# Comparison of Costs between Bus, PRT, LRT and Metro/rail

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**This is a chapter from a forthcoming report for the project entitled**
**European Demonstration of Innovative City Transport (EDICT)**

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## General cost aspects

An important issue in marketing the idea of Personal Automated Transport is the relative cost advantages of PRT as compared to the more traditional modes of public transport such as bus, LRT, metro and commuter rail systems. This chapter forms a basis for a comprehensive cost-benefit analysis for and costs of a PRT system at Kungens Kurva, At Huddinge Municipal. There are two cost factors that are most relevant to compare, and they are:

**Investment cost** for track, vehicles and stations

**Operating and Maintenance cost** (O&M cost) for the entire system

A difficulty in comparing the cost components between systems, already existing, and PRT, as an almost entirely new mode of public transport system, is that the existing systems could benefit from some economics of scale, as buses, but also LRT vehicles and metro cars are produced since a long time ago, in rather long series, which ought to lead to falling unit costs. PRT – being a totally new transport mode – are more prototype like, with normally yields higher unit costs. On the other hand, there is risk that some forms of operating costs might be under-estimated, without a long time period of operating experiences. Thus, there is a certain degree of uncertainty as regards the true long terms costs for the PRT mode. This is almost impossible to overcome without a true real-world test period. This is therefore also a good argument to start implementing PRT test tracks in as many places as possible.

## Cost comparisons between public transport modes - The Stockholm case

Among the traditional public transport modes, the following ones have been compared:

Bus

Light Rail Transit (LRT)

Metro

Commuter rail

with data from the Stockholm Region, completed with some international comparisons as well. The following PRT systems are included in the comparisons:

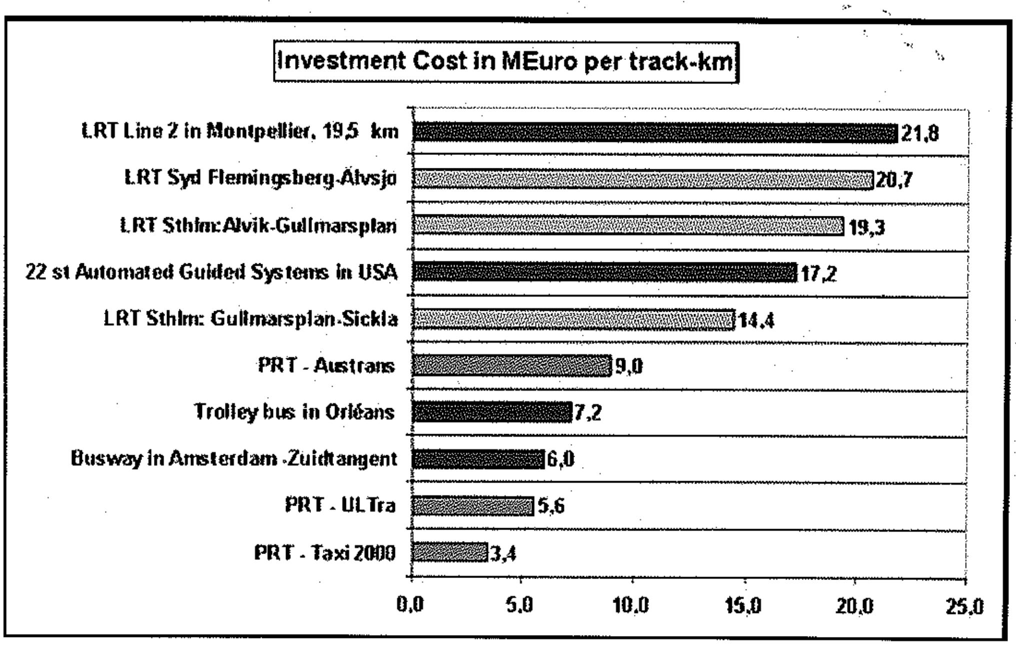
Ultra

Taxi 2000

Austrans

## Investment costs – PRT three times cheaper than other systems

The total investment costs for guideway, vehicles and stations are compared to ten different systems:



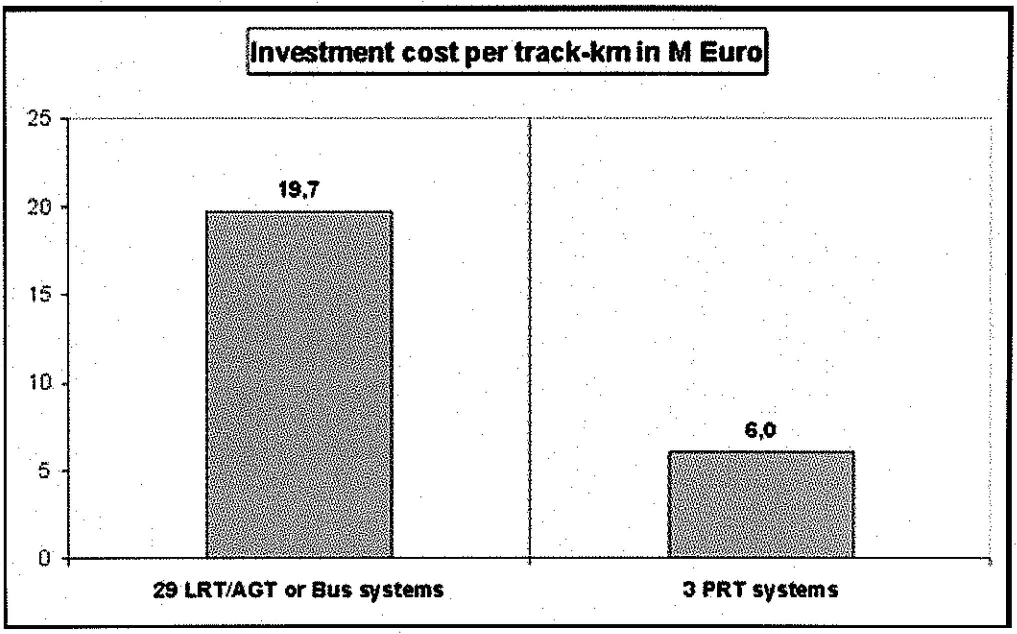

Bars in blue colour are Stockholm systems, in green are PRT systems and in Brown are other systems. The Three Stockholm LRT systems costs around 15-20 M Euro per track-kilometer. The new LRT Line 2 in Montpellier costs approx. 22 M Euro per km. A summary of 22 Automated Guided systems in the US have an average cost of 17M Euro per track-km.

