DC REGENERATIVE BRAKING IN THE UK

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SUMMARY
When a train brakes regeneratively its kinetic energy is converted to electricity that can be recovered. The reuse of this electricity on the UK’s 25kV AC system is relatively simple. However, on the UK’s 750V 3rd rail DC network regenerated power cannot be returned to the grid supply, and hence the benefit of regenerative braking is hard to quantify. Due to this, and other historical reasons, trains use regenerative braking on the UK AC network, but not on the DC network. Solving this issue may have been instigated by a business imperative, but the significant environmental benefit is not to be underestimated.

This paper describes the process followed by Southern, a UK train operator, in conjunction with Bombardier, its train supplier, and Network Rail, the infrastructure owner, to introduce regenerative braking to its third rail stock. To achieve this goal the project have had to overcome both technical and operational challenges, as well as address many misconceptions within the UK rail industry. The creation of a theoretical model to address fault masking enabled a significant obstacle to be removed. The approach to testing drew on the experiences of many previous projects, enabling a much more rapid and productive testing regime. The partnership approach with London Underground demonstrated to the industry that by working together, taking a sensible and pragmatic approach, changes can be made whilst ensuring the continued safe and reliable operation of the railway.

The project has delivered a real and tangible reduction in traction power requirements, with in excess of 18% of traction power now being recovered.

INTRODUCTION
During regenerative train braking the kinetic energy of the train is converted to electricity that is returned to the supply network. On the UK’s 25kV AC system this is achieved in a relatively simple manner that is easily quantifiable. However, due to the design of the supply network the same is not true for the UK’s 750V DC network. On this network the regenerated power cannot be returned to the grid supply, and hence the benefit of regenerative braking is hard to quantify. This issue, combined with other historical impediments, meant that while trains regenerate on the UK AC network, the same was not true for the DC network. The desire to reduce operating costs in the face of rising electricity prices drove a change in thinking that also delivered a significant environmental benefit.

Southern, a UK train operator, assembled a cross-industry team to introduce regenerative braking to its relatively new, Bombardier built, Electrostar trains. This paper describes how the various obstacles were overcome to successfully deliver this project, generating significant financial and environmental benefits.

The project team developed a strategy aimed at clearly demonstrating DC regenerative braking could be achieved, challenging beliefs with indisputable data and ensuring key stakeholder requirements were identified, met and proven.

Initially, train system parameters were developed with Bombardier and Network Rail. Southern and Network Rail (the infrastructure manager) established a “test track” on the UK Network. Bombardier’s engineers used the “test track” to develop and monitor the traction software.

Fault masking, a long held industry perceived risk, occurs when a regenerating train hides a short circuit fault from substations. Network Rail created a model using the train and network parameters to assess and prove this to be very low risk. Perceptions regarding the ability of older stocks to withstand regenerated voltages were also successfully challenged.
Network Rail’s electrification system interacts with that of London Underground. The team worked with London Underground engineers to agree a phased introduction process, enabling practical demonstrations confirming that their operations were not impacted.

By tackling these issues there are now trains regenerating in passenger service for the first time on the UK’s DC Network.

THE UK ELECTRIFIED NETWORK

The mainline electrified railways within the UK have been developed with two electrification systems, the 750V DC third rail system and the 25kV AC overhead line system.

The history of the third rail network in the UK dates back to 1890, when it was introduced on the City and South London Railway.

When operating on this system electric trains collect power from the third rail via a top contact collector shoe, with the running rails being used as the return. Substations at regular intervals throughout the network convert high voltage AC power from the National Grid, through a rectifier arrangement, to a smoothed lower voltage DC supply.

This system is installed on over 4,900 km of railway tracks in the UK, the vast majority of which are deployed in the area of the UK south of London.

A significant factor in the overall system capability is the loop impedance of the electrical sections. Initially, 100 lb/yd and 106 lb/yd steel conductor rail was used. However, since the 1960s, it has been policy to install 150 lb/yd steel rail. Likewise, the running rails have also increased in size from 95 lb/yd and 109 lb/yd, through to 113 lb/yd and now UIC 60. The current return system utilises all available running rails, which are cross bonded around every 800m to allow for current sharing and reduce the impedance of the system. Impedance bonds are used to provide continuity of the DC traction return current whilst maintaining segregation of the AC track circuits.

