVE BRAKE CONTROLLER

A brake controller is fundamental to regenerative braking functioning properly. The electronic device enables remote brake control. Without the controller, the system is unable to determine when to begin braking, end braking, or how quickly the brakes need to be applied [6]. In vehicles using regenerative braking, the controller not only monitors the speed, but also calculates the rotational force (torque) available to generate electricity to be fed back into the batteries or the electric grid. In the midst of braking operations, the brake controller guides the energy produced into the batteries/energy storage devices from the motor making sure an optimal amount of power is received. Another essential element is ensuring the amount of inflowing electricity isn't exceeding what the batteries can handle. The rotational torque, T_R, is related by:

$$T_R = \frac{i \cdot N \cdot T_{REG}}{\eta} W_1 W_2 \tag{3}$$

Where T_R is the rotational torque, i is the continuously variable transmission speed ratio, N is the final reduction gear ratio, T_{REG} is the regenerative torque by the motor, η is the generation efficiency, and W_1 and W_2 are weight factors [7-8].

The most imperative function of the brake controller, perhaps, may be determining whether the motor is presently competent of handling the force necessary for bringing the vehicle to a halt, based on the speed and inertia. If the motor is incapable, the brake controller deviates the operation over to the friction brakes, averting possible catastrophe. In vehicles that use the regenerative braking technology, the brake controller makes the entire regenerative braking process attainable [6].

4. OPPORTUNITIES FOR REGENERATIVE BRAKING

Regenerative braking is starting to be recognized as an unharnessed source of energy and a potentially very beneficial technology of the future. Due to the numerous benefits that regenerative braking offers, many corporations are beginning to fund and implement a developmental process for these systems. In addition to improving the overall efficiency of the transportation, regeneration can also greatly extend the life of the braking system as its parts do not wear down as quickly. Slower degradation of the braking system lowers maintenance costs of the mechanical brakes and requires fewer replacements. Consequently, regenerative braking has potential to reduce the down-time of trains [8].

Another perk of regenerative braking is air quality improvements. Lowering electricity demand will lower the emission of air pollutants: SO_2 and NOx [8]. Fossil fuel use in power generation is notably decreased also resulting in less carbon output. There has been a colossal movement to reduce these types of emissions in recent years in order to lessen global warming and climate change. Many transportation systems are owned by cities or states so they are using regenerative braking as a way to meet certain regulatory requirements in emission cutbacks and energy reductions. Energy consumption savings, lower emission yield, and break wear deterioration avoidance are valuable factors of regenerative braking. These technical and environmental advances are paramount in the railway industry and cannot be overlooked.

5. CHALLENGES

If the regenerative energy produced exceeds the energy required by loads, the extra energy would raise the distribution at the station or capacitors located on the trains. Unfortunately, these cases cause regenerative braking technology to fail in regards to supply and conventional braking systems like friction braking would take over to decelerate and come to a complete halt. Dynamic braking is not as common as ideally hoped at this point; the technology cannot be fully relied on so dynamic braking must be used in conjunction with friction braking in an electrical system as both a backup and a way to cease motion. The dynamic braking effect quickly diminishes in minimal speeds less than 10-12 mi/h and therefore conventional friction braking is usually needed to come to a virtual stop. Consequently, regenerative brakes cannot save 100 percent of the braking energy. Additional complexities and costs must be added for multiple systems.

Another challenge to take note of is AC locomotives versus DC locomotives. DC powered locomotives have barriers of relatively low voltages and hindrance of feeding generated electricity back into the public grid [8]. Currently, the effectiveness of regenerative braking in DC locomotives is rather low but it may be enhanced by possible technological upgrades of vehicles and/or substations. Unfortunately, these upgrades usually come with relatively high investment costs due to expensive technology and equipment [10]. AC powered locomotives, on the other hand, complement regenerative braking well and these systems can be implemented with practically no additional costs [8]. For the recaptured energy that is not immediately used and planned to be stored, all energy storage systems have individual drawbacks.