All three PRT systems show a lower investment cost than the studied LRT systems. With Austrans at 9 M€, ULTra at 5,6 M€ and Taxi 2000 at 3.4 M€ per kilometre. **An average of the three PRT systems yields an investment cost of 6M€ per track-kilometre.** This is the same cost as for the newly opened Zuidtangent Busway outside Amsterdam and even lower than the Trolley bus in Orléans, France.

**The average investment costs for all the other systems (AGT, LRT and Busway/Trolleybus route) are more than three (3!) times higher than for the PRT system.**

**Conclusion: A Personal Rapid Transit system is three times cheaper than traditional Light Rail systems in investment cost.**

A simplified comparison between 29 various LRT/AGT or Bus systems (se page above) with the 3 PRT systems, show the following investment cost differences:

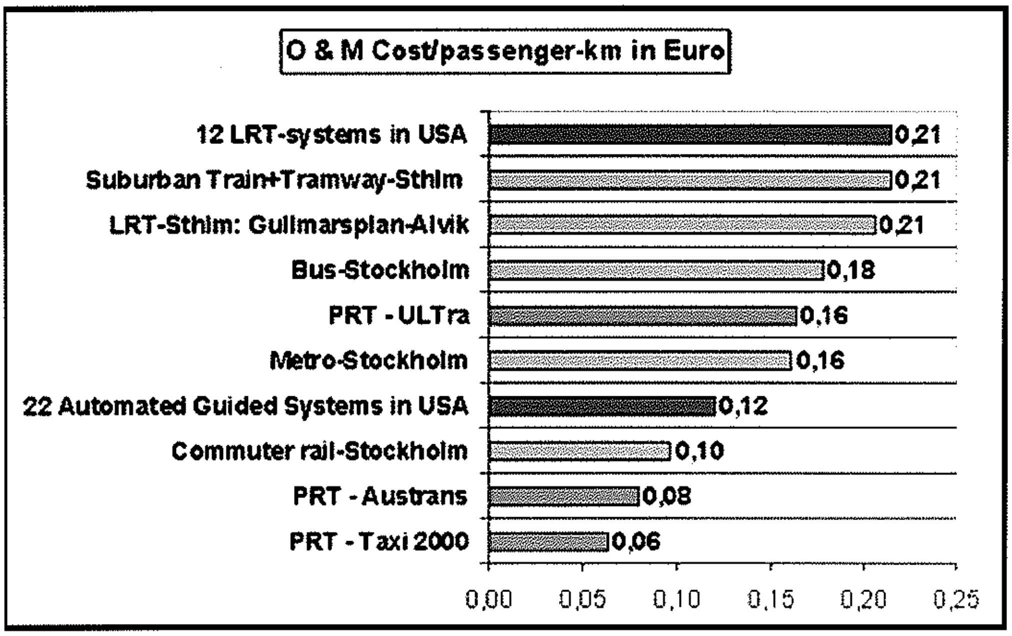



**PRT is therefore a low-cost system from the investors point-of-view.**

**[Line 2 in Montpellier, 19.5 kms, 424 M€, opens in 2005; Orléans LRT: 22.7 kms, 34 stops, 25 vehicles; Source: Rail & Transport, 3rd July 2002 (Consultant: Semaly)]**

## Operating & Maintenance costs – PRT 40% cheaper

The operating cost experiences stem from the Greater Stockholm Transit Company; AB Stor-sStockholms Lokaltrafik, Annual Report 2001. The PRT Operating costs have been obtained from each supplier in January-February 2003. The American experiences are from the Trans 21 Database (Lawrence Fabian's database). The following results are found:



As can be seen from the figure above, PRT systems perform very well also from the operating cost point-of-view. Most LRT-systems, both in the US and in Stockholm, cost around 0.20 Euro per passenger-kilometer and the bus network (9 153 km; 1 674 buses) in Stockholm costs 0.18 Euro/pass-km.

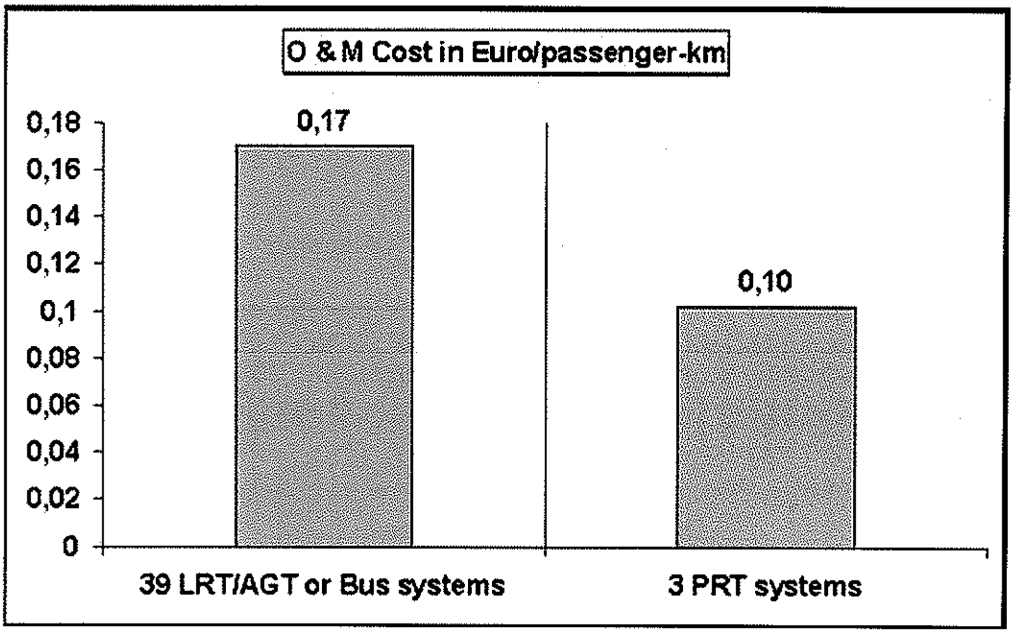
The ULTra PRT cost figure (calculated for the first phase network at Kungens Kurva) show a lower cost, 0.16 Euro per passenger-km, which is the same level as for the Stockholm Metro system (108 km; 800 metro-cars). The average operating costs for the 22 Automated Guided systems in USA cost 0.12 Euro per passenger-km and the Commuter rail network in Stockholm (186 km: 292 vehicles) cost 0.10 €/pass-km.

