ENERGY EFFICIENCY, STORAGE AND GENERATION IN A RAILWAY ELECTRICAL DISTRIBUTION SYSTEM THROUGH HYBRID DIESEL-ELECTRIC LOCOMOTIVES

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ABSTRACT

The diesel-electric traction is a well known and established technology for railways operators, but electric traction presents a considerable superiority and some problems too. For example, it is not possible to use regenerative braking if there is not another locomotive which demands power in the same supply section at the same time. This is a common problem in substations providing DC voltage to locomotives. We present the possibility of a diesel-electric locomotive working together with electric ones. It supposes an efficient energy management because the diesel locomotive could acts as a dispersed mobile generation unit when working under electric overhead line. In this way, it can be used as a distributed resource for this specific electric power system.

INTRODUCTION

Diesel-electric haulage is a well known technology, but this alternative has a considerable uncertainty in the future because electric traction has a considerable superiority: More power, efficiency, or lower maintenance costs. Besides, diesel-electric engines waste energy when non-regenerative braking is used (about 10-20%). So, it is important to develop new strategies to increase the possibilities of diesel–electric haulage.

Nowadays, diesel locomotives are in excess in some countries and are used at a minimum level. In our theoretical study, an actual itinerary has been chosen. This itinerary has an electrified overhead system (3kV, DC with two-track catenary and 150km length) and a not electrified one (single track, 250 km length). The idea is to optimize efficiency, storage through regenerative braking, and besides to study the possibilities of diesel-electric generation) in the electrical zone while the diesel locomotive has a generation surplus capacity, or the possibility of storage of energy generation of electrical units in braking zones.

It is necessary to take into account that diesel-electric locomotives need the full power of diesel engine in a limited percent of time (for instance 10%) and often work with low efficiency. From 80% to 90% of time the locomotive has a surplus of energy (up to 1.5 MW) available to be supplied to the catenary if they could dispose a pantograph to supply energy from main generator or storage devices to the overhead DC contact line (for example, when other train starts near our loco in the itinerary).

This generation could have interesting benefits: voltage regulation, power demand and traffic increase in electrified zones (both are key performance limiting factors in an electrified railway network). The potential use of this distributed generation is a new topic in railways.

Figure 1. Electric class 250 and Diesel-Electric class 333.

Fortunately, recent developments in energy storage devices, particularly supercapacitors and flywheels [1], [2] have made energy storage a viable alternative to apply to railway systems and specifically for diesel-electric units. This paper explores these possibilities using a real intercity passenger train “Altaria” and a freight train as a case study.

CASE STUDY: THE ITINERARY

In order to simulate the possibilities of standard diesel-electric units working together with electrical one, and with the objective of dimensioning the main elements (storage, diesel engine, etc), a typical itinerary was selected: Madrid-Cartagena (southeast of Spain). This itinerary has an electrified overhead system (3kV, CC with two-track catenary) from Madrid to Chinchilla (around 300km) and a

non electrified one from Chinchilla to Cartagena (single track, 250 km) without change of the diesel locomotive.
Specifically our interest in focused in a section of this itinerary (from Alcazar to Chinchilla, 150 km long) because both cities are junction nodes on the Spanish Railways Network, having important freight traffic (Madrid, Valencia, Seville). The results presented are only valid for the chosen itinerary (Alcazar-Cartagena) and it was selected due to their rough profile. The profile conditions the size of the storage and engine. The curve of the selected itinerary (altitude versus time) and electrified section are given in Fig. 2.

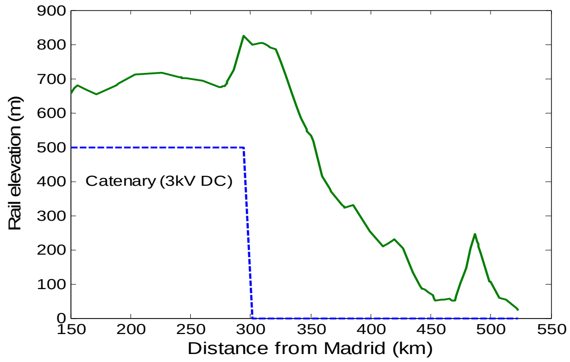

Figure 2. Alcazar-Chinchilla-Cartagena line profile

Coaches were built by Patentes Talgo, locomotives by Alstom-Macosa, Spain (class 333 or JT26TW class licensed by General Motors), and ABB-CAF, Spain (class 250). Main characteristics are shown in table I.