6. ENERGY STORAGE SYSTEMS

One way to capture the energy from regenerative braking in locomotives is to use storage systems. Energy storage devices allow regenerative energy to be used efficiently by improving the stability of DC supply, lowering the peak load at train stations, and reducing heat in subway tunnels. There are four main energy storage devices considered when storing the regenerative energy: battery storage, ultracapacitor storage, flywheel energy storage and superconducting magnetic energy system (SMES). Each storage device has advantages and disadvantages to consider.

6.1 Battery Storage
Battery Storage has not been commonly used in regenerative braking for traction systems because it has low power density, low energy efficiency, and charge-discharge cycle limitations. However, a metro in Germany has been utilizing this storage technology since the 1990s. Regenerative braking however, allows batteries to be used for longer periods of time without the need to be plugged into an external charger which is a huge advantage and extremely convenient. This is a completely electric application [11].

6.2 Ultracapacitor Storage Systems
Ultracapacitor Storage Systems are an electric application like battery storage; however, they offer a low voltage capacity and connection via series parallel modules. This system has potential to fail when there is any major wavering in ultracapacitor parameters because it results in voltage fluctuations. The capacitor therefore experiences a shortened service life and a notable reduction in its reliability for regenerative energy applications [12]. Consequently, the capacitors are designed rather small; thus the capacitor cannot fully absorb the regenerative energy generated by several trains on high traffic railways. Several implementations of ultracapacitor systems have appeared in Europe and Asia: Frankfurt, Germany, Madrid, Spain, and Beijing, China [11]. Beijing saves an estimated $3.6 million annually across 16 stations using the ultracapacitor storage system.

6.3 Flywheel Energy Storage

The basic idea is rotating part of the engine that incorporates a wheel with a very heavy metal rim, which drives the vehicle the engine is connected to. Huge momentum is generated where significant effort is required to stop or change speed [10]. The flywheel also acts as a compensator allowing the vehicle to run smoother. Other advantages of Flywheel Energy Storage Systems include high energy density, high reliability, easy maintenance, low environmental impact, and low impact charge-discharge cycle [7]. A disadvantage is the extra weight from the heavy metal rim, which depletes energy having to carry around all the time. Nonetheless, it cannot store energy for a long time, making it suitable for a short discharge time and high-power applications. Currently, Flywheel Energy Storage Systems have been applied in the New York City subway in New York and in the tramway in Hong Kong, China [11].

6.4 Superconducting Magnetic Energy Systems

Lastly, SMES can store energy for a prolonged period with efficiency higher than 95%. It also offers a large storage capacity, fast response time, simple maintenance, pollution free energy production, easy manipulation, and increased longevity. SMES has not been widely utilized for large scale station applications for a multitude of reasons: superconductive material production limitations, high refrigeration and operation costs, and research of protection/ecological influence of high intensity magnetic fields [11].

7. EXISTING IMPLEMENTATION

More and more applications of regenerative braking technology are surfacing as awareness and concern over fuel shortages and costs grow. Taking notice in the fuel and energy saving capabilities, companies in the United States, Europe, and Asia have all taken steps to implement the innovative, regenerative braking technology.

A common application situation for the implementation of regenerative braking technology is in new high-speed trains. Japan, France, India, New Zealand, and Germany have all stepped forward and made an initiative to execute the utilization of regenerative braking technology [5]. It is feasible to use regenerative braking technology on high speed trains because most cars have their own electric motors, contrasting with trains in which only the locomotive has electric motors. Another form of regenerative braking is used underground in England. Small slopes lead up to and down from the stations allowing for the train to slow up the slope and regain kinetic energy later converting to gravitational potential energy as it travels down the slope [8]. With their motors functioning as generators, locomotives on downgrade trains could literally provide power to other trains going uphill.

In 2012, a Northeastern transportation company in the United States used a $900,000 state grant to install batteries and a controller wayside. That year, the company also secured a $1.44 million grant from the Federal Transit Administration to test a hybrid system, combining batteries with supercapacitors [13]. The batteries are saving energy costs and turning the transportation company into an electricity provider. The company could save up to $190,000 a year in energy costs and reduce energy use by 30%. Each project is expected to have a three-five year payback [8]. Also, a utility company in Illinois plans on partnering with the public transit system in order to implement similar regenerative braking technology as the Northeastern transportation company mentioned previously.

