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A reconfigurable series-parallel hybrid powertrain for plug-in vehicles

C. Pronovost[1], J. Xu[1]
[1]*TM4, 135 J.A. Bombardier, Boucherville, Qc, Canada, transport@tm4.com*

Abstract

This paper presents the concept of a clutch reconfigurable series-parallel hybrid powertrain that optimizes the use of its components. The hybrid system features a combustion engine, an electric generator and an electric motor coupled through a clutch system. The paper describes the system, its components and the different operating modes. Then the conditions influencing the switch from one mode to the other are developed from the analysis of benefits. A platform and component models are established to evaluate the powertrain. Finally simulation results on performance and fuel efficiency are presented.

Keywords: AC motor, permanent magnet motor, series HEV, parallel HEV, PHEV

1 Introduction

Fuel economy and CO2 emissions are major forces bringing regulations in all industries particularly in the transportation sector. Because of regulations, hybrids are increasing their market penetration. It is expected that around 13% of cars in Europe could be hybrids by 2015 according to L'Observatoire de l'automobile Cetelem. Moreover, as the technologies evolve, the level of hybridization [4] of vehicles increases and will lead to the introduction of plug-in.

1.1 Motivation - Focus

Hybrids have different ways to improve fuel savings [1]:

1. **Eliminate idling**; cut off the engine whenever it is not delivering power. This means to stop and restart the engine from deceleration to acceleration if possible.
2. **Regeneration**; regenerate the kinetic energy of the vehicle into reusable energy when breaking.
3. **Downsize of the Internal Combustion Engine (ICE)**; reduce the size of the combustion engine to reduce its friction losses.
4. **Set the ICE operation points**; use the ICE at higher power operation points and limit the speed operation range. This will help improve efficiency.
5. **Make use of grid power**; Grid energy can come from cleaner source than petrol.

Today hybrids are classified in four categories [4]: series hybrid, parallel hybrid, series–parallel hybrid, and complex hybrid. Of the two simplest systems, parallel hybrids are viewed [3] as more efficient than series hybrids because of the path between the ICE and the wheels. Another concern about serial hybrids is the presence of three machines which need to be sized for the maximum continuous power of the vehicle if one wants the battery not to be depleted.

The pros of serial hybrids are seen in plug-in vehicles. The complete decoupling of the combustion engine allows for maximum downsizing of ICE and well defined operation points. Also, the ICE being completely decoupled from the wheels renders the ICE optional and non intrusive in the vehicle performances. The vehicle has the same performances whether being used in electric only mode or with the combustion engine.

1.2 Paper Content

This paper presents a new hybrid system version designed by TM4's engineers. The internal name of this system is *Mogen*, it has not yet been named commercially. The hybrid system makes use of a 4-position clutch instead of the former 3-position used in the previous version. The clutch arrangement allows an additional mode in which the ICE is coupled parallel with the motor and the generator for parallel hybrid operation.

In the first section of the paper, the history of the *Mogen* is presented.

Then the mechanical topology of this new system will be presented, with the technology choices put in the system. Rules for sizing of the components are discussed with the presentation of the actual sizing of the prototype hybrid system.

A third section presents the different operating modes available in each configuration. The paper discusses the logic governing the changes to gain maximum efficiency.

The last section presents simulation data comparing consumption and performances of both the former version and the new version of the *Mogen* system.

2 TM4's *Mogen* System

2.1 TM4's first *Mogen* – *Mogen* 3p

In 2004, La Société de Véhicules Électriques introduced the Cleanova II vehicle that employed a new hybrid powertrain developed by TM4 [2]. The powertrain uses a series hybrid configuration where the electric generator (MG2) can be decoupled from the ICE and recoupled to the electric motor (MG1) to provide more torque. This powertrain, internally called *Mogen* makes use of a 35kW motor and a 15kW range extender generator. The power ratings of the motor (MG1), the generator (MG2) and the internal combustion engine (ICE) were chosen with the intent of having a plug-in vehicle that runs primarily in electric mode. The generator is used to extend the range of the vehicle; it has insufficient power to keep the vehicle running continuously at full speed without depleting the battery.

The innovation of this system relied in a 3-position clutch system that enables a generator (MG2) to be used in parallel to an electric motor (MG1) to provide more acceleration torque when the vehicle is used in electric mode. The generator (MG2) can also be used to recharge the battery as a range extender. The system can switch from one mode to the other accordingly to the road conditions and the driver's requests.

