

Hybrid powertrain design using optimal control strategies

Francis Roy^{1,2}, Angela M.Catania², Florence Ossart², Claude Marchand²

¹*PSA Peugeot Citroën, La Garenne-Colombes, France, e-mail : francis.roy1@mpsa.com*

²*Laboratoire de Génie Electrique de Paris (LGEP), CNRS UMR8507, SUPELEC, UPMC, Univ. Paris-Sud, Plateau de Moulon 91192 Gif sur Yvette, France,*

e-mail: amarte.ct@gmail.com, florence.ossart@lgep.supelec.fr, claude.marchand@lgep.supelec.fr

Abstract

The urgent need of CO₂ emissions saving leads automakers to develop more efficient powertrains. The present work compares different electric hybridizations to identify key guidelines to design efficient systems. The optimal energetic performances of different powertrain architectures (series, parallel and combined) are calculated by using optimal control strategies and dynamic programming.

The aim is to point out the limiting factors of a given architecture and to define how electric power components should evolve to achieve a better global efficiency of the system. The battery capacity influence on CO₂ saving is discussed. The distribution of electric loads is presented for different INRETS driving cycles. The influence of the electric machine efficiency on regenerative braking and internal combustion engine working points optimization is analysed. This work leads to technical specifications to choose an optimal architecture and to size the electrical components.

Keywords: HEV(Electric Hybrid Vehicle), passenger car, energy consumption, optimization, power management

1 Introduction

1.1 Context

In the current context of increasing demand for personal transportation, on-going oil stock depletion and growing environmental concerns, profound technological mutations are needed to design passenger cars. During the last century, automotive industry has been dominated by internal combustion engine (ICE) based powertrains, despite their rather low efficiency. Improvements in ICE efficiency are still expected, but further enhancements can be achieved by coupling fossil energy source with a complementary on-board one. Nowadays, research and development activities are focussing on hybrid systems.

This study regards hybrid-electric vehicles (HEV). An optimal design aims at taking advantage of both technologies, in order to reach the lowest vehicle fuel consumption: ICE are fuelled by oil, which has a high energy density and easy on-board storage, while electric machines have high efficiency and zero tank-to-wheel emissions. Furthermore, their reversible behaviour allows regenerative braking.

Hybrid-electric vehicles have a classical IC-engine and at least one electrical machine, which allows to operate the ICE closer to its optimal working point. Fuel is still the primary source of energy but the global efficiency of the system is improved.

1.2 Study objectives

The goal of this study is the comparison of different HEV powertrain architectures to establish

guidelines for the design of lower CO₂ emission hybridization. It was chosen to study the potential of electric hybridization of a B segment vehicle (Peugeot 208), without possibility of recharging the battery from the grid (vehicle without Plug In function). Different powertrain architectures (series, parallel or combined) are considered and modelled. Their optimal performances, obtained by means of a proper control, are compared and analysed, so as to quantify the pros and cons of each structure. Guidelines are established for an optimal choice and sizing of the components.

At this stage of the study, the same power components are used in the different architectures. The ICE is a 1.0-liter 3-cylinder in-line gasoline motor and the electrical machines are synchronous motors, modelled by their efficiency maps. Three mechanical coupling devices are tested: discrete speed ratio, continuous speed ratio and planetary gear.

Several driving cycles are considered: NEDC and INRETS ones, which are more representative of customer use [2][5]. The lowest fuel consumptions of the studied architectures are calculated by using optimal control strategy [3][4] and dynamic programming algorithms [1]. This simulation tool provides various information about the use of each component, and especially their working point and efficiency during the cycle.

First, this paper presents the studied architectures and the problem of the optimal control. Then, the topologies are compared in terms of CO₂ saving. The electric machine loads of the most performing powertrains are calculated for the considered driving cycles and the influence of the electric machine efficiency is also discussed. Finally, results are summarized and directions for future progress are highlighted.

2 Hybrid powertrain modelling and consumption minimization

2.1 Powertrain architecture

The two basic types of hybrid powertrain architectures are the series and the parallel ones. Combined architectures mix both. Fig.1 shows the synoptic of the power flux for the considered architectures.

