

Regenerative Braking: A Good Source of Green Energy

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Abstract - This paper attempts to highlight the role of green energy through regenerative braking, especially on railway traction made possible with advanced electronics and three phase AC traction motors. Transport sector is a major contributor to air pollution and global warming. In metropolis vehicular and industrial pollution and peak energy requirement further aggravate the grim situation. Energy savings, reduced emission, reduced brake wear, extra peak power are some of the many benefits of regenerative braking.

Regenerative braking on DC traction, AC traction, hybrid diesel/battery traction; issues such that receptivity, over voltages, loss of regeneration at higher speed and remedies thereof such that of onboard energy storage devices have been deliberated. Ni-H battery, pure electric braking, electric traction without catenary, hybrid car may make it more rewarding in future. It would go a long way to save fossils and contribute to reduce air pollution and global warming.

Keywords: regenerative, renewable, energy, railway, traction, transport, suburban, metro, braking, hybrid, global warming, receptivity, battery.

I. INTRODUCTION

Among all forms of energies those exist, *Green Energy* is the need of day in this world struggling with global warming and its potential hazards to the very existence of living beings on planet Earth. Yawning gap between desirable and current scenario in foreseeable future is a matter of serious concern. The sustenance of life is critically dependent on energy transformations and since only a tiny fraction of the original chemical energy in fossils is used for work, efficient transformation is, therefore a necessity at least till such time renewable energy sources take over a significant portion of total energy requirement.

II. GREEN OR REGENERATIVE ENERGY

Green or regenerative energy includes natural energetic processes or persistent flows of energy in the immediate environment that can be harnessed with little or no pollution. Anaerobic digestion, geothermal, wind, small-scale hydro, solar, biomass, tidal and wave energy fall under such a category. Regenerative or renewable energies naturally renew themselves within human timescales. These are derived from sustainable alternative sources of energy as

opposed to non-renewable or polluting energy sources, which sometimes referred to as '*Brown energy*'. By definition these are very different from fossils (coal, natural gas, oil) and atomic fuel, which took millions of years of geological processes. Proven fossil resources are limited; however newer discoveries of materials and technological developments to harness solar and other renewable energies, rekindle hopes for their sustenance and rapid augmentation in years to come.

Renewable resources however look promising for sustainable development as seen from rapid growth of 261% in other renewable and substantial increase in their share 0.57% to 1.59% in the total primary energy consumption [1, 2]. Growth in installed capacity of wind energy from 24.84GW to 238.49 GW and solar energy from 1.76GW to 69.37GW from 2001 to 2011 are remarkable. More significant is growth in generation from these two renewable sources, see Table I. But considering potential of solar, which is 7500 times the world's current annual primary energy consumption, progress on large scale is yet to be seen.

TABLE I
RAPID GROWTH IN CONSUMPTION OF OTHER
RENEWABLE THE PREVIOUS LAST DECADE [1]

Energy consumption	1991	2001	2011	Growth
Total primary energy (mtoe)	8146	9434	12274	30%
Oil (mtoe)	3157	3596	4059	13%
Natural gas (mtoe)	1808	2215	2906	31%
Coal (mtoe)	2176	2381	3724	56%
Nuclear (mtoe)	474	601	599	-
Hydropower (mtoe)	501	587	791	35%
Other Renewable (mtoe)	30	54	195	261%
Other Renewable (TWh)	131	238	862	261%
- Solar (TWh)	-	1	56	5500%
- Wind (TWh)	4	38	438	1053%
- Geothermal, biomass and others (TWh)	127	199	368	85%

III. TRANSPORTATION

Energy supply, **transport**, industry & forestry are fast rising contributors to global greenhouse gases (GHG) emissions. CO₂, CH₄, N₂O, SF₆, HFC (Hydro Fluorocarbons) and PFC (Per Fluorocarbons, organic compounds that contain carbon and fluorine bonded together in strong C-F bonds) are major anthropogenic GHG having varying global warming potential (GWP) and regulated under Kyoto Protocol. CO₂ though has least GWP but most significant amongst GHG and growing. Transport sector causes about 20% of the global CO₂ emissions, and it is one of the sectors where CO₂

emissions increasing the most. CO₂ Emission is proportional to the population, output per head, energy intensity of output and carbon intensity of energy.

