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Evaluation of the energy saving potential of a Power Electronic Transformer for rolling stock under 25kV, 50Hz

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Abstract

Nowadays, the rolling stock powertrains under AC supply have a bulky and heavy electromagnetic transformer. A possible solution to replace it could be the solid state transformer. In this paper we simulate the most representative French rolling stocks, on different services, in order to emphasize the energy gains obtained by the replacement of the classical transformer by an electronic one, under 25kV 50Hz. These simulations have been used to estimate the gains of an entire regional fleet for Alsace region (France). Important gains in energy (kWh) are highlight but they are not enough to have a good ROI (€) in France, without adding new value to the power electronic transformer functionality's, as the mass and volume reduction, redundancy, reliability and easy switch between different voltage supply's.

Keywords: Solid state transformer; AC 25kV 50Hz supply; Railway vehicle; Main transformer efficiency; Regional fleet energy gains.

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1 Introduction

Today, in railway vehicles drive powertrain, the power (electromagnetic) transformer is a well-known and well-mastered component but it is also bulky and heavy. Weight, volume and maintenance generate constraints for the embedded transformer which often lead to less efficient transformers (than those in substations).

A possible solution to remove these drawbacks is to replace the classical transformer (TFP) by a solid state transformer. Solid state transformers are studied for a decade, mainly in distribution grid applications Maitra (2009), Kolar (2014), Liserre (2016). They can adapt AC or DC single or three phase voltage to other AC level or frequency or to a DC voltage. We call power electronic transformer (PET) a solid state transformer with a topology adapted to transportation constraints (like in Fig. 1).

To the best of our knowledge, only one prototype of PET has been installed on a rail vehicle: the ABB's power electronic transformer installed in a shunting locomotive Dujic(2011), Zhao(2014), Chaudhuri (2014). In railway applications, most of the experiments were stopped at laboratory stage (TRL 4) Engel(2003), Steiner(2007), Weigel(2009). All those experiments are made for rolling stocks fed by AC 15kV 16.7Hz grid. Literature is less rich in studies about PET set up in rolling stocks fed by AC 25kV 50Hz Casarin(2015). The main reasons are the higher voltage level which requires more IGBT's or high voltage semiconductor devices, still in development Casarin (2012), Dujic (2014), and the higher frequency, 50Hz, which would generate fewer immediate gains than the bulky and heavy transformers operating at 16.7Hz.

Improvements in TFP technology (like ABB's Effilight® Chaudhuri (2016)) are interesting options but a PET can bring more services that a TFP: 1) the possibility to distribute the volume and mass, 2) redundancy, 3) adaptability to different input voltages. For all this reason it worth to investigate PET on AC 25kV 50Hz grid.

In this paper we will firstly describe the simulation hypothesis. The simulation results are discussed in chapter 3 for one rolling stock and extrapolated in chapter 4 for a whole regional fleet.

2 Simulation hypothesis

Nowadays, the energy gains of a PET for AC 25kV 50Hz network are not clearly identified in literature. In this paper, rolling stocks simulations has been realized to identify the possible energy gains generated by PET as a function of the rolling stock type (EMU or locomotive-drawn trains) and the mission characteristics (commuter, intercity, local traffic "Transport Express Régional"(TER) or high-speed train).

The method to identify energy gains of PET consists of the comparison of two simulations. In the first one the rolling stocks is a conventional one, with classical magnetic transformer and a front-end rectifier. In the second simulation only the transformer and the front-end rectifier has been replaced with a PET.

Simulations are realized with a Matlab train simulator developed by the French rolling stock engineering department (CIM) of SNCF. To simulate the train's mission, the simulator needs two inputs: railway network data and rolling stock data.

2.1 Rolling stocks

All the sub-systems of a classical rolling stock powertrain are simulated (see Fig. 1), mainly by a constant efficiency (like all the power converters: active rectifiers - 97.5% in this study, inverters, choppers …, mechanical reducer, wheels diameter) or a map of losses versus power (like the transformer model or the electrical motors). The real rimpull effort is also used to limit the traction or braking torques.