2.2 TM4's new system – *Mogen* 4p

To increase the versatility of the system, a fourth position was added to the system. That fourth position adds the possibility to connect the ICE directly to the wheels and in parallel to MG1 and MG2. Thus this added clutch position allows the system to reconfigure itself from a series hybrid to a parallel hybrid.

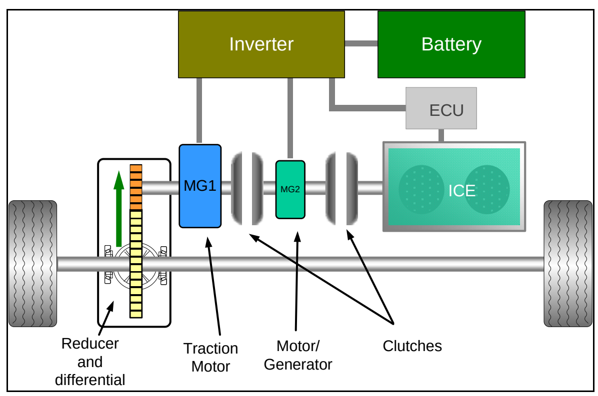

Figure 1 –TM4 *Mogen* schematic view

3 Mechanical Topology

3.1 Electric Machine Topology

The permanent magnet motor and generator used in the *Mogen* powertrain are based on an inverted rotor configuration, where the rotor is on the outer of the stator, as seen in Figure 2.

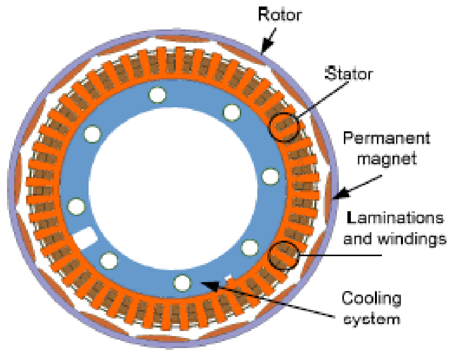

Figure 2 - Section of the active components of the reversed rotor topology

The rotor cylinder shape holds formed magnets on its internal face. The stator is placed right over a cooling circuit and allows efficient extraction of the power losses. The center of the motor is empty allows insertion of a second motor concentrically to the first.
The cooling circuit is located inside the laminations [7][8]. It cools the stator components by thermal conduction. It is made with an aluminum casting over copper tubing where a mixture of 50% water 50% glycol flows. The copper tubing is coiled in a way that it covers the surface of the aluminum casting to extract heat while generating minimum temperature differences within the stator. The cooling circuit is spring loaded to keep a good contact with the laminations [9]. The rotor, and in a smaller proportion, the stator are cooled by air convection. The air itself is mixed within the motor with the rotor rotation and is cooled by the outer assembly casing and the cooling system.

3.2 *Mogen* Description

The *Mogen* is a reconfigurable system consisting of two electrical machines, a combustion engine, a clutch system and a gearbox with differential. The key item in the *Mogen* system is the clutch which allows the system reconfiguration. The *Mogen* can be classified as a complex hybrid [13].

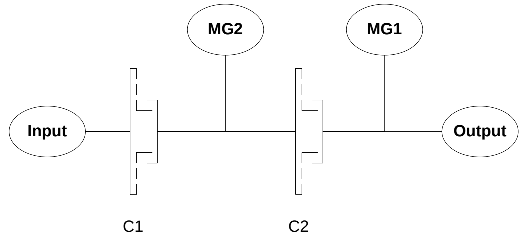

Figure 3 - Schematic of the *Mogen* powertrain system

The clutch used in the *Mogen* enables 4 possible operating modes:

1. **Motor, Generator and ICE unlinked:** Used when the vehicle is in standby or in high speed EV mode.
2. **Generator and ICE linked:** The generator can then use the ICE to bring additional power to the range extending mode (ICE in operation)
3. **Generator and Motor linked:** Low speed EV or Acceleration mode
4. **Motor, Generator and ICE linked:** Hybrid mode (Only on newer *Mogen* 4p)

The former *Mogen* had 3 operation modes; the system could use mode 1 to 3 but could not connect the ICE directly to the wheels (mode 4). It was designed to achieve lower cost and better vehicle integration with the concentric motors and the reuse of MG2 as a motor for traction when the system had to output high torque.