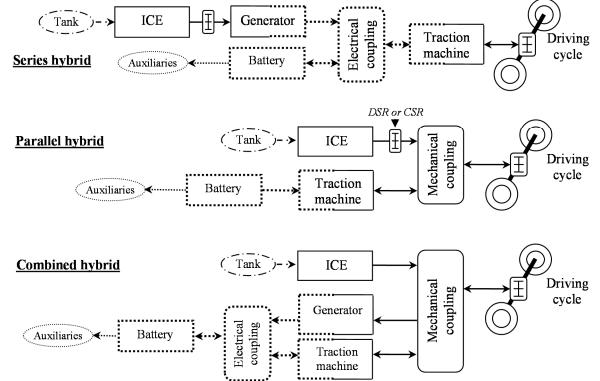


Figure 1: Series (top), parallel (middle) and combined (bottom) hybrid powertrain architectures - Solid lines are for mechanical power flux, and dashed ones for electrical power flux

The series architecture is commonly used in plug-in vehicle to extend the duration of purely electrical mode by supplying the electric power both by a battery and by an engine-driven generator (Fig. 1 top). Since this generator is mechanically independent from the wheels, it can be operated at its optimal working point either to directly feed the electrical motor or charge the battery. Furthermore, the battery is recharged by exploiting the reversibility of the electric machine for regenerative braking. On the other hand, the maximum power supplied to the wheels is the electrical motor's one; two electrical machines are needed, and the fuel energy flows through both of them, which cumulates losses.

The parallel architecture can be seen as an ICE one, improved by additional electric power (Fig. 1.middle). It requires only one electrical machine in addition to the ICE. Both are mechanically coupled, and can power the vehicle either individually or simultaneously. To accommodate the rotational speed of the ICE to the wheels one, a speed ratio system is required. The discrete speed ratio system (DSR) corresponds to a classical gear box, with 5 fixed speed ratio, whereas the continuous speed ratio system (CSR) corresponds to an ideal one, with an infinite number of speed ratio. A 97% efficiency is assumed for both systems.

For the combined hybridization (Fig. 1.down), the mechanical coupling between the motors and the wheels is made by a planetary gear. In this architecture a continuous speed ratio is produced by proper control of the electrical generator.

The battery is used for temporary storage of the electrical energy generated by braking or by the ICE. At each step of time, the fraction of energy provided by the ICE and the battery must be

adjusted to maximize the global efficiency of the system. Typically, the electric power is used either when the ICE efficiency is poor, or to provide extra power when the demand is high.

2.2 Optimal control of the powertrain

As pointed out in the previous section, hybrid powertrains use two power sources, and the global efficiency of the system depends on their combination. Each motor has its own optimal operating area, but they do not necessarily coincide. Furthermore, energy transfers have an energetic cost: for example, operating the ICE at its highest efficiency may result in Joule losses in the battery, which degrade the global efficiency of the system. Hence, the whole powertrain must be taken into account to optimize the control strategy and obtain the lowest fuel consumption. For a given architecture and a given driving profile (power and speed to be provided to the wheels versus time), the total fuel consumption of the powertrain, denoted J , is a function of the ICE power control $u(t)$. The internal variable which describes the state of the system is the state of charge of the battery, denoted SOC . It is constrained between two values (SOC_{min} and SOC_{max}); furthermore, the consumption must be calculated for identical initial and final states of the system ($SOC(t_{initial}) = SOC(t_{final})$).

An off-line optimization is considered here, which means that the whole driving cycle has to be known. The optimal command $u^*(t)$ is found by solving the following optimization problem: find $u(t)$ in the space of possible control functions U , so that the total consumption over the cycle $J(u)$ is minimum, and that the constraints on the battery state of charge are fulfilled.

$$\left\{ \begin{array}{l} u^*(t) = \operatorname{argmin}_{u(t) \in U} J[u(t)] \\ SOC_{min} \leq SOC(t) \leq SOC_{max} \\ SOC(t_{initial}) = SOC(t_{final}) \end{array} \right. \quad (1)$$

This problem is numerically solved by applying classical dynamic programming algorithms [1][2]. The control function $u(t)$ and the following quantities are calculated: electric power, intensity of the battery, SOC of the battery, and of course the total fuel consumption converted to CO_2 saving, ...

3 Results

3.1 Powertrain comparison

Fig. 2 compares the CO_2 saving as a function of the mean speed of the vehicle on ten driving cycles (INRETS), with no constraints on the SOC . The reference system corresponds to a conventional ICE vehicle with a classical gear box (DSR).