Both the Austrans and the Taxi 200 PRT systems are even cheaper in operation with 0.08 and 0.06 Euro per passenger-kilometer respectively.

**An average of the three PRT systems yields an operating (and maintenance) cost of 0.10 Euro per passenger-kilometer. The average operating & maintenance costs for all the other systems (AGT/LRT; Bus, Metro and Commuter rail systems) are 70 % more expensive to operate than for the PRT system.**

**Conclusion: A Personal Rapid Transit system is more than 40 % cheaper than traditional Light Rail systems in operating costs.**

The Operating & maintenance costs comparison is summarized in the figure below:




**Traditional public transport systems such as bus, Light rail and Metro is about 70 % more expensive to operate than the new and innovative transit systems such as PRT**. In Stockholm, only the commuter rail system has such low operating costs as PRT.

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1. Introduction

Among a multitude of possible power converter multi-stack candidates structures, INRETS LTN has focused its study and evaluated a HV – HV (high voltage – high voltage) interleaved boost converter for the power converter interface between the FC multi-stack generator and on-board DC bus. The converter should meet the following objectives: compactness, reliability, high efficiency, adaptability or degraded working modes (one FC stack out of work, converter fault, DC bus voltage fluctuation). Minimised current ripple for the fuel cell is also a key criterion ([11]-[12]-[15]) of the specifications (Tab.1).

The 3-phase interleaved boost converter structure has been chosen mainly because of its simplicity (it uses only a few standard components), redundancy (if a converter phase is out of work, the others still can be used as a backup system and without power break). The choice of 3 phases is justified by the specifications of the FC stack current ripple. In order to reach a 1% current ripple rate using an interleaved boost, two solutions could be envisaged: either using coupled inductors [10] or increasing the number of phases [5]. The first solution was thrown down because it makes use of specific inductors. The second one, a number of phases beyond 3, is a question of optimum and compromise between mass, volume, loses, redundancy .... Making the choice of simplicity, we studied the 3-legs converter.

Another reason for this choice could be the cancellation of the ripple near to the FC stack rated power and the use of an appropriate integrated IGBT technology. In [6], it can be seen that the power semiconductor technology could be an important parameter for the design of the converter; it can impose different architectures for the converter.

2. Converter design

The chosen converter topology is illustrated in Fig. 3, PEFC stack and power converter specifications are shown in Tab. 1. Each phase of the converter is composed of an inductor ($L_i$) and a semiconductor module ($S_i$+$D_i$). They are linked by two filtering capacitors.

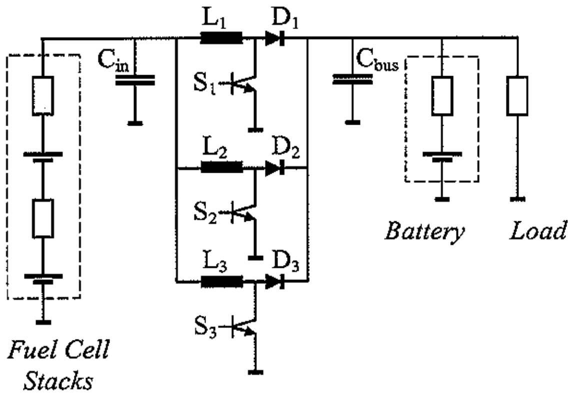



Fig. 3 Chosen power converter topology

| | |
|---|---|
| Converter rated output power | 100 kW |
| Converter maximum output power | 120 kW |
| Converter input voltage | 2 x 230 V |
| Converter rated DC output voltage | 540 V |
| DC output voltage fluctuation | -20..+15% |
| Maximum FC stack current | 600 A |
| Minimum FC generator power | 25kW |
| FC stack current ripple | 1% (6A) |
| Power converter efficiency | > 94% |

Tab. 1: FC generator and converter specifications

The input capacitor ($C_{in}$) plays the role of a low-pass filter (taking into account the inductance of the connection wires) which smoothes the FC stack current ripple. It was deducted by simulation: for a 5kHz cutt-off frequency and assuming a stray inductance of 2μH, we found a 500μf capacitor.

One of the issues of that converter is the large size of inductors and of the DC link capacitor.