Mobility increases with growing economy. So there is a need to plan and develop a more sustainable mobility. Road is responsible for 84% of transport sector emissions, and a trip by airplane is 5 times more polluting than train [3]. CO₂ advantage of Railways and Public Transport offer a way forward as the backbone of any sustainable transport systems. The needed modal shift has to be accomplished by appropriate interventions and integrated transport policies.

IV. BRAKING

Brake is an integral part of any transport. For slowing or stopping the motion of a vehicle, or to restrain it from starting to move again, some kind of braking is required. In the conventional braking process, the kinetic energy of the moving part is usually converted into heat by friction and getting lost. Thus braking not only results into loss of energy and brake wear, as seen in Figure (1); it also needs additional energy for brake application, e.g., disc or drum brakes on automobiles, see Figure (2).

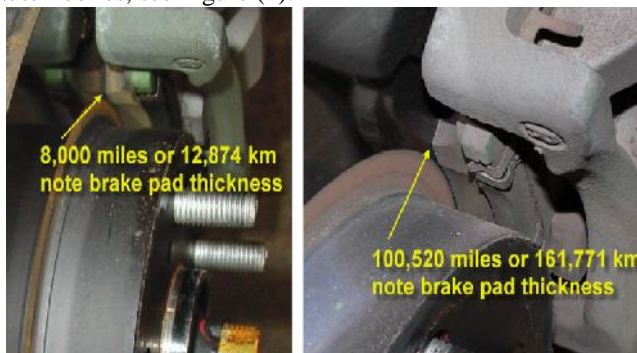


Figure (1): Brake wears 8k to 100k miles

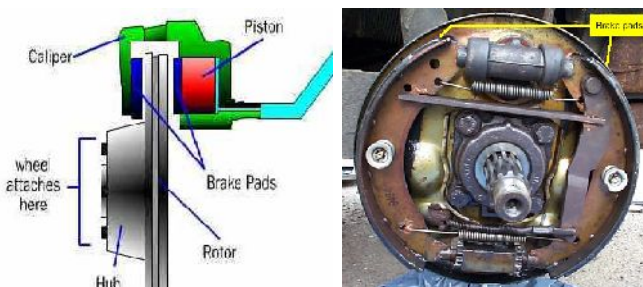


Figure (2): Working of disc and drum brakes

Alternatively, in regenerative braking, most of the kinetic energy ($E = \frac{1}{2}mv^2$) is recovered and stored in a flywheel, a capacitor, a battery for later use or fed back to the grid instantaneously. As mass or velocity increases (high speed passenger trains or heavy haul freight trains), a significant amount of energy gets lost where regenerative braking is not used. Dynamic brakes dissipate the electric energy regenerated as heat through a bank of resistors thus saving on brake wear but they are not regenerative in true sense.

V. REGENERATIVE BRAKING

When a motor turns faster than the commanded speed as set by its drive, the motor in effect acts as a generator. An example of this would be the control of an elevator car as it descends or brake application on moving rail/road vehicle having regeneration capability.

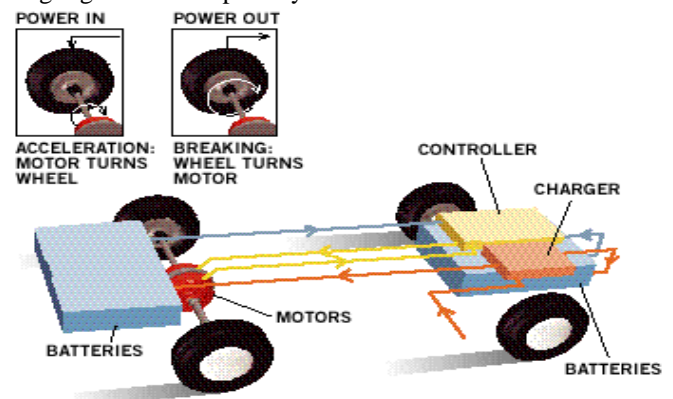


Figure (3): Working of regenerative brakes

During regenerative braking vehicles' electric motor is reconnected as a generator and its output is connected to an electrical load, which provides the braking effort, see Figure (3). The current thus generated could be employed either for rheostatic/dynamic or regenerative braking.

