Hybrid shunter locomotive

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Abstract

Locomotives performing shunting activities are fulfilling very specific mission profiles characterized by short runs, hauling variable loads and a high proportion of idling time. Traction based upon hybrid technology is a very suitable solution for shunter locomotives, bringing substantial benefits in terms of fuel savings, emissions and noise reductions. This paper present the main technological choices with their justifications, and explains and quantifies the expected benefits. Hybrid technology has been tested and validated in “full scale” on a demonstrator, the BR 203H locomotive.

Introduction

Shunting is a core activity of railways operations. Rail vehicles shunting is required in depots, in freight yards, in passengers terminal stations, in industrial plants connected to rail network, in harbours and multimodal terminals. Railways operators dedicate specific shunter locomotives fleets for those duties. Industrial sites connected to the rail network own shunter locomotives for freight wagons shunting on their premises. In order to be able to operate independently from the overhead voltage, or on non-electrified tracks, most shunter locomotives are diesel electric or diesel hydraulic locomotives. In an increasingly demanding and competitive business environment, the efficiency and environmental friendliness of those shunter locomotives is becoming a challenge. Hybrid technology is an excellent answer to these challenges. Many of those shunter locomotives in operation today have been manufactured some decades ago and still have a significant potential of operational life. But they feature diesel engines of older generation with low fuel efficiency and a high level of emissions. In the automotive industry, hybrid technology has successfully entered the market, demonstrating clear benefits in urban traffic. Hybrid technology can be proposed as a renovation package for existing shunter locomotives, limiting the capital expenditures and extending the expected life duration of the existing fleets. It can also be offered for new shunter locomotives.

Shunting mission profile

There is clearly a very great diversity of shunting duties depending from local railroads configuration and practices. But it is possible to identify some common characteristics:

- Shunting is operated at low speed, typically below 30 km/h.
- The distance traveled with the shunted vehicle or train is relatively short.
- The loads to shunt vary in a wide range (from one vehicle to a full freight train).
- Shunting is a “on demand” activity, to be performed when required, without delays. This results in waiting time between “shunting missions” during which the crew and the shunter locomotive must be ready to move and go to another mission “on call”. Between 2 shunting missions, the locomotive will not go back to its depot, but stay in the place where it generally operates.
- During a shunting trip, the train may have to stop and restart several times (for example, it may encounter red signals).
- Brakes tests and brakes releasing before moving is requiring large quantities of compressed air.

As an example, typical “trips” performed by a shunter locomotive are described in the following table. But there may be a significant variation between operators.
<table>
<thead>
<tr>
<th>Type of trip</th>
<th>Light duty trip</th>
<th>Medium duty trip</th>
<th>Heavy duty trip</th>
<th>Empty long distance</th>
<th>Shunting Trip empty</th>
<th>Filling the brake system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (sec)</td>
<td>900 sec.</td>
<td>900 sec.</td>
<td>900 sec.</td>
<td>6 h.</td>
<td>300 sec.</td>
<td>1000 sec.</td>
</tr>
<tr>
<td>Loco mass</td>
<td>70 T</td>
<td>70 T</td>
<td>70 T</td>
<td>70 T</td>
<td>70 T</td>
<td>70 T</td>
</tr>
<tr>
<td>Train mass</td>
<td>300 T</td>
<td>600 T</td>
<td>1500 T</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Top speed</td>
<td>25 km/h</td>
<td>25 km/h</td>
<td>25 km/h</td>
<td>60 km/h</td>
<td>30 km/h</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Distance</td>
<td>3000 m</td>
<td>3000 m</td>
<td>5000 m</td>
<td>360 km</td>
<td>3000 m</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

The mission profile for one day of a shunter locomotive will be a combination of the above described cycles. For instance, the daily duty could be 10 light duty trips, 4 medium duty trips and 2 heavy duty trips, 16 shunting trips empty and 16 times filling and checking the brakes system. There maybe also some long distance trips if the locomotive operates on several locations. Between those trips, the locomotive will spend a substantial amount of time waiting in standstill for its next shunting trip. This amount of time is recognized by operators to be comprised from 30 to 85 % of the total operation time. During this time the crew is generally waiting on board of the locomotive. The diesel engine will be idling, in order to supply the energy requirements of the locomotive at standstill (heating or air conditioning, lighting, compressed air …)