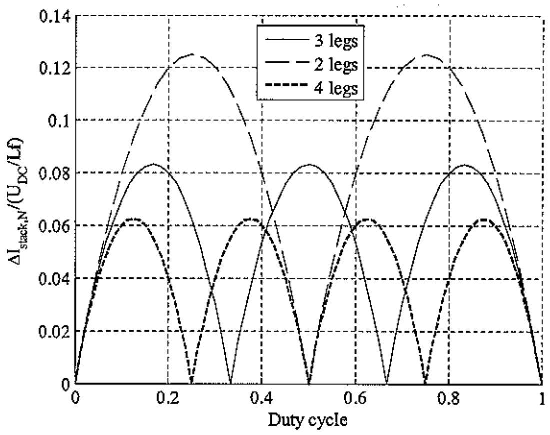
In order to calculate the inductors value, usually we use the ratio between the ripple of a 3 interleaved converters and the ripple of a single-level converter:

$$\left(\frac{\Delta I_{P,3}}{\Delta I_{P,1}}\right)=\begin{cases}\frac{1-3D}{1-D}, 0<D<\frac{1}{3}\\ \frac{(3D-1)(2-3D)}{3D(1-D)}, \frac{1}{3}<D<\frac{2}{3}\\ \frac{3D-2}{D}, \frac{2}{3}<D<1\end{cases} \text{ si } \Delta I_{P,1}=\frac{U_p}{Lf}D$$

In our application the DC link is assumed almost constant, so is much interesting to write the ripple in function of DC voltage:

$$\frac{\Delta I_{SC,3}}{\left(\frac{U_{SC}}{Lf}\right)}=\begin{cases}\frac{(1-3D)D}{1-D}, 0<D<\frac{1}{3}\\ \frac{(3D-1)(2-3D)}{3(1-D)}, \frac{1}{3}<D<\frac{2}{3}\\ 3D-2, \frac{2}{3}<D<1\end{cases}$$

The ration is shown in Fig.2:



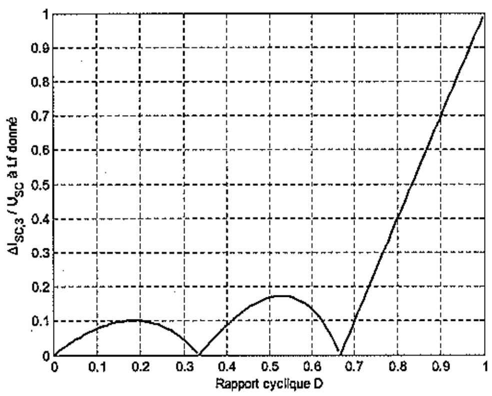
## Dimensionare inductantza Li :

In ipoteza unei conductii continue la nivelul IGBT, (continous current mode) pentru a dimensiona inductantza de bratz a CVS trebuie pornit de la ecuatiile urmatoare :

$$\left(\frac{\Delta I_{P,3}}{\Delta I_{P,1}}\right)=\begin{cases}\frac{1-3D}{1-D}, 0<D<\frac{1}{3}\\ \frac{(3D-1)(2-3D)}{3D(1-D)}, \frac{1}{3}<D<\frac{2}{3}\\ \frac{3D-2}{D}, \frac{2}{3}<D<1\end{cases} \text{ si } \Delta I_{P,1}=\frac{U_p}{Lf}D$$

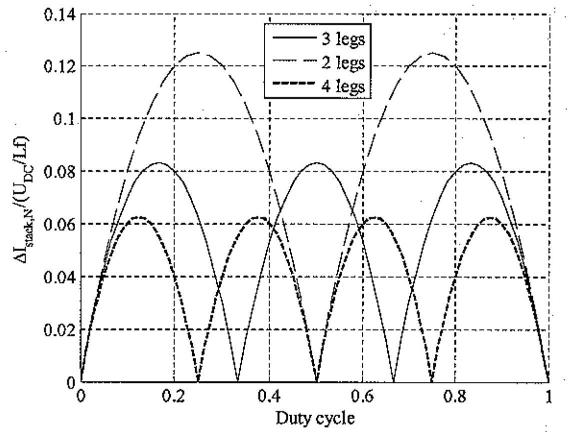
In care Up este tensiune PAC, si ΔIp1 = "ripple of a single-level step-up converter" iar ΔIp3 = "ripple of a 3 interleaved step-up converters".

Deducem ecuatia : $\frac{\Delta I_{SC,3}}{\left(\frac{U_{SC}}{Lf}\right)}=\begin{cases}\frac{(1-3D)D}{1-D}, 0<D<\frac{1}{3}\\ \frac{(3D-1)(2-3D)}{3(1-D)}, \frac{1}{3}<D<\frac{2}{3}\\ 3D-2, \frac{2}{3}<D<1\end{cases}$ ce corespunde graficului urmator :




- pentru o tensiune Usc (=Up), L,f constante : deltaI3 este maxim in plaja 0.2-0.6 pentru alfa=0.53, iar val max este 0.17.

Cum in cazul nostru tensiunea PAC variaza, este mai bine sa exprimam riplul in functie de tensiune de iesire, care este tinuta constanta, si de raportul cyclic :
Udc=Upac/(1-alfa) => (0<alfa<0.33) deltaI3=(1-3alfa)*alfa*Udc/(Lf)
Udc=Upac/(1-alfa) => (0.33<alfa<0.66) deltaI3=(3alfa-1)(2-3alfa)Udc/(3Lf)
Valoarea maxima este de N=3 ori mai mica (0.083=0.25/3) decit daca am fi avut un singur boost si se obtine (in interiorul plajei de variatie) pentru alfa=1/12 sau alfa=0.5 :




Daca impunem un deltaI3max=6A pentru alfa=0.5 => L=0.5*0.5*540/3/3000Hz/6A obtinem o inductanta de bratz de 2.5mH. Dimensiunile unei astfel de self, chiar daca curentul este divizat in 3, sunt mari.

Din cauza asta acceptam o <u>conductie discontinua la nivelul IGBT</u>, ceea ce conduce la un noua dimensionare a inductantzei.
Limitatia pe care ne-o impunem este curentul maxim comutat in IGBT (deltaI=200A), la o frecventza de f=3kHz (din cauza pierderilor). Daca exprimam riplul in functie de tensiunea de iesire a CVS (Udc=540V=constanta), obtinem :

Upac=L*deltaI/(alta*T) & Udc=Upac/(1-alfa) => Lmin=Udc*alfa*(1-alfa)/deltaI/f=225μH pentru alfa=0.5

Voila de ce am ales o inductantza de 200μH.