VI. TRANSPORTATION & REGENERATIVE BRAKING

Amid a growing concern on environmental issues, global warming, climate change, air pollution; the transportation industry is embracing regenerative braking as a means to save energy and reduce maintenance costs. Rising fuel costs provide momentum to these efforts. In regenerative braking on railways, the regenerated current is either returned to the overhead line/third rail or stored in onboard energy storage devices. Three types of traction systems are given below:

A. DC traction

Regenerative braking became popular for normal service braking in the DC traction era of the late 1960s after a humble beginning of its application for steep and long down gradients in the 1930s. In the 1980s, AC motors started replacing DC motors and regenerative braking capability became inherent. DC trains using inverter-fed AC traction motors have similar torque speed characteristics in powering and braking modes. Braking power in regenerative mode can be around 30% greater than that of powering but inferior to dynamic braking where braking power typically exceeds two and half times that of powering. Regenerative braking on existing DC traction has additional disadvantage due to high currents, up to 4000 A on a 750 V DC line, poses a risk that current from a regenerating train could prevent the protection equipment in substations from detecting an earth fault in the supply. However, this can be prevented by linking the protective systems of adjacent substations, known as *inter-tripping*.

B. AC traction

On AC electrified lines, the introduction of power electronics made regenerative braking with DC traction motors technically feasible. With the change from DC to three-phase asynchronous traction motors, the potential benefit from regenerative braking swung significantly in favour of AC traction as the complete traction package became reversible. Thus large scale DC to AC traction conversion projects became economically viable, significant one in Indian subcontinent is 319 route km DC traction network of Mumbai suburban, which was taken up for conversion into AC traction at an estimated cost of INR 11.17 billion [4]. EMU with regeneration capability using three phase traction motors are regenerating up to 30% of energy consumed, more so on slow corridor, characterized with stop at all stations. When fully implemented, 193 EMU rakes in 9, 12 and 15 car combination would help reduce CO₂ emission by 380,000 tonnes, save 443 million units of electricity annually while transporting 7.2 million commuters daily on 2650 number of train services [5].

C. Hybrid diesel/battery traction

An early example of the regenerative brakes on automobile was developed in 1967 for the *Amitron*, an American electric concept car, to increase the range of the automobile. Hybrid traction system using a diesel-alternator and battery can utilise regenerative braking effectively, thus facilitate the diesel engine to operate at higher efficiency. Hybrid system cut fuel consumption up to 20%. To reduce emissions the engine can be switched off in standing condition, and started as the train approaches 30 km/h. On-board stored energy from braking, which would otherwise be lost as heat, is utilised to start the train and up to achieving speed of 30 km/h. After allowing for energy losses in charging and discharging, 80% of the regenerated energy becomes available for the next powering cycle.

VII. ISSUES AND REMEDIES

A number of issues obstruct implementation of regenerative braking. But with continuous research and development, growing cost of energy supplies and environmental concerns, these issues are getting resolved.

A. Receptivity

A DC substation using diode rectifiers cannot pass regenerated energy back into the grid, so it can only be consumed by other accelerating trains in the same feeding section. On a busy suburban service at peak times receptivity can be as high as 15% whereas on long sections with low service frequency it can fall below 5%. Even if enough trains are accelerating, where there is a long distance between the source and the load, the pantograph voltage tends to be high because of the line resistance. In such cases, the regenerating current itself has to be limited so as to avoid excessive voltage on the regenerating train.

Countermeasures to improve this situation include: lower circuit resistance of the DC feeders; additional power-consuming equipment in the substation or elsewhere along

the trackside; an additional inverter in parallel with the rectifier enabling surplus power to be fed back into AC grid and two-way power converters instead of conventional rectifiers. To reduce the feeding circuit resistance of double-track DC lines, unified electric feeding of down and up lines can be used for improved regenerative braking.