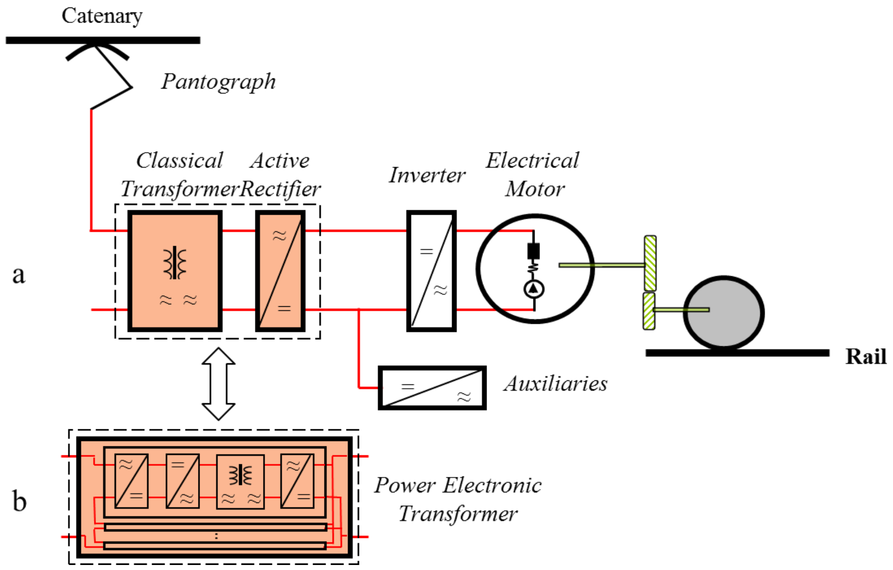


Fig. 1. Power train of a rolling stock: (a) with TFP and active rectifier; (b) with TFP and active rectifier replace by a PET

The mechanical equations of the rolling stock simulator use the weight and the running resistance.
The catenary voltage is considered constant during the trip. The recovered energy during braking is split between rheostatic braking, and (comfort or traction) auxiliary's.
Rolling stock data are specific for each simulated train. French fleet is composed of several rolling stocks working on AC 25kV 50Hz network such as locomotives, multiple units, high-speed trains, with each different services and specifications. Simulate all fleets to identify gains of PET would be long and tedious. To reduce study's duration, we simulate only some of the most representative French rolling stocks. The multi-purpose electric locomotive BB 27300 (Alstom Prima family) is used in Paris metropolitan axes with double deck cars. More than 200 electrical multiple unit B 83500 (Alstom Coradia Régiolis, the simulate one is the PPG trainset) are used in local traffic (TER) or intercity. The high-speed double-deck train TGV 2N2 is the last one arrived in TGV's fleet family compatible with European STI. 100 trains has been purchased to replace almost 25% of the TGV's fleet. These electric rolling stocks are simulated in their own services: commuter, intercity or TER, high-speed service or freight. Some characteristics of selected rolling stocks are presented in Table 1 (M = locomotive, R = passenger car).

Table 1. Simulated rolling stocks Redoutey(2016)

Rolling stock (year)	BB 27300 (2006)	B 83500 (2013)	TGV 2N2 (2011)
Type	Locomotive	EMU	High speed
Services	Commuter	Intercity, TER	High speed
Composition	M+6 double-deck passenger cars (VB2N)	6 cars	M+8R+M
Passengers number (for AW2)	-	354	509
AW0 (*t*)	325 (90 + 6 * 39)	223	428
Nominal power (*MW*)	4.2	2.6	9

2.2 Lines profiles and services

SNCF's train management software returns "course sheet" of selected train containing all information about the line: crossing points, hours to stops, stops positions, and even an estimation of the passengers number in the train. Thanks to those data, simulation model generates train speed and position which make it possible to respect constraints.

A question to be answered by these simulations is the type of service where the PET may be the most valued. If commuter and local lines have a lot of stops, approximatively one stop every 3 km, the Intercity service has less stops and a larger gap between them: between 10 and 100 km. Finally, TGV have very low number of stops and can make directly several hundred kilometres without stops.