Table I. Train's characteristics

Locomotive	**Class-333**	**Class-250**
Total weight	120t	123t
Power	2237kW	4600kW
Max. Tractive effort	320kN	256/410kN
Max. speed	120/146 km/h	160/100km/h
Coaches/Wagons	**Talgo IV**	**Tank Car**
Weight	118ton /9 units	90ton/1 unit

BASIC TRAIN SIMULATOR

The train simulator was developed by the Universidad Politécnica de Cartagena (Spain) and was presented in detail in a previous work [3]. The main forces being considered for simulation are: internal resistance of the locomotive, journal friction, flange and air resistances, external loads (lighting, HVAC), the curve resistance, and finally starting and grade resistances (the main factor for energy storage). The resistance and haulage forces are examined in detail in [4]. With these forces and the attractive effort-speed curves of the diesel and electrical engines [5], the speed of the train, acceleration, energy and power can be obtained easily. Results for our itinerary are shown in figure 3.

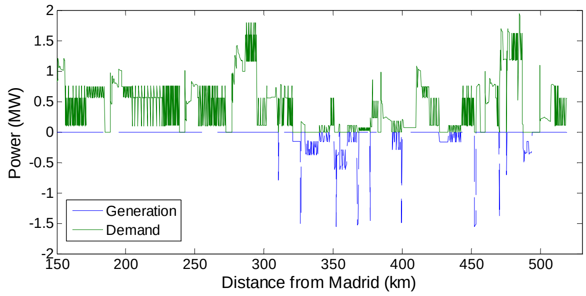

Figure 3. Diesel train power demand&generation

DYNAMIC BRAKING

From figure 3, it can be seen that the train has negative acceleration (braking) mainly on the not electrified track. The train needs its maximum power to overcome starting forces after train stops or at the beginning of the grades. Electrical locomotives have two kinds of braking: dynamic (Joule effect) and regenerative through the catenary (the traction motor works as a generator). The diesel units often use a dynamic braking (the power supplied by motors are used to feed roof resistors cooled with forced ventilation). This represents a non efficient use of energy. In electric locomotives, the dynamic braking is necessary because DC supply systems have rectifiers in substations. The maximum dynamic brake effort curve is shown in figure 4 for classes S333 and S250.

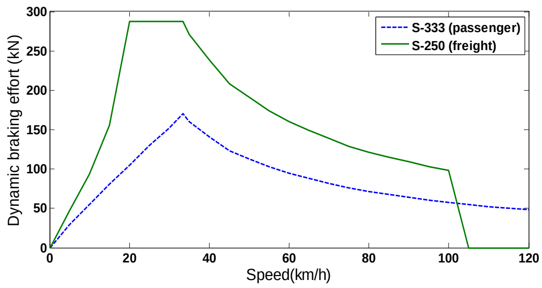

Figure 4. Dynamic braking effort curve.

This dynamic braking represents the second main "losses generator" for a diesel locomotive [4]. The idea proposed in the previous paper [2] (also used in some prototypes worldwide, for example Plathée project in France [2]) is to recover and store braking energy. In this paper we propose the possibility of generation and storage using the diesel engine as a Mobile Distributed Generator (MDG) in the electrified zones. The reason is that electric locomotives can use regenerative braking if and only if there is some "accelerating" train at the same substation that could absorb the regenerated power (20km is typically the area covered by each substation in 3kV DC lines [6]). If there is not the case, the DC voltage could exceed the maximum acceptable limit and the braking generation available should be changed to dynamic (rheostatic) braking for the sake of train's security. Another possibility is to stop the train, but this delays the freight traffic and reduces its average speed (and its competitiveness with respect to road).