**Typical requirements for shunter locomotives**

Railway operators dedicate specific locomotive fleets to shunting duties. Those shunter locomotives must be able to provide a high traction effort, with a good adhesion at low speed. They also have to offer good and quick reactions to the driver, since shunting is requiring precise control of the locomotive movements. Classical diesel electric or diesel hydraulic traction drives within a power range from 500 kW to 1000 kW can fulfill most shunting mission profiles. But classical shunter locomotives suffer drawbacks due to diesel power. During a shunting trip, the diesel engine will be used for relatively long periods of time at a low power output, far from its optimum set point. In these conditions, the engine efficiency will be low, impacting the fuel consumption performance. During a shift, the proportion of idling time is considerable, up to 85% of the total operation time. During this idle time, the diesel engine is operated at very low regime, in order to provide auxiliary energy for the comfort of the crew (for heating or air conditioning, lighting…), and also to ensure that the shunter locomotive will be ready to operate immediately on a call (air brakes pressure, engine temperature…). This idling operation of the diesel engine is generating “non productive” fuel consumption, noise, emissions and engine life duration reduction.

Fuel consumption, noise and emission reductions are becoming growing concerns for shunting operators. They are looking for solutions to improve the performance of their shunting activities towards those criteria, but are not ready for large investments for their shunter locomotives fleets.

**Hybrid diesel electric traction: a good solution for shunter locomotives**

Growing awareness of the limitations of the classical diesel shunter locomotives have pushed to investigate the feasibility of alternative solutions. Given the considerable impact of long idling time and variable power requirements during shunting activities, a hybrid technology combining electrical traction drive, accumulators’ batteries and a diesel generator have been investigated.

The basic features of this hybrid solution are (figure 1):

- A combination of electrical accumulator batteries and a diesel generator as power supply, connected to an electrical “power bus”
- A traction power converter supplying power to the electrical traction motors.
- An auxiliary converter supplying 3 phase AC currents for Air compressor, air conditioning and other auxiliary system
- A battery charger and auxiliary batteries supply DC low voltage for the control functions of the locomotive.
- An Energy Management System, based upon continuous monitoring of the requested power and of the state of charge of the batteries.
The traction power converter, the auxiliary power converter and the battery charger receive primary energy from the “power bus”.

If the total power requested by the loads connected to the “power bus” is lower than the maximum power output from the batteries, the locomotive is operated on the batteries only. If the total requested power exceeds the maximum output of the batteries, then the diesel generator is operated in parallel with the batteries. Reaching the threshold for low state of charge of the batteries will trigger the diesel generator, which will operate as a batteries charger. This is illustrated in the figure 2. In figure 2 the locomotive is performing 13 shunting trips, with idling intervals in between. In this case the minimum acceptable state of charge of the batteries is 65% of full load.

The maximum power output of the batteries and the diesel generator set is constantly monitored during operation of the locomotive. In order not to exceed this level, the Energy management System will automatically reduce the traction power, if the power requested by the driver is in excess of the power available for the traction.

Depending of the customer requirements and the specificities of each mission profile, the hybrid solution must be customized in terms of dimensioning for each application.

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**Fig 1:**

![Diagram of the Traction System](image)

- **Ni-Cd battery**
- **Diesel engine**
- **Generator**
- **Traction inverter**
- **Auxiliaries**
- **Compressor**
- **24V battery charger**
- **24V battery**
- **4 fan motors**
- **Gearbox and axles with gearboxes**

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Fuel consumption savings

The fuel savings are generated by:

- The good efficiency of the diesel engine of the generator set. When the Generator set is on, the engine will always be running very close to its optimum set point, and its efficiency will be at its best. The volume of fuel consumed per kWh will be constant, with no dependencies from the mission profile.