In Table 2 are presented the selected lines for simulations:

Table 2. Simulated lines

Journey	Paris St Lazare – Mantes la Jolie	Le Mans – Angers	Le Mans – Nantes	Marne la Vallée Chessy TGV – Marseille St Charles
Rolling stock	BB 27300	B 83500	B 83500	TGV 2N2
Service	Commuter	Intercity	TER	High speed
Time travel (t)	01:17	01:10	01:30	04:06
Distance (km)	57.6 km	96.6 km	184 km	739 km
Number of stop	18	10	4	2

In Fig. 2 is shown train speed and line profile, which's obtained by grouping incline and curve of the line, for the local journey Paris St Lazare – Mantes la Jolie. Line profile is intrinsic data. Train speed is computed and can't exceed the limit speed on the line.

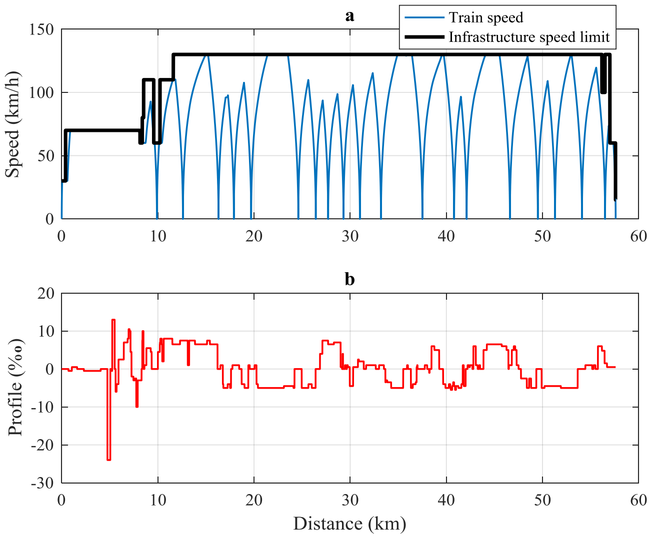


Fig. 2. Simulation data for the journey Le Mans – Angers with B 83500: (a) train speed; (b) line profile

2.3 *Focus on transformer and PET modeling*

Efficiency of some traction chain's elements varies in function of the power. It is the case of the traction transformer for which «Efficiency vs power» curve is implemented in the model. Indeed, the variability of efficiency as a function of the operating point requires simulating rolling stocks on their entire journey to determine their consumption. Then consumption will be impacted by a number of zones where transformers work with a bad efficiency.

As shown in Fig. 3(a), the efficiency of Multiple unit B83500's transformers are worse than that of the locomotive BB 27300 or the high-speed train TGV 2N2. This is due to the conception of B83500 transformers. Placed on the roof, a compromise between performance and volume must be found.

For the PET, the «efficiency vs power» curve shown in Fig. 3, and presented by Zhao (2014) on ABB prototype "power electronic traction transformer (PETT)" fed by AC 15kV 16.7Hz, has been implemented in simulation. We supposed PET performance on AC 25kV 50Hz grid will be similar with an accuracy of ±2%. All study's results have been done tacking into account this hypotheses.

As the mass gains are not really achieved today, we supposed in ours simulations that the weight doesn't change.