Effectively 25 kV AC electrification provides unlimited receptivity allowing electric braking to be the normal operational mode. With receptivity no longer an issue, energy savings up to 17% can be achieved on inter-city routes and much higher (up to 30%) savings on suburban services and metro services owing to frequent starts and stops.

The *Pendolino*, an Italian family of tilting trains, is able to achieve very high level of savings because of its distributed power configuration with motored axles along the train. The quoted energy recovery is double that achieved using the end power cars. New trend in high speed trains is distributed power, e.g., *French AGV*, a successor to TGV trains; the name stands for *automotrice à grande vitesse*, or 'high-speed self-propelled carriage, and thus more regenerated energy.

B. Regeneration at higher speed

AC-motored EMU with regenerative braking capability on DC traction have two associated problems: occasional regeneration failure due to lack of line receptivity and inferior braking characteristics at the higher speeds when compared to dynamic braking. These problems can be addressed by introducing on-board and/or wayside energy storage devices.

C. Over voltages

The quantitative difference between powering and braking on DC trains using inverter-fed AC traction motors arises from two factors: the voltage drop between substation and pantograph, and mechanical and electrical losses. In regeneration mode over-voltage capability cannot be used because the motor voltage is restricted by the catenary voltage. To cope with this situation, the two difficulties should be eliminated simultaneously by achieving over-voltage at the traction motor without much increase in pantograph voltage, and to reduce over-current from pantograph to the feeding system. On 1.5 kV DC traction, typical voltage drop may vary from 18% to 24%.

D. Energy storage devices

Regenerative braking has been a long-standing feature of developed Railways. Energy storage technologies are getting more attention to overcome receptivity issues. On-board and wayside energy storage devices (ESD) combining higher power and energy density with acceptable losses and longer life, such as lithium-ion or nickel-hydrogen (Ni-H) batteries and electric double-layer capacitors (EDLC), promise more efficient train operation. On-board energy storage are an accepted means of conserving energy.

E. Double-layer capacitors (EDLC) or ultra capacitors

Electrolytic double layer capacitors (EDLC) has much higher power density as well as a much longer life than a Li-ion battery, but the energy density is inferior. EDLCs are efficient, compact and capable of extremely high power cycling. There are no moving parts and no routine maintenance. The energy content and the power capacity of

EDLC storage units can easily be scaled by connection in series and parallel to meet the requirement.

EDLC development is focussing on better relationship between power density and energy density, together with internal resistance. EDLC represent the most innovative energy storage technology and can be considered as the future for onboard energy storage. On Electric Vehicles EDLC can achieve higher accelerations and braking with least stress on battery and minimum energy losses.

IGBT Buck-Boost module is connected to the ultra-capacitor bank at the Boost side, and to the main battery at the Buck side. The control of the system measures the battery voltage, the battery state-of-charge, the car speed, the instantaneous currents in both the terminals (load and ultra-capacitor), and the actual voltage of the ultra-capacitor. A microcomputer control manipulates all the variables and generates the PWM switching pattern of the IGBTs. When the car runs at high speeds, the control keeps the capacitor discharged. If the car is not running, the capacitor bank remains charged at full voltage. Medium speeds keep the ultra-capacitors at medium voltages, to allow future accelerations or decelerations.