The 25kV AC network came later, with development starting in the UK in 1955. This system follows the near universal arrangement for 25kV systems.

HISTORY OF REGENERATIVE BRAKING IN THE UK

Traditionally, train brakes convert kinetic energy, via friction, to heat in order provide braking effort. The process was originally mechanical, but since the 1960s an electric braking process has been possible using the electrical traction motors in reverse to supply a load to rheostatic brake resistors. These are normally located on train roof or undersides, with the resultant heat vented into the atmosphere.

Almost all electric trains manufactured for use in the UK since the early 1990s have been designed with the capability of distributing this train generated electrical energy back into the electrification system. For trains operating on the DC network this is achieved by the train supplying power to the network at a higher voltage than that being supplied by the substation, raising the line voltage.

Regenerative braking testing first occurred on the UK’s DC third rail network in 1982. In the early 1990s the first DC regenerative braking capable trains (Networkers) were introduced to the UK infrastructure in the North Kent area. This coincided with significant infrastructure upgrade projects including station platform lengthening, reinforcing the integrity of the DC electrification system and installing an intertripping system.

The intertrip system ensured that both circuit breakers feeding an electrical section opened in the event of one possibly detecting an electrical fault. It was never fully commissioned as privatisation led the industry to follow other priorities, and so regenerative braking was never enabled. In the late 1990s, a project was initiated to commission the intertrip system, and produce a safety case to allow Networkers to operate with regenerative braking enabled, but again events overtook the project, and it failed to deliver regenerative braking on the DC electrification system.

Since then, a New Trains Programme (2000 – 2004) replaced all old style slam door DC traction rolling stock with modern trains. All trains procured were capable of regenerative braking, but it was seen as too great a risk to project timescales to enable, and so was left unutilised. This resulted in an electric rolling stock mix, where the majority of DC rolling stock had the capability of regenerative braking, but none had this functionality enabled (see figure 1).

![Figure 1: Braking on the UK Electric Train Fleet – January 2008](image)
A perception had developed within the UK rail industry that regeneration on DC trains was dangerous for the following reasons:

- Short circuits could go undetected, leading to fires;
- Isolated sections could be livened up, leading to the death of people working on the track;
- Older trains could see high voltages and simply explode; and
- London Underground's escalators will run faster when a train regenerates, causing passengers to be thrown to the bottom.

SOUTHERN – A UK TRAIN OPERATOR

Southern, a Govia company, provide train services for commuters, airport users, business and leisure travellers between central London and the South coast, through East and West Sussex, Surrey and parts of Kent and Hampshire.

In 2009, 140 million passenger journeys were taken on the Southern network and they operated over 2,100 trains each weekday. Each year, over 2,000 million passenger miles are covered on 414 miles of track.

Southern operate the vast majority of its services using a fleet of 182 Class 377 Electrical Multiple Units (EMUs). This fleet was built by Bombardier Transportation in the UK, and are part of Bombardier’s Electrostar family. They were delivered into service between 2000 and 2004 in various tranches. An IGBT traction package, controlled by Bombardier’s MITRAC train control system, enables operation at speeds of up to 100mph.

PROJECT CONCESSION

Under the terms of its operating agreements Southern pay Network Rail (the UK’s rail infrastructure manager) for the electricity that the trains are estimated to use. Since Southern commenced operations in 2001 there had been a steady increase in electricity prices (see figure 3). There was a significant and sustained rise in 2006/2007 and there was no indication that such price rises were going to cease in the near future. These increasing prices were starting to directly impact Southern’s profitability, and hence reducing electricity consumption on its fleet became a major business imperative.

![Figure 2: A Class 377 Unit](image)

THE BUSINESS CASE

A fully costed business case was created that used estimated saving rates of between 3% and 6%. This case showed that if the projected savings could be delivered within a relatively short timescale the project would pay for itself within a number of years.

However, to ensure the successful delivery of the business case the identified technical challenges had to be quickly overcome. Hence the project team, consisting of representatives from Bombardier (train manufacturer), Network Rail (infrastructure manager) and Southern (train operator), came together with the Booz & Company project management and engineering management team to work towards delivering the vision.