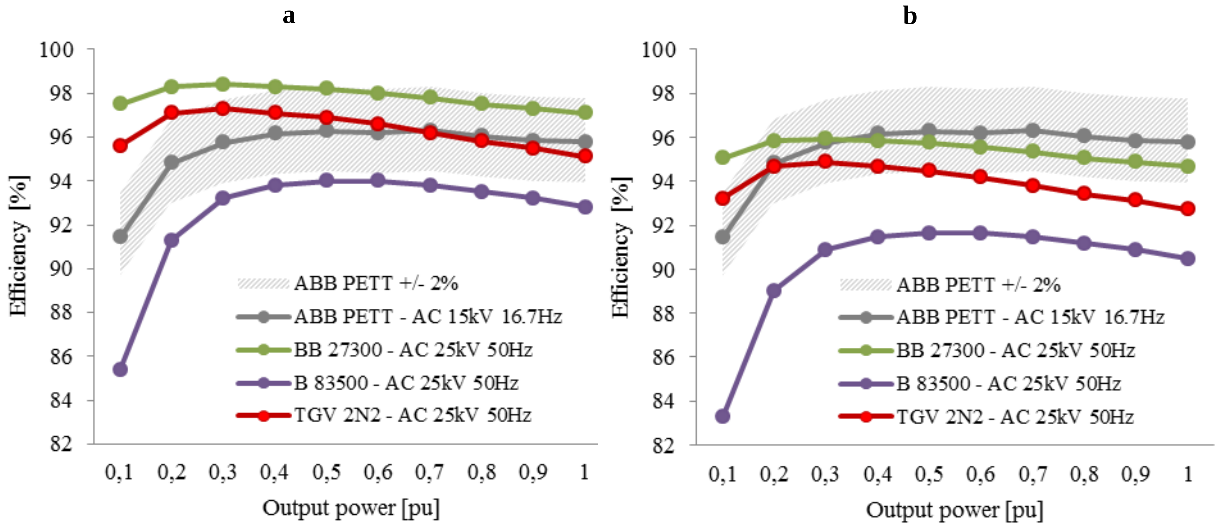


Fig. 3 "Efficiency vs power" curves for: (a) TFP vs PET; (b) TFP and active rectifier vs. PET.

As it can be seen in Fig. 3(b) PET's efficiency curve much more interesting for B 83500's power train and PET efficiency should be as good as TGV and BB 27300 power train efficiency (transformer + active rectifier).

3 Simulations results for one train

The goal of the simulation of one train is to determined energy gains by replacing TFP and active rectifier by PET. For each journey, simulations have been realized with SNCF's Matlab train simulator model. This chapter presents results and conclusion of simulations.

In Fig. 4, for each service and rolling stock, the top bar represents the energy consumption of rolling stock with PET. The bottom one represents consumption of rolling stock with a TFP and the active rectifier.

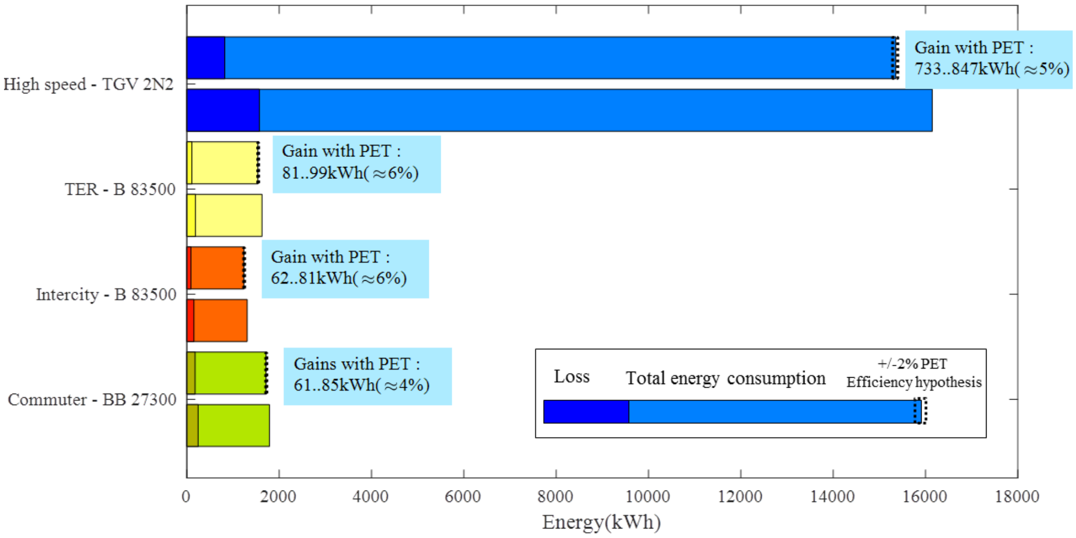


Fig. 4 Energy consumption for each simulated journey

In the annotations, the gains with PET vs. conventional powertrain are emphasised. Taking into account uncertainty represented on the bar graph, results of Fig. 4 allow to clearly identifying energy gains between 4 and 6 %.

Results in Fig. 4 show a gap between PET gains on the BB 27300, TGV 2N2 and B 83500. Indeed, installation of PET in the powertrain of the BB 27300 is revealed less interesting than for the B 83500. This is due to original better efficiency of the TFP of the BB 27300 locomotive compare to the B 83500 EMU. In the locomotive, there are enough volumes to equip an optimized transformer. The energy gains of PET mainly depends on rolling stock types. Roof transformer of the B 83500 should be a better candidate to be equipped of an PET. All the more so that, with his modular structure, PET could be split on several part on the roof of a rolling stock.
As it can be seen in Fig. 4, a PET generates an important gain also for high speed trains. This can be justifying by a good efficiency at high power which is the rated functioning point for this trains.