- The fact that the generator set will not be operated for most of the duration of the idling time. In this case the energy needed by the locomotives to sustain the standstill periods is produced by the generator set with its constant level of efficiency. On the contrary, on a classical diesel shunter locomotive, this energy will be supplied by the diesel engine in idling mode, with a poor efficiency. Large engines idling consumption is not depending from the power output (provided it is relatively small; less than 10 % of nominal power), but from the duration of the operation.

- No hydraulic torque converter, which generate poor efficiency in the lower speed range.

As a result, it is clear that the level of fuel saving will closely depend from the real mission profile of the locomotive. Depending of mission profiles, fuel savings up to 40% can be demonstrated. This is the key economical driver for hybrid shunter locomotives.

Accumulator batteries technology

The requirement was to use a battery technology with sufficient positive return of experience. Three technologies were investigated, with comprehensive lab tests for performances and aging:

- Lead Acid batteries: Cheap and proven concept, but requiring large volume and having relatively high internal resistance causing voltage drop and internal heating.

- Ni-mH batteries: compact and performing batteries, but with relatively reduced return of experience and needing a complex battery management system.

- Ni-Cd batteries: A good compromise between cost, volume, weight and internal resistance. Extensive return of experience has been accumulated in rail environment. The internal resistance is acceptable, but will nevertheless generate internal heating. Special attention has to be taken for batteries rack ventilation, in order to keep the batteries internal temperature within acceptable limits (exceeding those limits will reduce the batteries life duration potential and increase the life cycle cost of the locomotive)

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**Fig 2**

**Genset and battery operate in parallel at high power demand, SOC remains > 65 %**

**Battery SOC <65 %, genset recharges battery**

**Movement of the loco**

**Genset and battery operate in parallel at high power demand, followed by recharge**
The choice has been Ni-Cd batteries.

In order to provide a power in excess of 350 kW at a nominal voltage of about 600 V, the batteries pack is made of 536 cells fitted in several drawers, with a weight of more than 6 tons. Weight is generally not a constraint on shunter locomotive, Additional weight per axle is providing additional adhesion, which is a valuable benefit. Special care must be taken regarding safety in case of crash, derailment or fire given the large amount of energy stored and the amount of corrosive liquid.

**Traction drive technology:**

Simple and classical electric traction drives are considered. They are connected to the DC “power bus”. The standard solution consists of a 3-phase inverter feeding AC traction motors. The traction motors have forced ventilation, in order to be able to cope with high traction efforts at low speed, typical for shunting operations. In case of modernization of diesel electric locomotives already equipped with DC traction drive, a chopper can replace the inverter. Regenerative braking is not considered since it will bring limited benefits in shunting activities. There are no specific requirements to the traction drive due to Hybrid traction. This is making possible the use standard traction drive equipments. The traction drive control system has to limit the traction power output below the maximum available power for traction declared by the Energy Management System.

**Diesel generator set technology:**

The diesel generator set consists of an integrated module with diesel engine, water-cooled permanent magnet alternator flange mounted to the engine, cooling system, rectifier and control module. Specific care is taken for the noise reduction contributing to the overall noise performance of the locomotive. Due to the hybrid operation, the number of engine starts per day of operation is considerably higher than on a classical diesel shunter. This is requiring a highly efficient and reliable starting system. The voltage and power output of the diesel generator set is controlled by the Energy Management System by controlling the diesel engine rotation speed. This is allowing fine adjustment, required during the batteries charging. This power and voltage adjustment happens within a narrow range, corresponding to a narrow variation interval for the diesel engine rotation speed. The diesel engine is selected and adjusted so that it has its best efficiency in this range, meaning that its fuel consumption per kWh produced will be minimum, and that the level of emission and particles rejected per kWh produced will be minimum as well. The diesel engine can be selected from standard industrial engines range, fulfilling the latest regulations regarding emissions. The exhaust line is equipped with a particle filter. The expected life duration of the diesel engine is shorter than the life duration of the locomotive. This is meaning that this engine will have to be replaced during the life of the shunter locomotive. This will give the opportunity to replace it by an engine compliant with the emissions standards at the time of the replacement, keeping up to date the friendliness of the locomotive towards the environment. The arrangement of the generator set as a compact module permits efficient and simple noise insulation.