SIZING OF STORAGE RESERVOIR

The first purpose is to recovery energy during braking (from diesel or electric locomotives). The stored energy should be compatible with the energy needs for each railway traction application (speed limitations, start up) and the diesel loco should have the necessary volume for storage and electronic devices. This volume is available because the loco will use a diesel motor unit with fewer power and size (1900HP, 1.4MW), but working at a higher efficiency level [2], [3]. The energy storage system is considered as an energy buffer, dedicated for smoothing power constraints on the resized diesel engine. Several technologies can be considered in actual prototypes: batteries, super-capacitors and flywheels [1], [2]. For the sake of simplicity, super-capacitors have been chosen. The negative values in figure 3 represent a percent of the energy that should be stored.
The criteria applied for sizing the reservoir are the following. First we analyze the power demand (figure 3). We obtain the defect of energy (note that 1900 HP of new diesel engine are not sufficient, sometimes, to accelerate the train and to satisfy the timetable assigned to the train). To restore the power of the original locomotive (3300HP, 2.2MW) we need an additional supply from the reservoir (the points in figure 3 over 1.4MW). The integration of the figure 3 gives 105MJ of storage needs. Second, we analyze storage periods (negative values in figure 3) and the maximum of these periods: the result is a size of 150MJ. To take the maximum profit of storage, 150MJ is chosen as the right level for storage.

RESULTS AND PROPOSED APPLICATIONS

Gains in the overall efficiency

The supercapacitors chosen for our application were BCAXX form Maxwell Technologies, USA [7]. Nominal capacitance ranges from650 to 3000 F and the maximum voltage is 2.5 Volts. Technical characteristics are given in [8]. The cost and volume are shown in table II.

Table II. Cost of storage alternatives (capacitors)

Option	Lifetime (years)	Volume (m3)	Cost (k€)
BCAP3000	20	5,5	770

The volume available in the locomotive for storage and converters is 8m^3. The energy balance for the electrified and not electrified itineraries is evaluated in terms of fuel cost. The diesel engine needs an average of 4.44 l/km. If the loco performs two travels a day during five workdays (45 weeks a year), and we assume actual efficiencies: Diesel engine: 37 to 41%; Main generator: 90%; Electronic converters: 95%; Traction motors: 75-80%; Capacitors: near 100%.
The annual cost fuel of a locomotive in this itinerary (2*375km) ranges from 600 to 700 k€/year (depending on the fuel cost fluctuations).The overall gain of efficiency is closed to. The results are shown in table III.

Table III. Gains in energy efficiency. (*): electrified track

Itinerary	Demand (GJ)	Storage (GJ)	Efficiency (Δ in %)
Alcazar to Chinchilla*	2.99	0	8.4
Chinchilla to Cartagena	2.34	0.59	
Cartagena to Chinchilla	6.08	0.27	4,6
Chinchilla to Alcazar *	2.14	0.11	

The increase in efficiency supposes a reduction in fuel expenses of about 85k€/year, i.e. storage is a cost effective alternative in the medium term (see table III).

Generation and storage from electrical locomotives

The diesel-electric locomotives usually haul coaches and goods wagon under electrified itineraries (from Alcazar to Chinchilla in our case, around 150km). The diesel locomotive only needs the full power of diesel engine, and storage reservoir if available, in a limited percent of time (for instance 10%, see figure 3). From 80% to 90% of time the locomotive has a surplus of energy (around 1.1 MW because the average power is 330kW) to be supplied to the catenary if we could dispose a pantograph in the roof (this disposition is common in new hybrid trains and locomotives, see [9]). So, the locomotive could supply energy when other train starts near our loco in a track feed by the same substation [7].
To evaluate this possibility, let us considerer the power profile demand of electric locomotives S-250 that hauls a standard freight train (720ton). The worst case has been studied: a freight train braking at the same substation. This braking energy should be stored by our diesel unit through its pantograph or alternatively can be used to haul its train. The worst case appears in Chinchilla substation (due to the railway profile and the necessity to brake the train in a train stop, i.e. power demand =0, see figures 2&5).