On very different service type (Intercity and TER), the B 83500 have the same consumption reduction about 6%. The service type as a low impact on energy gains of PET on this vehicle. This can be explaining because of acceleration phase. This phase can be seen on Fig. 5. Even if acceleration phase is about 100s, the time spent at low efficiency (less than 50km/h) represent only a few seconds for each acceleration (~15s). For example, the cumulated time spent for a journey at low efficiency, in TER or intercity service, represent only 5 to 10% of the total travel time.

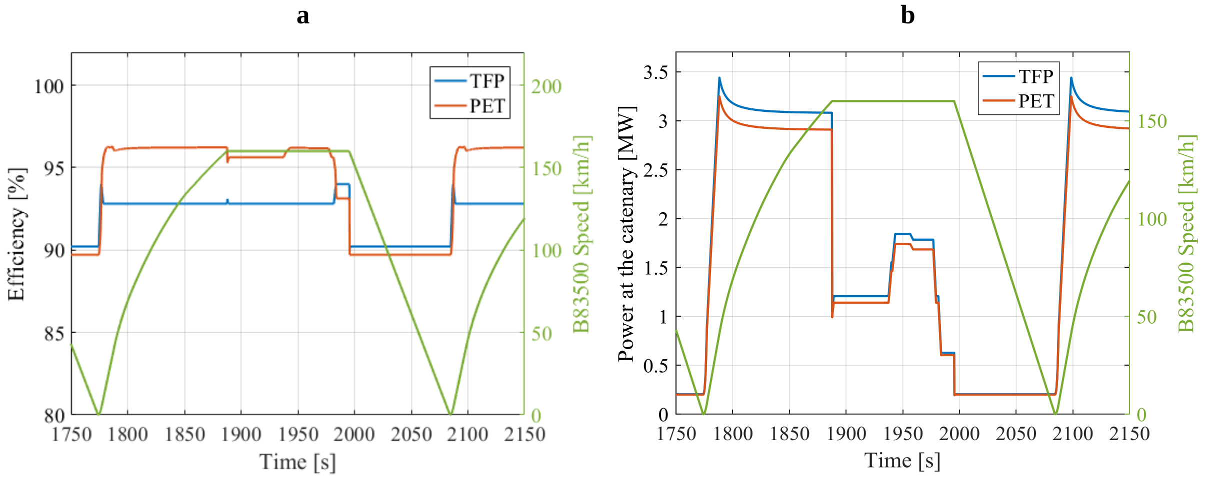


Fig. 5 Simulation results for a part of journey Le Mans – Angers with B 83500 with TFP and PET: (a) Efficiency; (b) Catenary power