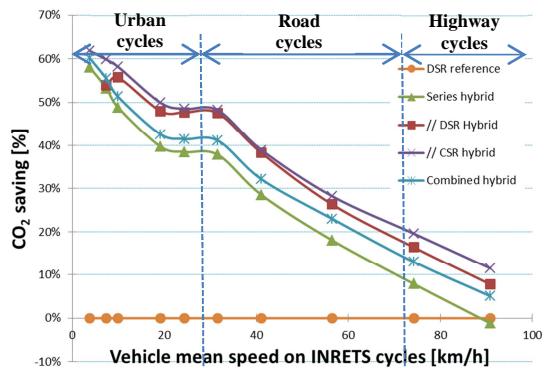


Figure 2: CO_2 saving performances of the studied powertrains for different INRETS driving cycles

All hybridization topologies show the same trend: the lowest the speed, the highest the CO_2 saving. The highest CO_2 saving is achieved by the parallel CSR powertrain. The parallel DSR powertrain is slightly under, because the ICE speed cannot be as precisely adapted to the wheel speed, especially at very low speed and during the starting phase, where a clutch is necessary.

The combined hybridization produces the desired continuous speed ratio, but with an efficiency limited by the losses in the electrical devices, resulting in a global gain about 7 points under the parallel CSR powertrain.

The series hybridization is the less efficient one, with a global gain 10 points below the parallel CSR hybrid one. A remarkable point is that for urban cycles in congested traffic (very low mean speed), all hybridizations topologies seem to converge towards the same level of CO_2 saving.

It is also interesting to look at the ICE efficiency (Fig. 3). The series hybridization makes it possible to operate the ICE at its best efficiency during the whole cycle, but this gain is balanced by electrical losses and the global gain is less than for the parallel architecture.

These results show that the parallel CSR topology seems to be the best one, provided that the CSR coupling device has a very good efficiency.

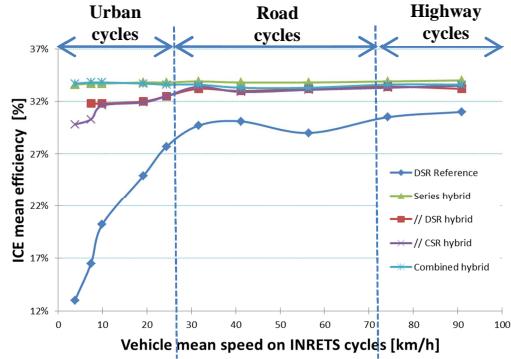


Figure 3: ICE mean efficiency of the studied powertrains for different INRETS driving cycles

3.2 Battery capacity impact on vehicle consumption

The previous results were obtained with no constraint on the battery state of charge. It is interesting, however, to study the influence of SOC constraints on the vehicle consumption in order to size the battery capacity.

Fig. 4 shows the evolution of the energy stored in the battery during a NEDC cycle (red line). The battery energy is given by: $E_{batt} = SOC * 100 * Q_0$ where Q_0 is the battery capacity, set arbitrarily at 1 kWh. A decreasing energy means that the battery is providing electrical energy to the wheels, whereas an increasing energy means that the battery is recharged either by the wheels or the ICE.

Fig. 5 represents the power at the wheel during the NEDC cycle and the corresponding energy. It shows that the NEDC cycle ends with a braking phase, during which an energy of 100 Wh can potentially be recovered. If the battery capacity is larger than this quantity, the system can actually store this energy and maximizes braking energy recovery during the whole cycle.

Simulations are made with smaller battery capacity, and the optimal control adapts itself to the battery limitation. For battery capacities larger than 100 Wh (Fig. 4a and 4b), the vehicle consumption is not affected, but for battery capacities below (Fig. 4.c and 4.d), the vehicle consumption increases as the battery capacity is too small to permit full recovery of the braking energy.

This analysis enables to define the optimal battery capacity: for example, for a NEDC cycle, the optimal battery capacity is 100 Wh, whereas for a representative highway cycle a 50 Wh capacity is enough. Similar results were obtained for all the considered powertrain architectures, leading to the same battery size.