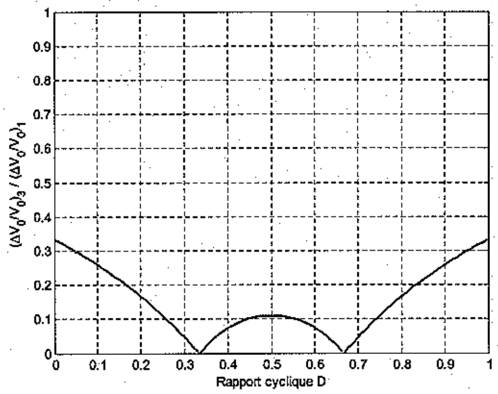
Tehnologia inductantzei este importanta, pentru a nu avea pierderi suplimentare in self (pentru ca parcurgem un ciclu intreg de histerezis, nu microcicluri in jurul unei valori medii).

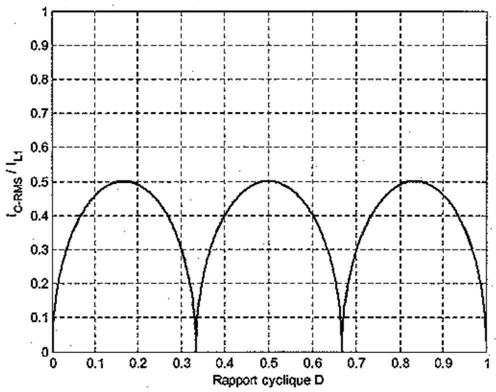
Comanda convertorului nu mai este una liniara, in zona de discontinuitate (relatie intre raportul ciclic si tensiunea de iesire), ceea ce conduce la o lejera modificare a plajei de functionare a CVS (0.1 – 0.65).

## Dimensionare condensator iesire Cbus :

Tensiunea de iesire nu este supusa unei sever constraint din punct de vedere al riplului. Daca facem aceeasi ipoteza de <u>conductie continua</u> expresia riplului este :

$$\frac{(\Delta V_0/V0)_3}{(\Delta V_0/V0)_1} = \begin{cases} \frac{1-3D}{3(1-D)}, 0 < D < 1/3 \\ \frac{(3D-1)(2-3D)}{9D(1-D)}, 1/3 < D < 2/3 \\ \frac{3D-2}{3D}, 2/3 < D < 1 \end{cases}$$




Ceea ce inseamna ca in plaja 0.1-0.65 ripple va fi redus de 4 ori. Daca impunem un riplu de 5V obtinem o valoare minima de Cf=880µF pentru o frecventza de 3kHz.
The max rms value is half of the (Ip/3), which means 35A:

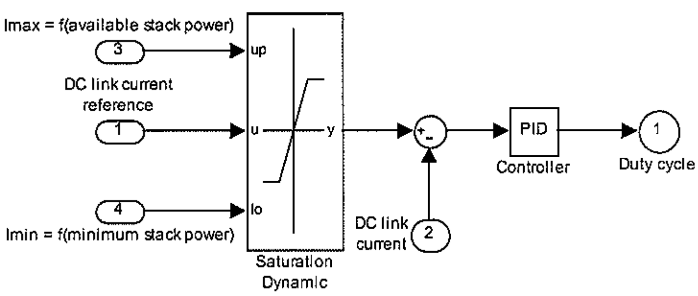
$$\frac{I_{C\_RMS}}{I_{L1}} = \begin{cases} \sqrt{3D(1-3D)}, & 0 < D < \frac{1}{3} \\ \sqrt{(3D-1)(2-3D)}, & \frac{1}{3} < D < \frac{2}{3} \\ \sqrt{3(3D-2)(1-D)}, & \frac{2}{3} < D < 1 \end{cases} \quad \& \quad I_{L1} = \frac{I_{load}}{3(1-D)} = \frac{I_p}{3}.$$

## Dimensionare condensator intrare Cin :

Condensatorul de intrare joaca rolul urmator : « It plays the role of a low-pass filter (taking into account the inductance of the connection wires) which smoothes the FC stack current ripple ».
In consecinta, am ales o valoare astfel incit frecventza de taiere sa fie in jur de 5kHz estimind o inductantza de 2µH, deci un condensator de intrare about 500µF
[C=1/(L*Omega0^2)=1/(2e-6*(2*pi*5000)^2) => 506µF]

## Comanda

La nivelul semiconductorilor : There are 3 single boost converters, drives by synchronized pulses, equally phase shifted in time.
f denotes the semiconductors switching frequency and Nf the frequency of the input current and output voltage.
La nivelul aplicatiei : power or DC current/stack current could be controlled in a closed-loop with a simple PI controller and a dynamic limitation depending on available stack power:

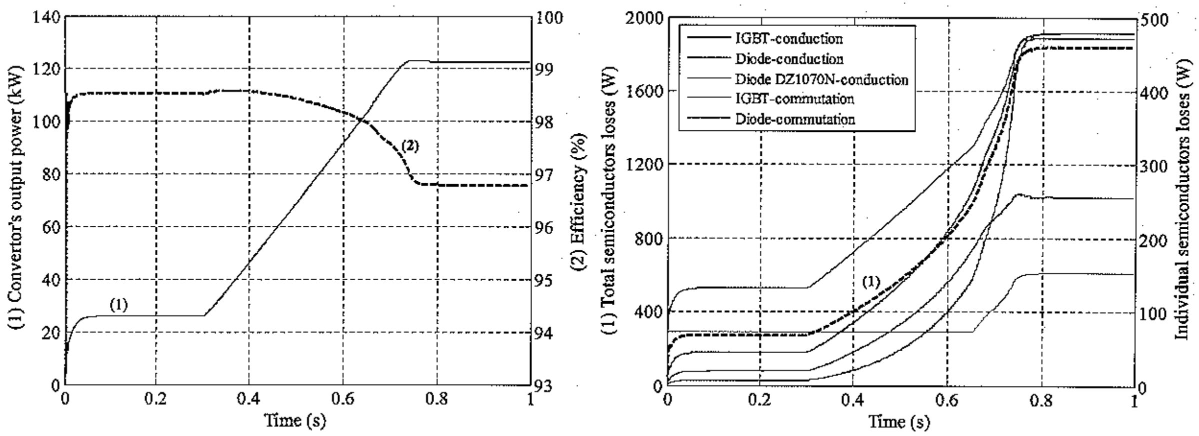



## Polyphase boost converter

Alegerea intre 3 si 4 bratze nu este usoara. 4 bratze inseamna o frecventza mult mai mare in self si condensatorul de iesire, deci apriori dimensiuni mai mici. Inseamna deasemenea curenti mai mici in semiconductori. Este deci o decizie de optimum. Noi am decis ca nu cistigam prea mult in riplu (4 bratze = reducere la 1/4=25%, 3 bratze = reducere la 1/3=33%), sau in dimensiuni, utilizind technologia la zi in domeniul IGBT, self & condensator.

## Randament

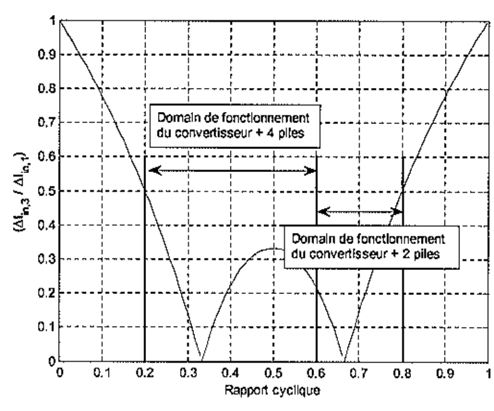
PLOTYY_art_figRANDAMENT() ne da urmatoarele curbe :



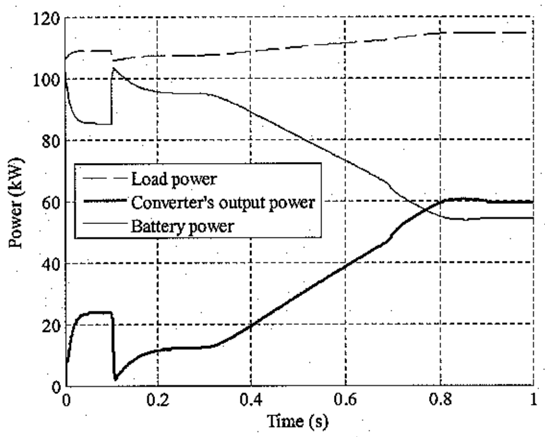

Conditiile de simulare : functionare normala, rampa de putere intre Pmin & Pmax. In randament tinem cont de pierderile din semiconductori+pierderile in inductantze (r1self~8mOhm).
Attention : tsimul << treel de montée en puissance de la pile !!! = HYP de simul, juste pour avoir un tsimul petit.

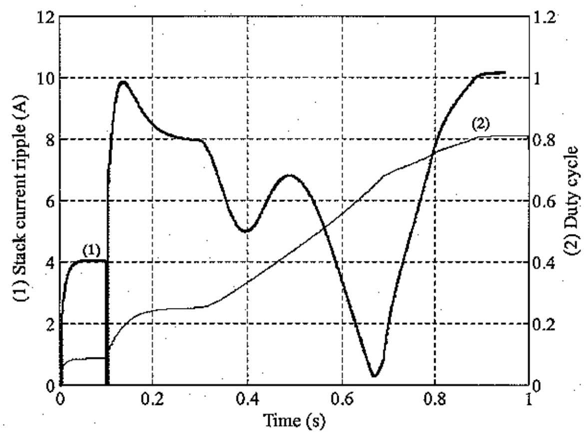
## Modes dégradés

1) 1 PaC HS : l'ondulation du courant Ipile est affectée par la chute de la tension du générateur et par conséquent la modification de la plage de variation du rapport cyclique.
D'une part, si la tension chute de 214V à 107V (pour 560A, donc à puissance maximale), le rapport cyclique varie alors de 0,6 à 0,8. D'autre part, la puissance minimale à fournir aux auxiliaires diminue, de 25kW à 13 kW. Cela revient à une modification du rapport cyclique minimal, de 0,2 à 0,6. Ces considérations sont illustrées dans la figure suivante :

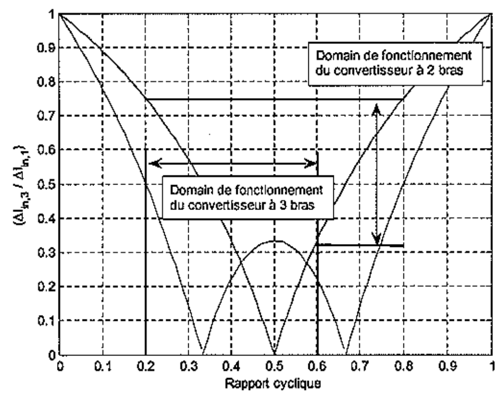


In ipoteza unui regim continuu, se modifica plaja de functionare a raportului ciclic (de la 0.2-0.6 la 0.6-0.8) dar nu se modifica riplul maxim ; din cauza regimului discontinuu, plaja de functionare este diferita, riplul mai mare dar acceptabil (<2%) :