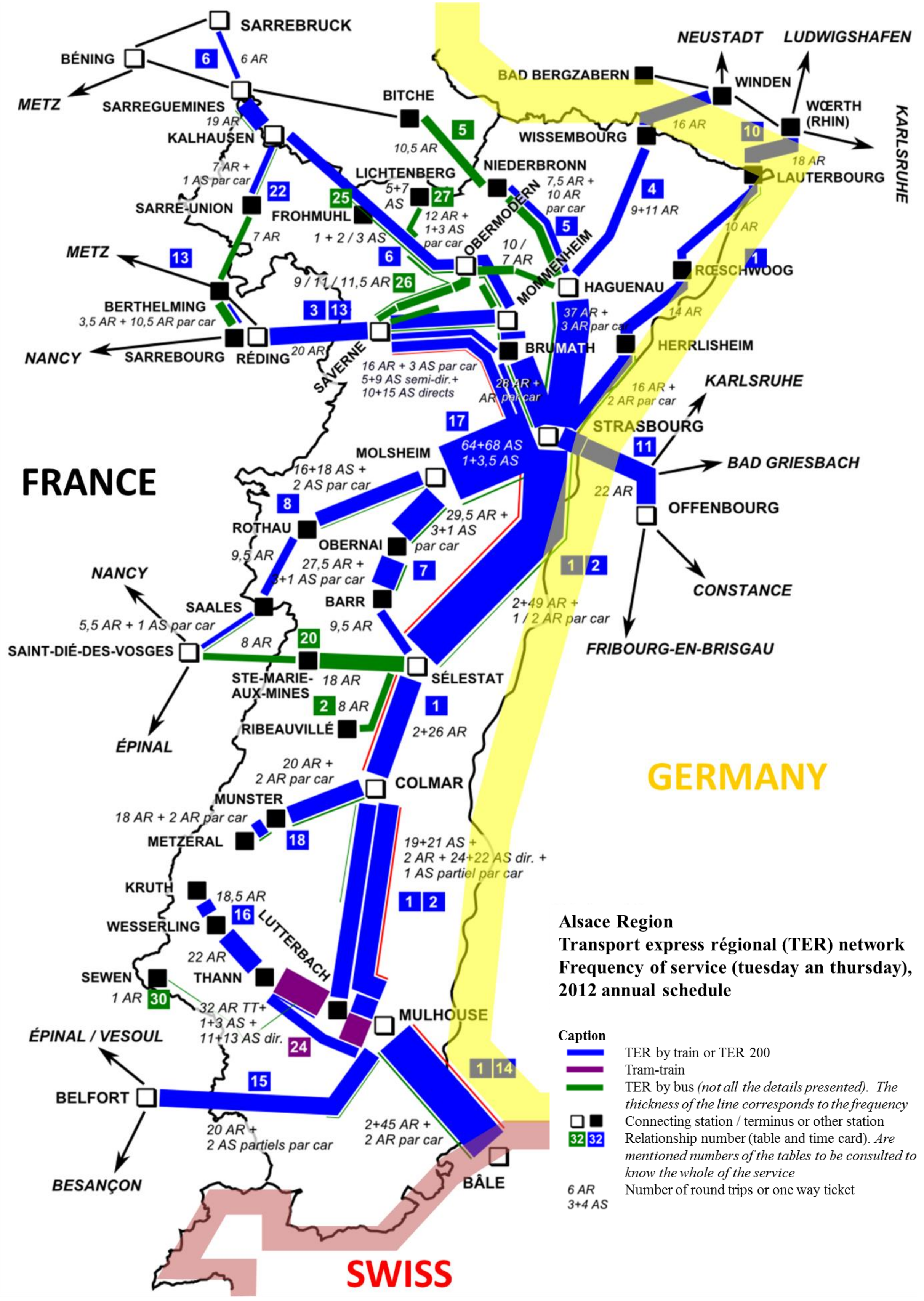
4 Extrapolation for a region

After had computed gains of PET on most representative French rolling stocks in the chapter 3, the following part present the extrapolation of one simulation to the entire fleet of a region. For this work, a region with a large fleet of electric rolling stock has been chosen: the Alsace region railway fleet.

Alsace regional rail network represented a total of 628 km and 26 main lines. In Fig. 6 a large blue line represent a heavy traffic. The associated figures represent the number of round trip “AR” and single trip “AS”.

Several types of electric rolling stock are employed in this region for a total of 61 engines. In order to limit the simulation time, we choose to simulate only the most used rolling stocks in this region and the more relevant to integrate PET. As we saw in previous chapter, vehicles with roof placed transformer will have better energy gains with PET. In Alsace Region, two fleets correspond to the criteria:

- 18 trainset Regiolis (29% of region’s electric train fleet), composed of B 83500 4C (also call PPM) of 4 cars, and B 83500 6C (also call PPG) of 6 cars.
- 13 trainset AGC (21% of region’s electric train fleet), composed of Z 27500 4C (also call ZGC) capable of running on both DC 1.5-kV and AC 25-kV 50-Hz, and B 82500 4C (also call BGC) capable of running on both diesel and DC 1.5-kV/AC 25-kV.
- Rest of the fleet is composed of BB25000, BB26000, BB67400, Z11500 and will not be simulate in this study.