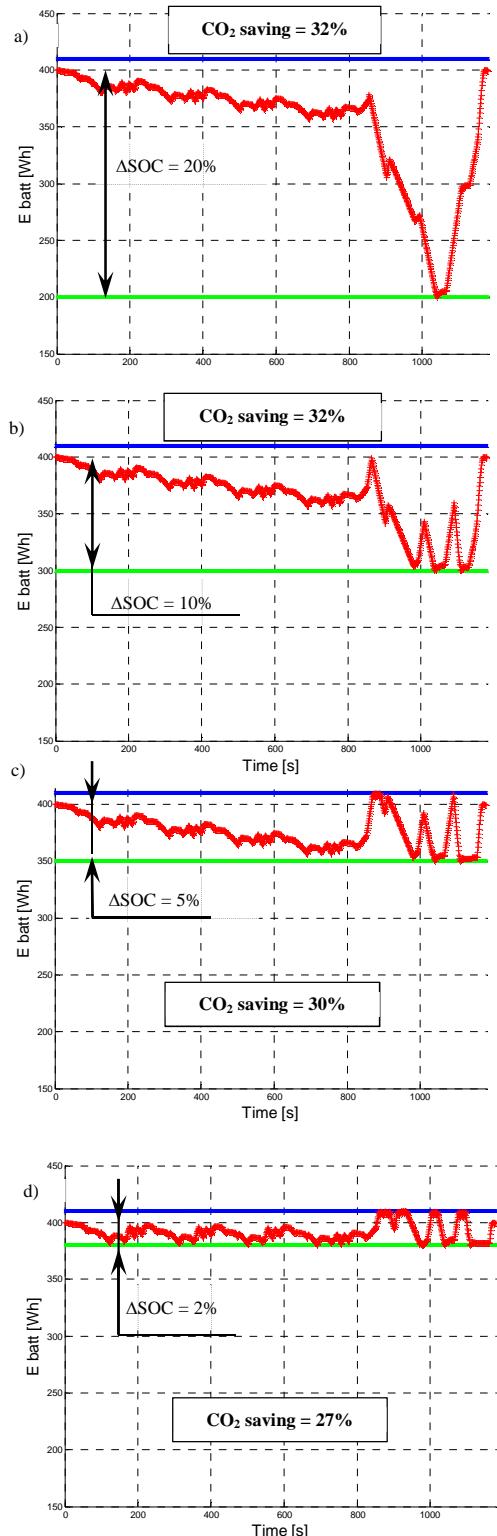


Figure 4: Battery energy versus time (red line) for // DSR hybridization with different SOC limitations on a NEDC driving cycle – The blue and green lines respectively correspond to the highest and lowest level energy in the battery

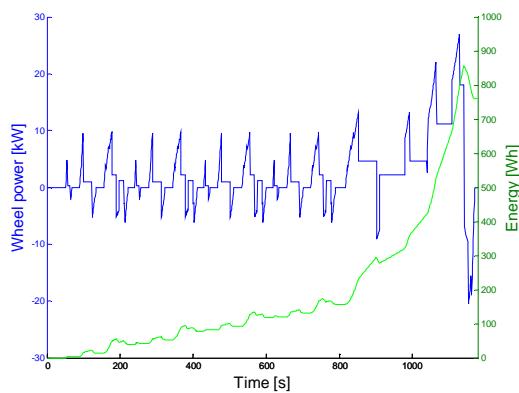


Figure 5: Power (blue line) and energy (green line) at the wheel during the NEDC cycle

3.3 Electric machine loads

At each step of time, the Smart Energy Management system calculates the best power split ratio between the electric and thermal energies to achieve the optimal global efficiency. Different operating modes of the vehicle are identified on Fig. 6 for the parallel DSR hybridization: pure electric traction, electric generator + ICE, electric boost + ICE, regenerative braking and stop phase.

Because of ICE speed limits, and as no clutch has been considered in the mathematical model, the optimal starting phase (up to around 15 km/h) is provided by a purely electric traction mode. Simulations made for the parallel CSR architecture show that it can be started either in a hybrid mode or in an electric one, thanks to the speed degrees of freedom. Series hybrid and combined one are also started in a purely electric mode or in a hybrid one.