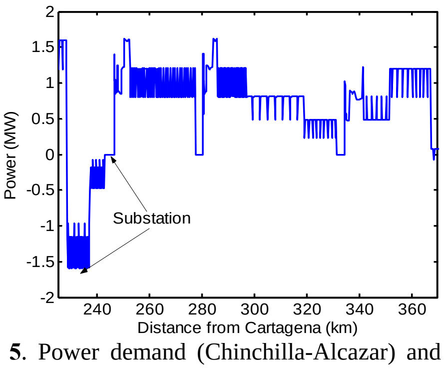

Figure 5. Power demand (Chinchilla-Alcazar) and substation location. Locomotive S-250 hauling 720ton. Max. speed 80km/h.

The overall demand is 5 GJ and the potential for braking generation is 0,54GJ (integration of the power shown in figure 5). The diesel locomotive can store a maximum of 150MJ (see previous paragraph), but at the same time the diesel could run in the opposite direction and needs some energy (0.74GJ, see figure 6). The possibility of this event is low, but freight trains often does not run all the time to allow the flow of passenger trains, i.e. they can be controlled by train operators. This possibility represents a capacity of response of these loads (like some loads in a conventional Power System).

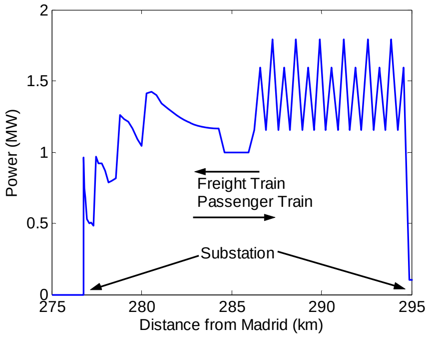

Figure 6. Power demand at last substation. Locomotive S-333

Table IV resume the gains of efficiency of each locomotive alone with respect to the possibility of storage inside the reservoir of the diesel unit due to the energy supplied by the electric one. It is important to remark here that our diesel unit can not store energy in the electrified itinerary from Alcazar to Chinchilla (due to the profile, see table III), so the reservoir is empty and 100% available for energy storage.

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Table IV. Gains in energy efficiency.

Locomotive	S-250	S-333	S-250&S-333
Energy (GJ)	5	2.99	5+2.99
Storage (GJ)	0	0	0.15
Res. Braking (GJ)	0.54	0	0
Reg. Braking (GJ)	0	0	0.15+0.39
Δ Efficiency (%)	**0**	**0**	**14.8**

This option allows the storage of 0.15MJ in the diesel unit and reduces in 0.39MJ its demand (to climb the profile). In this way up to 0.54MJ are recovered from resistive braking. The diesel unit can increase its efficiency from 8.4% to 18.5% if there were some freight train are on standby and available to start from Chinchilla station.

Substation demand profile

Finally, another problem is the capacity of the electrical substations during peak demands.

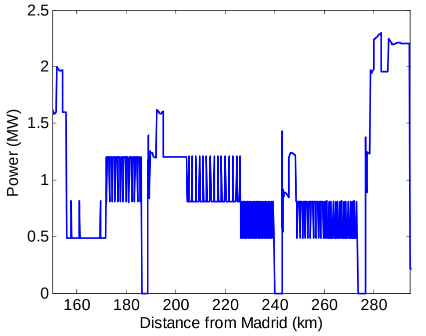

Figure 7. Power demand. Electric Haulage (S-250)

In this itinerary, each substation has two power transformers (3300kVA) connected to a 66kV network. These substations provide 3kV DC to the catenaries. In fig. 7 we consider the same itinerary shown in fig. 6 but when a freight train runs. We conclude (fig.7) that the number of trains is limited to 3 in the first and last sections of our itinerary (notice that it is double-track). With the DMG up to 1100kW are available. This provides the possibility to run a minimum of 4 trains in each substation, i.e. an additional 33% of freight traffic.

CONCLUSIONS

This paper presents an alternative for increasing the energy efficiency of a diesel-electric locomotive without impairing on its dynamic characteristics. This solution enhances the lifecycle of these units. Moreover, the braking energy from electric units can be recuperated and energy efficiency is improved with cost-efficient alternatives. The simulations presented are valid for the itinerary chosen in the example, but the same method can be applied through the software developed here to any other railway lines powered by diesel and/or electric units.

Acknowledgments

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