An intercity passenger train service has received the first of 70 high-efficiency electric trains destined for routes across DC, Massachusetts, New York, and Pennsylvania in the United States. Each train will have an engine centered on the regenerative braking technology and can recover up to 5MWh of energy, most of which is sent back to the grid [5]. In the Northwest United States, a light rail line has been designed so that power captured from braking trains can power accelerating ones due to regenerative braking [12, 13]. They use a system that utilizes a massive supercapacitor to store up the energy which allowed them to avoid the costly installation of a utility substation along the line. In 2009, a metropolitan transportation authority in California received a $4.5 million stimulus fund through the Federal Transit Administration to install a wayside energy storage substation (WESS). The transit administration decided the optimal clean energy storage system would be a flywheel storage system for this application. Many of these energy storage systems are beginning to surface in large scale applications.

8. CONCLUSION

Even though regenerative braking technology dates back over 60 years, companies are finally realizing its worth [5]. The energy harvested using regenerative braking technology is imperative. Utilities nowadays are starting to invest in smart technology that uses information and communications technology and is energy efficient. Regenerative braking fits as a smart city initiative with its numerous benefits. Some utilities are taking advantage of this opportunity regarding regenerative braking to partner with rail companies in order to further the development of smart cities and meet energy regulations.

The regenerative braking technology enables energy to be utilized more wisely. Applying regenerative braking to an AC powered locomotive is the best bet to implement the technology on for receiving optimal benefits. Although there are a few obstacles, regenerative braking has far more advantages that outweigh the negatives. In a world where fuel is becoming more and more costly and environmental concerns are increasing exponentially, this is incredibly vital. Regenerative braking is a small, yet very important, step toward our hopeful independence from fossil fuels.

BIBLIOGRAPHY

[1] McGonigal, Robert S. "Dynamic Braking, Power For the Down Grade." (Trains. Web. 14 July 2015)
[2] "Regenerative Braking." (CyberPhysics. Web. 14 July 2015)
[3] Woodford, Chris. "Regenerative Brakes." (Explain That Stuff! 22 Aug. 2014. Web. 14 July 2015)
[4] "Energy Efficiency Days." (UIC Energy Efficiency Days 2014. June 2014. Web. 14 July 2015)
[5] "Regenerative Braking Boosts Green Credentials." (Railway Gazette. 2 July 2007. Web. 14 July 2015)
[6] Lampton, Christopher. "How Regenerative Braking Works." (How Stuff Works. Web. 14 July 2015)
[7] "Regenerative Braking System." (Engineering Rox. 23 May 2013. Web. 14 July 2015)
[8] "Regenerative Braking in Trains." (Climate Tech Wiki, a Clean Technology Platform. Energy Research Centre of the Netherlands (ECN), Policy Studies, Web. 14 July 2015)
[9] Hoon Yeo, Donghyun Kim, Sungho Hwang, and Hyunsoo Kim. "Regenerative Braking Algorithm for a HEV with CVT Ratio Control During Deceleration." (Sungkyunkwan University. Web. 14 July 2015)
[10] "Regenerative Braking in DC Systems." (UIC Energy Efficiency Technologies for Railways. 9 Oct. 2002. Web. 14 July 2015)
[11] Y. Jiang, J. Liu, W. Tian, M. Shahidehpour, and M. Krishnamurthy "Energy Harvesting from Regenerative Braking of Trains for the Electrification of Railway Stations," (IEEE Electrification, Vol. 2, No. 3, Sept. 2014, pp. 39-48)
[12] Barry, Keith. "Portland's Light Rail to Power Trains With Regenerative Braking." (WIRED. 14 June 2013. Web. 14 July 2015)
[13] Levitan, Dave. "Transit Systems Have Started to Save Lots of Energy." (Scientific American. 5 May 2014. Web. 14 July 2015)
[14] Fingas, John. "Amtrak to Roll Out High-Efficiency Trains With Regenerative Braking (video)." (Engadget. 14 May 2013. Web. 14 July 2015)