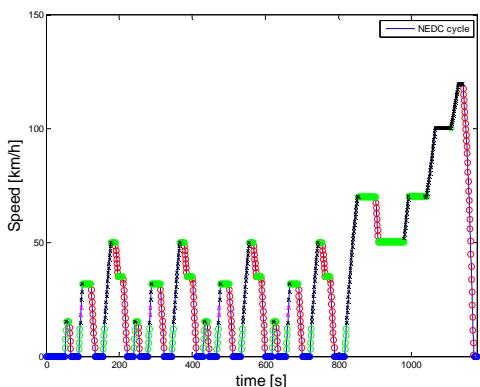


Figure 6: Operating mode for a DSR parallel hybrid powertrain - ● Pure electric traction - × Electric generator + ICE - × Electric boost + ICE - ○ Regenerative braking - ○ Stop phase

During acceleration phase (beyond around 15 km/h), the ICE is operated at a power level which optimizes its efficiency. If this optimal power is higher than the power needed at the wheels, the excess is stored in the battery (black points on Fig. 6). If it is too low, an electric boost is produced (magenta points on Fig. 6). During constant speed phases, when low power is needed, a purely electric mode is run (green points).

During deceleration phases, the optimal control leads to ICE stop and battery recharge (red points on Fig. 6).

Whatever the cycle, the system never runs in a purely ICE mode because ICE regime optimization is always operating.

It is also interesting to focus on the electric machine load, which is represented by working points on the efficiency map (Fig. 7) for the different operating modes:

- Braking Energy recovery (red points)
- ICE efficiency optimization (green, black and magenta points)

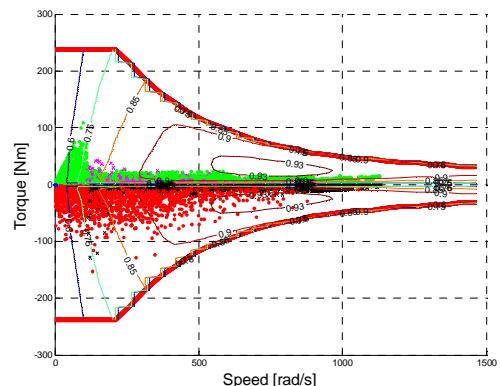


Figure 7: Electric machine load for a // DSR hybridization on all INRETS cycles (coloured points correspond to figure 6 definitions)

The current electric machine is more suited to regenerative braking than to the optimization of the ICE efficiency as less power is required. This result shows that the EM design should be optimized to increase the global powertrain consumption.

The next step of the study is to quantify the relative importance of CO₂ saving due to regenerative braking and ICE efficiency optimization. Fig. 8 shows the part of the kinetic energy recovery on the global CO₂ saving for a parallel hybrid CSR architecture and for the considered INRETS cycles.

At very low mean speed cycles, CO₂ saving are mostly induced by the optimization of the ICE operating point (blue area), whereas at higher mean speed cycles the optimization of energy recovery is the dominant mechanism of energy saving.

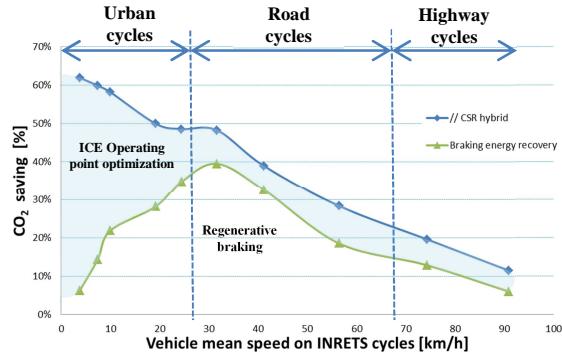


Figure 8: Contribution of braking energy recovery to CO₂ saving.

3.4 Influence of electric machine efficiency on consumption

The EM efficiency impact on CO₂ saving is studied through a sensitivity analysis.

Simulations were performed for a parallel CSR hybridization with different constant EM efficiencies: 70%, 80%, 90% and 100%. The results are presented in Fig. 9.

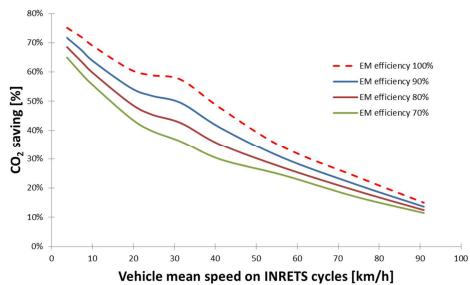


Figure 9: Influence of EM efficiency on CO₂ saving

Fig. 10 shows the contribution of braking energy recovery to the global CO₂ saving for two given EM efficiencies: 70% and 100%.