Alsace Region
Transport express régional (TER) network
Frequency of service (tuesday an thursday), 2012 annual schedule

Caption

🟦	TER by train or TER 200
🟪	Tram-train
🟩	TER by bus *(not all the details presented). The thickness of the line corresponds to the frequency*
☐ ■	Connecting station / terminus or other station
32 32	Relationship number (table and time card). *Are mentioned numbers of the tables to be consulted to know the whole of the service*
6 AR 3+4 AS	Number of round trips or one way ticket

Fig. 6 Frequency of service in the Alsace region (all rolling stocks combined) Commons.wikimedia.org(2017)

The problem to simulate those 2 fleets is the high number of journey to simulate. Regiolis and AGC fleet realize in a week more than 80000 km distance travelled for 75 different types of journeys (winter 2016's data). To limit the simulation time, only journeys with heavy traffic will be simulated. The 10 mains slots exploited by AGC and Regiolis have been selected, which represents 18 journeys (of a total of 75) and realized 41320 km in a week so more than 50% of total travelled distance of the Regiolis and AGC fleet. With this percentage, sample is large enough to represents all traffic. All simulated journey are listed in Table 3. The first column, represent the journey name and the number of stops during the trip. The second column specifies which rolling stock which are simulated on the line. The columns 3rd and 4th specify the number of journey and the total distance travelled for a week. Those entire journeys are simulated and extrapolated to obtain the energy consumed per week by the rolling stocks with or without PET.

Table 3. List of simulated journeys and results

Journey type (Number of stops)	Rolling stock	Number of journeys	Total simulated distance travelled [km]	Energy with TFP [MWh]	Energy with PET [MWh]	Gains with PET [%]
Haguenau_Strasbourg(8)	B 83500 (PPG)	34	1156	22,2	20,8	6,2
Strasbourg_Haguenau(8)		33	1122	21,9	20,5	6,1
Strasbourg_Nancy(6)		16	2416	25,7	24,1	6,0
Nancy_Strasbourg(6)		16	2416	24,3	22,9	6,1
Haguenau_Strasbourg(8)	B 83500 (PPM)	42	1428	18,5	17,3	6,4
Strasbourg_Haguenau(8)		50	1700	22,3	20,9	6,4
Strasbourg_Nancy(6)		20	3020	21,7	20,3	6,2
Nancy_Strasbourg(6)		20	3020	20,6	19,3	6,3
Strasbourg_Selestat(10)	B 82500 (BGC)	40	1720	23,1	21,6	6,4
Selestat_Strasbourg(5)		46	1978	18,5	17,3	6,4
Mulhouse_Belfort(9)		46	2254	27,3	25,6	6,3
Belfort_Mulhouse(12)		46	2254	27,2	25,5	6,4
Strasbourg_Nancy(6)		3	453	3,2	3,0	6,2
Nancy_Strasbourg(6)		3	453	3,1	2,9	6,3
Bâle_Mulhouse(8)	Z 27500 (ZGC)	131	4454	48,9	45,7	6,6
Mulhouse_Bâle(8)		130	4420	51,6	48,3	6,5
Mulhouse_Belfort(9)		72	3528	40,6	38,0	6,3
Belfort_Mulhouse(12)		72	3528	40,6	38,0	6,5
Total		820	41320	461,4	432,1	6,3

The energy gains are shown in column 7. The mean gains for the fleet are around 6.3%. This is better gain than expected, comparing to gains obtained in chapter 3, because of the mission profiles.

Gains for each journey obtained by simulation are extrapolated to obtained gains for a base week. Those gains represent an amount of 29,3 MWh in a base week. As only 50% of the fleets have been simulated, result is extrapolated for the Alsace fleet and for a year to obtain an amount of 2.93 TWh/year energy savings. This energy correspond to the consumption of about 700 household. By admitting an energy cost of 75€/MWh, this energy gain represent an economy of 220 k€/year which is not enough to refurbish the entire electrical fleet with PET's.

5 Conclusion

In this paper we shown that, in France, under AC 25kV 50Hz supply, power electronic transformer can replace a classical electromagnetic transformer and the active rectifier and important energy gains are emphasised for different kind of rolling stock and services. Unfortunately, these energy gains are not enough as an ROI and other services should be added in order to justify the installation of a PET. As example, Alsace region is also a border region, the same trains can go to Swiss or Germany much easier by automatic re-configuring of the PET for AC 15kV 16.7Hz grid. The new converter should also be much more available because of his native redundancy. If mass and volume could be reduced, the EMU could also carry more people. All these new added values are conditioned by an important reliability.

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