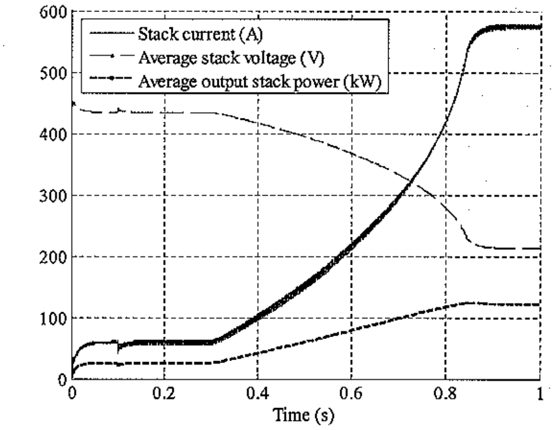


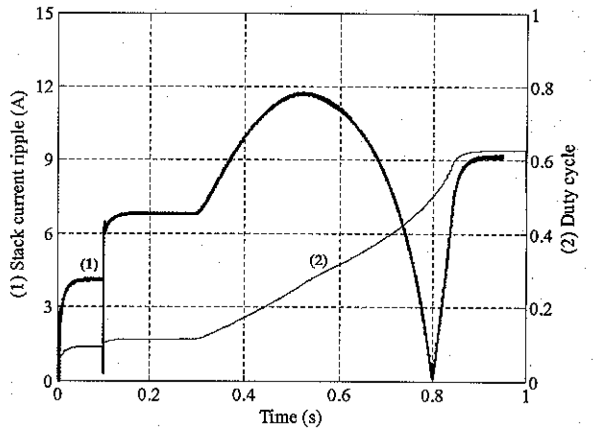




2) 1 bras du hacheur HS : une défaillance au niveau du convertisseur se traduit dans notre application par l'ouverture d'un IGBT, suite à un défaut ou à l'action d'une protection. Dans les simulations présentées dans la suite de ce paragraphe, le 3$^{\text{ème}}$ bras du hacheur est ouvert à l'instant 0.01s, et automatiquement (et idéalement) la commande du 2$^{\text{ème}}$ bras du hacheur est décalée d'une demi période par rapport au 1$^{\text{er}}$ bras. Conséquence : la plage de variation du rapport cyclique n'est pas affectée, mais le fait de fonctionner avec uniquement deux bras modifie la valeur de l'ondulation du courant Ip.
L'ondulation théorique (en régime de conduction continue) en fonction du rapport cyclique, pour un hacheur à deux bras, est illustrée dans la figure suivante :

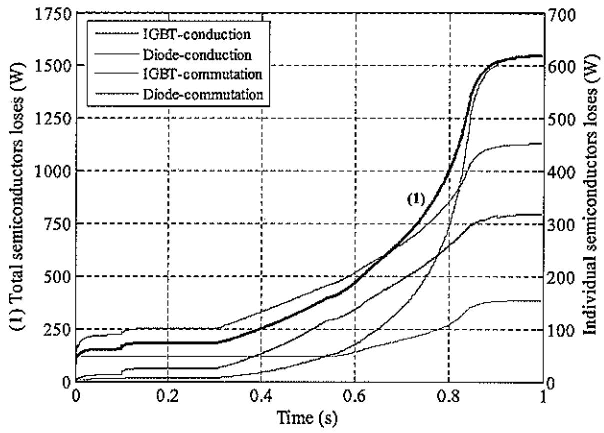



On constate que si le rapport cyclique reste constant à 0,2 l'ondulation du courant Ip augmente de 0,5 à 0,75. Pour un rapport cyclique de 0,6 l'augmentation du taux d'ondulation n'est pas significative. On doit donc s'attendre a une augmentation du ripple de Ipile :

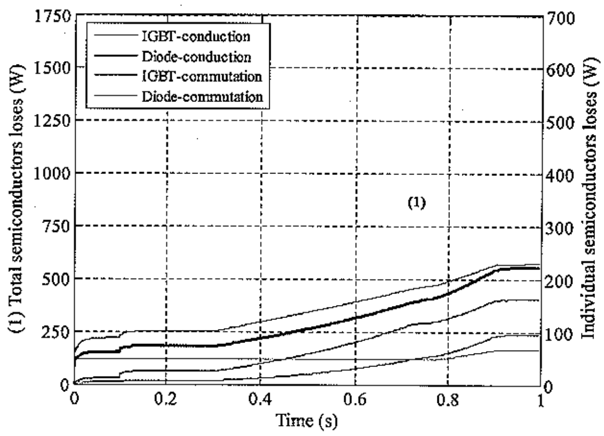


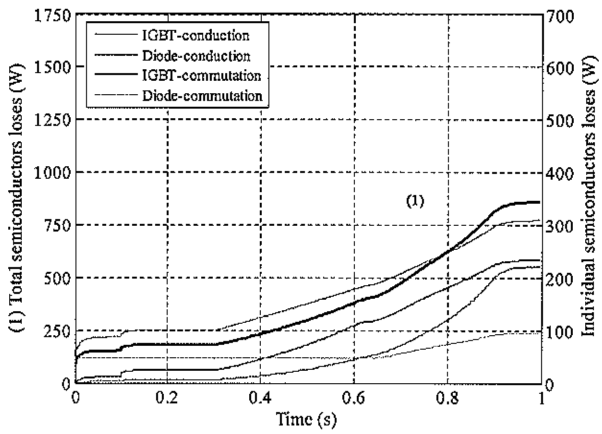

Daca mentinem puterea transferata la valoarea maxima (120kW), riscam sa ardem ceilalti semiconductori. Din aceasta cauza puterea poate fi limitata (la 100kW pentru technologia de IGBT folosita :deltaTj-sink[dioda100/120kW]=+25/+35°C & deltaTj-sink[igbt100/120kW]=+24/+49°C).