For an easier analysis of these curves, the influence of the EM efficiency for a given cycle is quantified by the sensitivity factor (S) defined by formula (2) :

$$S = \frac{\Delta \text{CO}_2 \text{ saving}}{\Delta \text{EM efficiency}} \quad (2)$$

with $\Delta \text{EM efficiency} = 30\%$.

The sensitivity S is plotted in Fig. 11, both for the global CO₂ saving and the regenerative braking contribution.

The largest impact of the EM efficiency on the global CO₂ saving is for fluent urban and road cycles, while the lowest is for highway cycles.

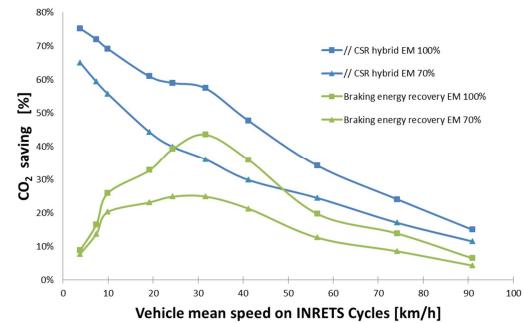


Figure 10: Contribution of braking energy recovery to CO₂ saving for two values of the EM efficiency

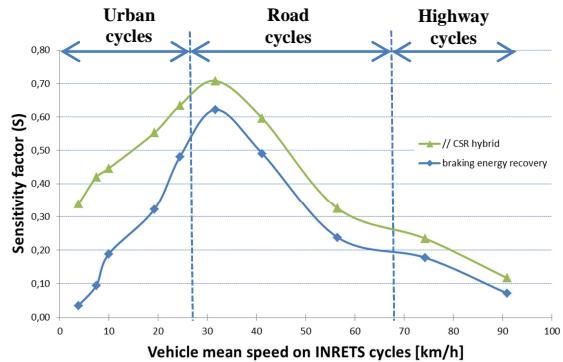


Figure 11: Sensitivity of CO₂ saving to EM efficiency

These curves confirm that the electric machine has to be designed to maximize braking energy recovery for medium speed cycles, and to optimize ICE working points for low speed cycles. For highway cycles, the EM efficiency has a very small effect on the vehicle consumption because of little use of the electric machine.

4 Conclusion

The present work uses optimal control and dynamic programming as powerful tools to calculate the minimum global consumption of a given hybrid powertrain. A comparative study of different architectures, for various cycles and EM efficiencies was undertaken, and the analysis of all these data enables to identify key factors and guidelines to improve the vehicle consumption. From a strict energetic point of view, the series architecture does not bring much benefit to electric hybrid vehicle (HEV) with no plug-in function. The combined hybridization is slightly more

performing. The parallel architecture is the most promising one, provided that the coupling device has a good efficiency and that a smart choice of discrete speed ratio is done if DSR is used.

The study focuses on electric power components to optimize the powertrain efficiency for parallel hybridization. It shows how the battery capacity can be sized according to the desired regenerative braking.

Guidelines for the EM design are given. They point out the need of optimizing the ICE working points for low urban cycles on one hand and braking energy recovery for urban fluent and road cycles on the other hand.

The next stage will focus on an optimal hybrid powertrain architecture derived from this study. Complementary analysis will be carried out in order to estimate the vehicle performances and the production costs.

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Authors

Francis ROY

PSA Peugeot Citroën, La Garenne-Colombes, France.

URL: www.psa-peugeot-citroen.com

1990: Mechanical engineer

1991: DEA in Process Engineering

Since 1992: PSA Peugeot Citroën Engineer – Project leader



Angela Martina CATANIA

Laboratoire de Génie Electrique de Paris, France

URL: www.lgep.supelec.fr



2011-2013: student in Mechatronic Engineering at Politecnico di Torino, Italy – Master's thesis at LGEP, France

Florence OSSART

Laboratoire de Génie Electrique de Paris, France

URL: www.lgep.supelec.fr

1991: PhD in Electrical Engineering

Since 2003: Professor at Université Pierre et Marie Curie, Paris, France



Claude MARCHAND

Laboratoire de Génie Electrique de Paris, France

URL: www.lgep.supelec.fr

1991: PhD in Electrical Engineering

Since 2000: Professor at Université Paris Sud, Orsay, France