**Energy Management System technology:**

The energy management system controls the balance between the available energy and the requested energy. The main control parameters are:

- Commanding the diesel-generator set ON and OFF and adjusting generator rpm to the appropriate voltage level.
- Adjusting the batteries charge current within the limits, in order to respect the batteries charging requirements. Non-respect of those requirements will reduce the life duration potential of the batteries.
- Requiring power limitation to the traction converter.
A key component of the Energy Management System is the Batteries Management System, which monitors the batteries system on batteries temperature, batteries section voltage compared to the average cell voltage. This allows calculating the actual state of charge of the batteries expressed in percentage of the maximum theoretical state of charge.

The actual state of charge will be kept within a window (typically between 65% and 80% of the maximum theoretical state of charge for Ni-Cd batteries).

The batteries management System will also monitor voltage discrepancies between cells and indicate when an equalization of the cells must be performed.

**The BR 203H demonstrator:**

Hybrid shunter locomotive is based on the assembly of the above-described subsystems, with the adequate dimensioning for each of them, provided the best response to the mission profile of the customer.

In order to validate the hybrid shunter locomotive concept and to verify the expected performances, Alstom transport has defined, built and tested a demonstrator hybrid shunter locomotive. This locomotive is based upon the German BR 203 locomotive type, which is a modernized BR 202. It is a four axles locomotive with a length of 14.2 meters, and a weight of about 60 tons. The hybrid demonstrator called BR 203H is fitted with a batteries rack with a total power of 350 kW and a generator set of 200 kW. The energy management system is interfaced with the classical locomotive control system. The traction drive consists of 2 inverter driven AC asynchronous motors with forced ventilation. The BR 203H is shown on the picture in Fig 3.

![Fig 3: BR 203H hybrid demonstrator.](image)

Traction characteristics of the BR 203H are shown on fig 4, with comparison to classical Diesel Hydraulic shunter locomotive of 500 and 900 kW.
Hybrid shunter performances – Demonstrator BR 203H tests results:

The demonstrator BR 203H has undergone extensive testing on test tracks and also performed actual shunting duties. Those tests have demonstrated that hybrid concept can bring substantial benefits to shunting operation.

Typical measured behaviour of the locomotive when shunting a 180 tons load is shown on fig 5. This graph shows the speed of the train (there are two successive train movements), and also the total power (Pot) with the batteries contribution (Pat) and the generator set contribution (Pen).

When the power of the batteries (Pat) goes into negative values, the batteries are recharged by the generator.

Those tests have also allowed measuring fuel savings. By using the BR 203H instead of a classical modern diesel hydraulic shunter on an industrial yard, where intensive shunting activities with loads in excess of 1000 tons are common, a fuel consumption reduction of 30% has been recorded.

Alstom transport carry on testing the BR 203H in order to accumulate comprehensive experience on hybrid locomotive operation and to confirm the key parameters and benefits.

Locomotive drivers who have had the experience of driving the BR 203H are delighted by the quick response provided by the locomotive and its flexibility in shunting service.
Perspectives:

The tests carried out in laboratory and with the BR 203H locomotive have brought a lot of useful knowledge on batteries behaviour, and hybrid technology critical parameters. With those results we have been able to define an improved battery pack, with enhanced cooling performances and a lower internal resistance. This new batteries pack will be fitted to the demonstrator BR 203H locomotive and subsequently tested. Additional real shunting experiences with customers are also planned. The outcome of those testing and validation activities will be the availability for the market of a range of hybrid traction packages for shunter locomotives. It will be possible to implement these packages as modernization of existing diesel shunter locomotives, with costs equivalents to a new build loco. Hybrid technology applied to shunter locomotives will bring substantial improvements in terms of smoke, emissions and noise. This will lead to “cleaner” shunting operations. But we have also validated that it is bringing considerable economical benefits resulting from fuel saving, in the range of 30 to 40 % for typical shunting duties. This is generating growing interest from railways operators in the context of oil price increase.