SYSTEM DEVELOPMENT

The main purpose of the Electrostar’s propulsion system is to convert the DC line voltage to a three-phase voltage with variable amplitude and frequency (VVVF), for powering or braking the traction motors.
There is a DC link that is fed directly from the third rail supply. This serves as a voltage source for the Motor Converter Modules (MCMs). Each MCM converts the DC link voltage into a symmetrical 3-phase voltage with variable amplitude and variable frequency. This VVVF voltage feeds two traction motors connected in parallel on each of the motor bogies. The power conversion utilises the latest technology high power IGBTs with microprocessor based control logic.

Some new UK rolling stock had blocked regenerative braking through the use of large diodes. However, the original design of the Electrostar trains used the traction control software and control of the brake choppers to achieve this. This approach proved to be very beneficial for this project, enabling the regenerative brake to be implemented through a relatively low cost software change. As of July 2010 the Electrostar fleet was the only one of the UK DC fleets to be operating with a regenerative brake in passenger service.

To enable the change Bombardier’s software engineers altered the operation of the brake choppers to enable them to divert power between the DC supply lines and the brake resistors.

Train system parameters were refined with Bombardier and Network Rail. These were designed to ensure that in all operating scenarios a minimum impedance level of 0.1Ω would not be exceeded. This would ensure that operation of the regenerative brake would not cause substation protection devices to act erroneously.

**TESTING**

In partnership Southern and Network Rail established a “test track” on a branch line of its network to enable Bombardier’s engineers to develop and monitor the traction software.

During each period of testing the substation feeding configuration was changed to prevent regenerated power being exported to the rest of the network. When necessary, stationary units were used to provide varying degrees of static load, which provided for some interesting logistical challenges. Buffer zones at either end of the test track reduced the risks of any unforeseen electrical interference impacting the operating railway, providing added safety.

To support the testing Bombardier’s engineers established an ethernet network on the test train, enabling the performance of all traction packages to be centrally monitored, and parameter changes to be quickly implemented. To enable the detailed recording of line current and voltage, as well as electrical emissions, Bombardier’s Propulsion Equipment Measurement System (PEMS) was installed.

Testing undertaken on this test track included:
- Initial software development;
- Basic functionality testing;
- EMI footprint testing;
- RFI measurement testing;
- Short circuit reaction testing; and
- Operation in floating sections.
In addition, testing with multiple unit formations was completed during a closure of the mainline between Brighton, on the South Coast, and London. This was used to determine whether there were any adverse interactions between Electrostar units during regenerative braking.

The commitment of all parties to the project led to the rapid completion of the initial test programme, with the system going from its first trial on 24th December 2007 to being declared ready for the start of fleet roll-out by April 2008.

**FAULT MASKING**

Fault Masking, a long held industry perceived risk, occurs when a regenerating train hides a short circuit fault from a substation.

![Figure 8: Fault Masking](image)

On the UK network impedance protection devices are set to cover faults in 100% of a DC electrical section when taking into account the maximum allowable wear of the conductor and running rails. The length of feed of the electric section corresponds to this impedance and is known as the "reach" of the protection system.

With regeneration, the current produced by the train reduces the current measured by the distribution circuit breaker. In addition, the magnitude of voltage drop normally associated during a fault is reduced. Consequently, the apparent loop impedance measured by the protection device increases for a given fault position beyond that of the set value. The effective reach of the protection system is therefore reduced to leave a portion of the electrical section at the remote end unprotected. This artificial increase in the apparent impedance is said to cause the protection system to "under-reach".

During fault masking both the train and the substation would continue to supply the fault until either:

- the train stops braking regeneratively;
- the train moves nearer the fault and detects it;
- the train moves away from the fault and into the next electrical section; or
- the fault self clears (i.e. burns up, or moves away).

A key pessimistic assumption in the described scenario is that the protection device is set to the fault impedance, when all the rails are at maximum wear. When this wear isn’t present, the protection device will "over-reach".

It is desirable to set the impedance protection as low as possible to provide discrimination between fault and load currents to avoid spurious trips, but on many sections of the DC system a practice of using route settings remains. This is a way of reducing wear of the High Speed Circuit Breaker (HSCB) contacts by setting the protection devices to impedances greater than the train load impedance, but less than remote fault impedance. This practice creates settings which deliberately, over-reach. The practice was common in the 1980s but has largely been ignored of late, with the focus on maximising capacity of existing infrastructure.