120kW

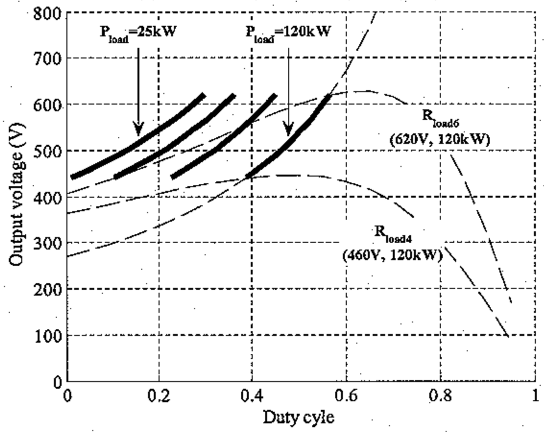



80kW

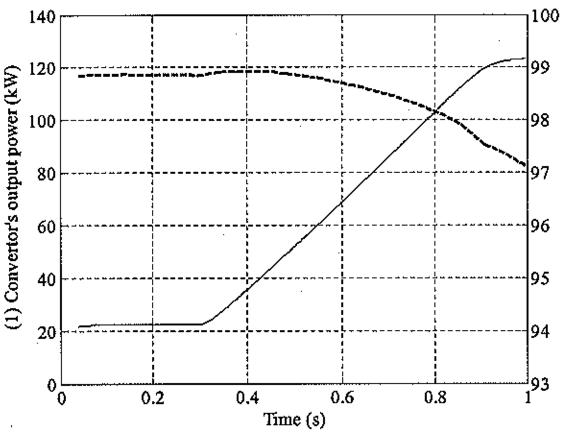


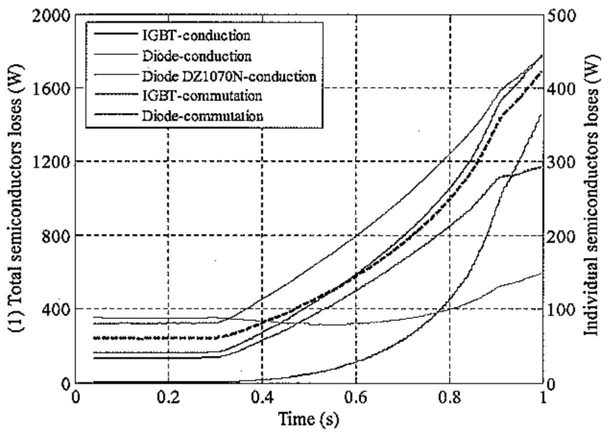

100kW

3) Tensiunea DC poate varia intre 435V (corespunzatoare unei puteri de 25kW) si 620V. It means -15% à +20% around the 540V, nominal value.




In figura de mai sus putem observa ca CVS'ul poate amplifica tensiunea PaC (pentru orice putere) in plaja 435-620V.
The dash lines represent the real gain of the boost converter tacking into account the stack ESR and the load (as equivalent resistance for a given power). As it can be seen, for a given power (120kW as e.g.) the duty cycle varies from 0.41 to 0.55 when the DC voltage varies from 460V to 620V.
Randamentul nu este afectat in cazul unei tensiuni DC minime:

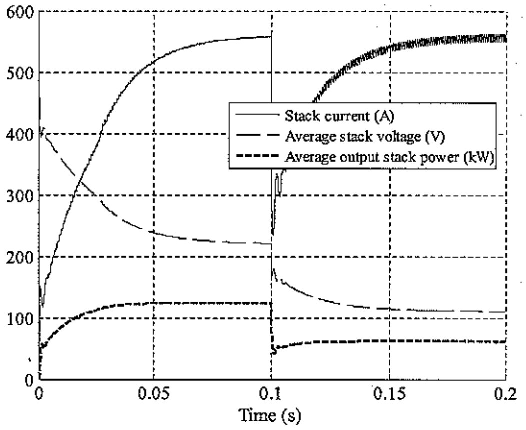


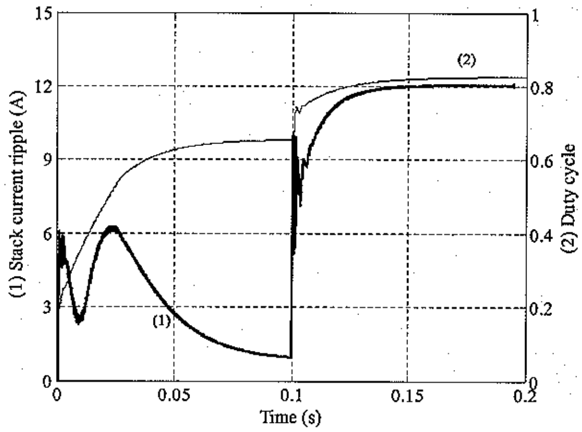

Fluctuations de la tension de bord + 1 stack HS : dans le cas d'une tension du réseau de bord minimale (de 432V) et dans le cas de la tension du générateur PAC de 214V (ou 107 si un module est défaillant) le rapport cyclique passe à 0,5 (ou 0,75), et donc l'ondulation du courant Ip reste dans les limites initialement prévues.

dans le cas d'une tension du réseau de bord maximale (621V), les points critiques qui peuvent apparaître seront les suivants : tension du générateur PAC égale à 214V ou encore plus basse (107V) dans le cas de la défaillance d'un module PAC. Dans ces cas, le rapport cyclique passe de 0,6 à 0,66 ou 0,83 (pour 107V). Si le rapport cyclique dépasse 0,8 l'ondulation sera supérieure à celle prévue initialement. Néanmoins, le système reste parfaitement contrôlé.

Ces prévisions sont théoriques et correctes pour l'hypothèse de la conduction continue. Les simulations démontrent que le raisonnement reste cependant valable pour le régime discontinue :



Stack current (A)
Average stack voltage (V)
Average output stack power (kW)
Time (s)

(1) Stack current ripple (A)
(2) Duty cycle
(1)
(2)
Time (s)