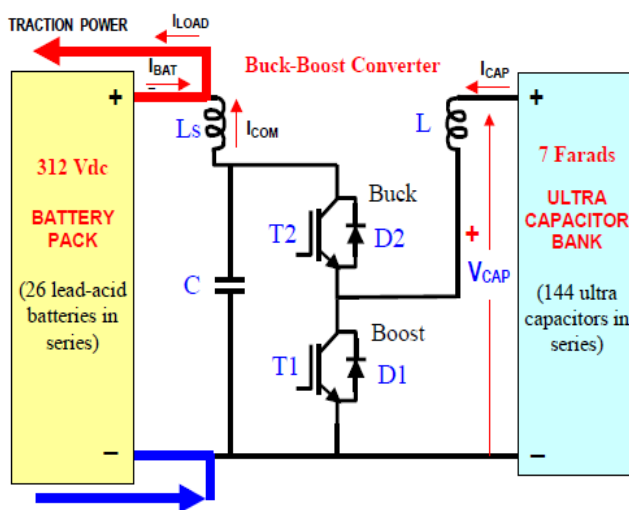


Figure (4): Ultra capacitors in buck-boost mode

The battery voltage is an indication of the car instantaneous situation. When the vehicle is accelerating, the battery voltage goes down, which is an indication for the control to take energy from the ultra-capacitor. In the opposite situation (regenerative braking), the battery voltage goes up, and then the control needs to activate the Buck converter to store the kinetic energy of the vehicle inside the ultra-capacitor. The battery state-of charge is used to change the voltage level of the ultra-capacitor at particular values. If the battery is fully charged, the voltage level of the capacitors is kept at lower levels than when the battery is partially discharged. IGBT controlled power resistor is used to dissipate energy when it cannot be accepted for the ultra-capacitors or the battery pack.

VIII. BENEFITS OF REGENERATIVE BRAKING

A. Energy saving potential

About 90% of the energy drawn by a typical urban rail vehicle is used for traction and 10% for auxiliaries. Up to 40% of the total energy consumed is theoretically available to be recovered. Without energy storage, a typical urban rail network might save about 15% of the total energy through regenerative braking. With efficient energy storage, this proportion might rise to 35%, or even 40%, average can be estimated at 24%. Assuming an energy storage unit on EMU train saving 55 kWh per hour for 350 days @ 20 hours a day, annual saving would be 385 MWh.

Feeder routes to iron ore or coal mines where loaded train moves down the hill provide substantial savings potential (up to 200%) through regenerative braking as train moving up the hill are usually empty. Distributed power on such freight trains in the form of electric multiple units, as used for passenger carrying, may further improve regeneration.

B. Reduced greenhouse gas (GHG) emission

In spite of limitations, regenerative braking can immensely contribute to overall energy efficiency of Railway systems. With demand side management, it helps to improve overall energy intensity and bridge the gap between demand and supply. With the reduction in energy requirement, GHG emission gets reduced which helps developed nations contain emission in line with 'Kyoto protocol' and developing one to earn carbon credits thus generating additional revenue.

In view of ever increasing electricity demand, world will be immensely benefited by green energy through regenerative braking. It would effectively lower cost of transport in general and railway transport in particular and help it attract more traffic from inefficient modes such as road. This would enable conservation of fossils; reduce global warming and extreme events caused by climate change.

C. Brake wear savings

While growing environmental concerns have resulted in the promotion of energy recovery as the principal benefit of regenerative braking, demand on friction brakes gets reduced significantly, in addition to operational advantages due to reduced maintenance time and costs. Incidentally, brake pad replacement and brake gear maintenance is one of the biggest constituent of maintenance cost in friction based braking.

On a three-phase drive trains operating on the 25 kV AC on commuter services characterised by frequent stops, disc pad life of 18 months reduce to just 18 days when the electric braking is switched off. With advent of 'Pure electric braking' it may be possible to eliminate brake wear.

D. Extra peak power

In addition to saving energy, storage units can reduce line voltage fluctuations and provide peak power when it is most needed. This can be used to improve the acceleration of trains during peak periods, especially in situations where traffic has grown and the existing supply can barely cope up. Under the most onerous condition with both rectifier and storage unit switched off the bus bar voltage may drops to 620V (by 17%) as the train struggle to draw 1200A. The voltage at

pantographs closest to substation would, of course, be even lower, and acceleration would be poor. With the storage unit, the voltage can be maintained at 700V while the cars accelerate, drawing 1200A consistently.

Alternatively, where a line is being extended, it is possible to space the substations further apart and locate energy storage units halfway between them, with a view to installing rectifiers at these locations later on when traffic built up.