Whilst the above shows that fault masking can exist; it is far more difficult to prove how often the situation will occur. Network Rail engineers created a complex model using the train and network parameters to assess the level of risk posed by fault masking. The risk of occurrence was calculated on a section by section basis for 4, 8 and 12 car trains. The calculations were also completed for conductor rail wear of 0%, 50% and 100%.

This exercise demonstrated that the probability of a fault masking event occurring was very low, with an estimated occurrence rate in the region of one event every ten years.

The risks presented to the network by the occurrence of the fault masking event were further assessed. Many of the events, as with many of the system faults, would self clear (such as occurs when the material causing the initial short burns up). Samples of the trackside equipment were placed in a laboratory and subjected repeatedly to extended periods of fault current. The results from this testing indicated that the reliability of the lineside power equipment would not be impacted by exposure to fault masking events.

On the basis of this work it was possible to establish that both the safety and performance risks posed by fault masking were acceptably low.
Figure 9: Fault Masking Model Output
LONDON UNDERGROUND

The London Underground network traction system utilises a four rail DC supply that is set at a nominal 630V. Within the operating routes for the regenerating trains, two substations, as shown in figure 10 below, supply traction power directly to London Underground at this reduced voltage.

![Figure 10: London Underground Connection](image)

When a train brakes regeneratively on the DC network the line voltage is raised by the train with the effect that the substation effectively disappears and the regenerating train becomes the primary power source for the supplied area. The impact of this at the points where the supply network also supplies London Underground is that it is theoretically possible for a regenerating train on the Network Rail system to raise the line voltage on the London Underground system to a level which could be supported by their rolling stock. That is, a regenerating Electrostar train could raise the line voltage to 880V, and this could damage a London Underground train that is designed to operate on a 630V system.

Before the regenerative brake could be fully implemented London Underground had to be satisfied that the operation of their trains would not be affected. The team worked with London Underground engineers to agree a phased introduction process, enabling practical demonstrations confirming that their operations were not adversely impacted.

Initial modelling suggested that even with no receptive loads in the area the power from the regenerating trains would be dispersed across a wide area, meaning that the increase in voltages seen at the London Underground system would be small. The results of this modelling were confirmed during a night of initial testing.

Following this testing a gradual service introduction programme was agreed. During this programme voltages on the busbars at the two key substations were monitored to ensure that London Underground’s permitted maximum supply voltages were not being exceeded.

![Figure 11: Example of Substation voltage measurement](image)

The results from this exercise were reviewed at regular meetings between the project and London Underground’s engineers. After several months of monitoring it was agreed that the regenerating trains were not impacting on the voltages seen by London Underground. Consequently London Underground provided their consent to the introduction of regenerative braking on the Electrostar fleet.

MORE CHALLENGES

As well as addressing these major challenges several more had to be overcome before implementation could commence.

1. **Older Stocks**

   Perceptions regarding the ability of older stocks to withstand regenerated voltages were also successfully challenged.

   There was a perception that higher line voltages resulting from regeneration would lead to more flashovers of DC traction motors, motor alternator sets, and compressors.

   There was also a perception that when a train brakes regeneratively the receptive train would be rapidly accelerated as a result of a huge increase in line voltage.

   To return power to the system the voltage level at the regenerating train must be raised above that of the system, and the maximum voltage at a regenerating train could be 900V (NR System limit). Many people made an assumption that if a train regenerates the line voltage will always be close to this 900V level. However, experience and calculations suggest that if a receptive train is present the regenerating trains tends to increase the line voltage only by approx. 50V. Once this was understood and proven the concerns regarding the ability of older stocks to operate...
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on a railway with regenerating trains lessened significantly.

2. Stray Currents
The introduction of regenerative braking will change the stray current characteristics of the system. Consequently the impact of this on structures and utilities needed to be considered to ensure that the change will not be detrimental to the system.

A model representing a 6Km cross-bonded double track section of 750V DC electrified third rail line, typical of that found in the UK was created. By linking simulations together it was possible to represent several supply configurations. The trains were modelled as blocks of 4-car EMUs to a maximum of 12 cars. The simulation permitted the modelling of multiple trains.

The model system was further expanded to examine the impact of a regenerating train with a range of earth points. The simulation concluded that for the majority of scenarios the effect of regenerating trains on the systems reduces the stray current effects. This is largely due to the increased supply sources in a particular electrification sector. This means that some stray current will return to the regenerating train situated closer to the load train than one or other of the substations for a typical double end feed scenario.

On the basis of this modelling objections to the introduction of regenerative braking on the grounds of the negative impact on stray currents were removed.

3. Isolations
There was an identified risk that should a regenerating train enter an electrical section that had been electrically isolated under emergency conditions the section would be livened by the regenerating train, potentially endangering staff in the area.

To address this risk Network Rail adjusted their operating procedures. When an emergency isolation of a section is taken it was already the operating procedure that an isolation of the two adjacent sections would also be taken. The procedure was adjusted to ensure that before the electrical controller informed staff that a section was isolated sufficient time had elapsed for any train braking regeneratively in any of the sections to come to a stand. This ensured that a regenerating train could not enter the emergency isolation from an adjacent section.

Should a regenerating train subsequently enter one of the adjacent isolated sections it would cease regeneration almost immediately, and hence could not proceed to liven the section that was the subject of the emergency isolation.

This adjustment to the operating procedures was fully briefed out to the impacted control room staff prior to the start of the implementation programme.

IMPLEMENTATION
With the changes to the train software identified and all safety approvals gained, the project moved to the implementation phase. On 19th May 2008 unit 377328 operated the first passenger service to make use of regenerative braking on the UK’s 750V DC network.

Southern operate a very reliable fleet of trains, and wanted to maintain this record. Hence, one of the key requirements of the rollout was to identify and rectify at an early stage any performance impacts of the change. To achieve this aim a phased implementation programme was followed. Initially only 28 units were modified, operating services that were mostly confined to the non-core commuter routes. Following the rectification of initial reliability issues the programme slowly increased the number of regenerating units in line with the plan that had been agreed London Underground, until by October 2009 100% of Southern’s Electrostar fleet was enabled.

One of the major issues identified during the rollout occurred when a regenerating unit was operated in service coupled to a non-regenerating unit. It was found that during the early mornings and late evenings, when there was a reduced load on the system, a mismatch in the settings of the over-voltage choppers between the trains (this having been revised down on the regenerating train) resulted in the regenerating train dumping power into the brake resistors of the non-regenerating unit. After a number of brake applications this resulted in the electric brake becoming isolated on the non-regenerating train in order to prevent the brake resistors from overheating.

Figure 12: Press photograph from launch day

Southern
NEXT STEPS

With trains now regenerating, Southern are committed to working with Network Rail to exploit opportunities for greater system efficiency and maximising the benefit of regenerative braking, leading to further reductions in energy consumption.

The DC system is not always receptive to a regenerating train. For example, when a train starts to brake there may already be several trains regenerating in a section and the line voltage will be high enough to prevent the train starting to brake from establishing a regenerative brake application. When there is not receptivity the energy generated on the train during braking is wasted as heat in the train resistors.

Analysis of the train data shows that only 90% of Southern’s electrical braking is regenerative. Hence for 10% of the time the line is not receptive and 10% of the possible energy recovery is being missed. Increasing the receptivity of the line will enable improved energy capture.

One method of capturing this energy is to store it within the substations, as shown in the figure below.

![Figure 13: Substation energy capture scheme](image)

In addition it is clear that a significant amount of regenerated energy is being lost within the system. During the initial operations regeneration was observed on sections of track when there were no receptive trains for many miles. This suggests that there are significant losses within the system, possibly resulting from tracking across poor insulation and heating conductor rails. Further work is needed to identify the sources of the losses and to reduce them as far as possible.

CONCLUSION

This paper has described the process followed by Southern, a UK train operator, in conjunction with Bombardier, its train supplier, and Network Rail, its infrastructure provider to introduce regenerative braking to the its third rail stock. The project has delivered a real and tangible reduction in its traction power requirements, with in excess of 18% of traction power now being recovered.

To generate this level of savings the team have had to overcome both technical and operational challenges, as well as address many misconceptions within the UK rail industry. The creation of a theoretical model to address fault masking enabled a significant obstacle to be removed. The approach to testing drew on the experiences of many previous projects, enabling a much more rapid and productive testing regime. The partnership approach with London Underground showed the industry that by working together, taking a sensible and pragmatic approach, changes can be made whilst ensuring the continued safe and reliable operation of the railway.

REFERENCES

The sources of information listed below have been used in the preparation of this paper.