On the hybrid trains, battery power alone accelerates from a standstill. With adequate peak power available, energy management system blends power from the vehicle's diesel engine as the speed reaches 30 km/h. Thus energy management system ensures the engine to run at its most efficient speed, with excess power not required for traction being diverted to the charge the battery. The energy management system automatically draws on the battery when more power is needed, either on an adverse gradient or for further acceleration.

IX. FUTURE PROSPECTS

As old locomotives and EMUs are due for renewal, it is an opportunity to adopt regenerative braking technology on all metro, suburban or mainline services in the future. The potential for faster acceleration using onboard ESD offers an opportunity to increase capacity on the congested networks.

The use of battery and EDLC for energy storage is also seen as a possibility, where the costs of adapting existing hardware for regeneration may be high. It may bring benefits of regenerative braking on high speed lines, which are not currently able to benefit from regeneration.

A. Ni-H battery

Li-ion battery is the best device for high density energy storage per unit mass, but there are two problems still to be solved before practical widespread application. Power (as opposed to energy) density needs to be improved, and battery life in relation to the practical depth of charging and discharging has to be extended. Concept of Ni-H battery called 'Gigacell' for on-board energy storage may produce a full-scale LRV to run without catenary. Battery life currently estimated at 8 to 10 years, may improve as the technology matures. This can be compared with the silicon chip market, where rapid technological progress brought huge increases in capabilities at the same time as costs fell.

B. Pure electric braking

'Pure electric braking' proposed after successful trials in 1997, is now very popular technology for electric braking down to a complete stop. With distributed traction motors, normal service braking can be all-electric, with the friction braking used only for emergency stops and for bringing the train to a halt that too can also be done away with in future.

C. Electric traction without catenary

On-board energy storage is not only a means of conserving energy; it can avoid the erection of overhead wires in scenically sensitive or historically important urban areas, especially for light rail and tram. A Li-ion battery tram

developed by the Railway Technical Research Institute (RTRI) is known for its ability to run without catenary [6].

D. Hybrid power cars

With experience gathered from hybrid system, fuel efficiency of has gone up substantially, as can be seen for some selected top models in Table II.

With more efficient and effective usage of regenerative braking and advancement in electricity storage technologies, hybrid and electric cars may provide an alternative mode of personal transport, whereas Railways (metro, suburban and mainline) and hybrid buses are used for public transport. This would help to reduce hydrocarbons usage while enjoying reduced pollution and GHG emission as an icing on the cake.

TABLE II
 MILEAGE OF TOP HYBRID CARS [7]

	Mileage (km/h)	CO2 (g/km)
Hatchbacks		
Kia Rio 1.1 CRDi EcoDynamics	38	85
Skoda Fabia 1.2 TDI CR	35	89
Volkswagen Polo Bluemotion TDi	34	91
Toyota Auris HSD	32	89
Saloons and small family cars		
Volvo S40 DRIVE	32	99
Toyota Prius T3 Hybrid 1.8 VVT	29	89
Volkswagen Passat 1.6 TDi	28	114
BMW 1 Series 116D	27	117

X. CONCLUSION

Regenerative energy provides distributed generation (DG) to loads in close proximity if not stored in battery. One unit (megawatt-hour, MWh) generated near load with a distributed generation can, depending on grid location, displace up to 1.45 MWh of grid power. During peak, each peak MWh from DG can displace 2 MWh to 2.25 MWh of peak grid power due to significant T&D losses. Thus optimal usage of regenerative braking provides a good and an ideal source of green energy.

REFERENCES

- [1] BP – *Statistical Review of World Energy*, June 2012
- [2] World Energy Council, '*Energy and Climate Change 2007*'
- [3] World Energy Council, '*2010 Survey of Energy Resources*'
- [4] Mumbai Rail Vikas Corporation Limited.
 (<http://www.mrvv.indianrailways.gov.in>)
- [5] Power Today, July 2010 (<http://www.powertoday.in>)
- [6] Railway Technology Research Institute
 (<http://www.rtri.or.jp>)
- [7] The Green Car Website
 (<http://www.thegreencarwebsite.co.uk/>)