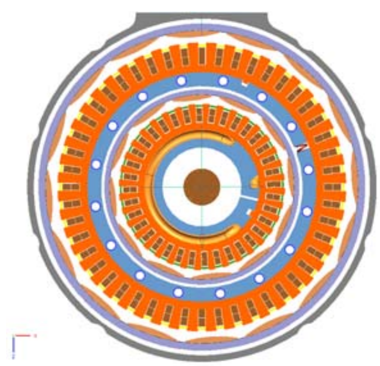

Figure 4 - MG1 and MG2 in concentric arrangement

3.2.1 Machine arrangement

The *Mogen* system uses two permanent-magnet machines placed concentrically one to the other. This increases the power density of the electromechanical part of the system by about 40%. The larger machine is connected permanently to the wheels and is used mainly as a motor (MG1). The inner machine is coupled to the center shaft and is intended mainly as a generator (MG2).

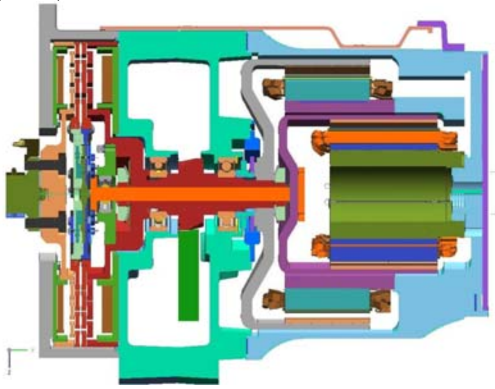

Figure 5 - *Mogen* cut showing clutch, gearbox bay and motor/generator arrangement

3.2.2 Clutch arrangement

MG1 and MG2 are linked through an electromechanical assembly. The assembly is composed of two clutches that are dry friction discs engaged electrically. The two clutches are made of four rotating discs. The two center friction discs are connected to MG2 shaft and are held by an independent flexible support, these center discs serve as armature to the coil. The two other discs are located on each side and are connected to the ICE and to MG1. A coil embedded in electrical steel lies behind each clutches. When a coil is energized, it creates a magnetic field that displaces the corresponding armature disc and engages the clutch. Both clutches are linked to coaxial shafts to allow the different intended modes.

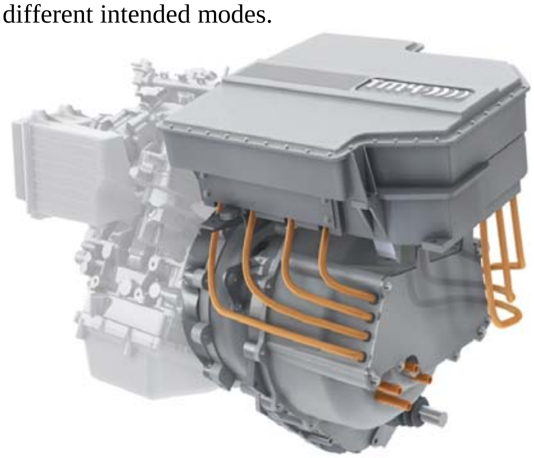

Figure 6 - *Mogen* 4p with attached power electronic

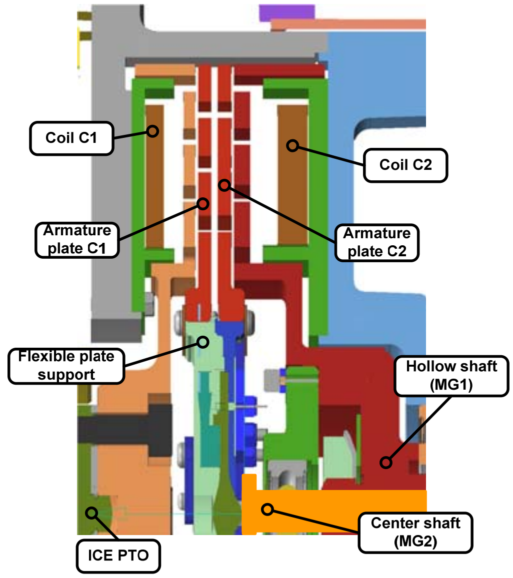

Figure 7 – 4 Positions clutch assembly

3.2.3 Power Electronic

For each of the electric machines, an inverter supplies a 3-phase voltage phasor. The voltage is built from a PWM excitation to the motor that works at different frequencies depending on the rotation speed. The switching devices are IGBTs.
Both inverters are located in the motor control unit. The motor control unit also contains a 1.2kW DC/DC converter that serves as an alternator. The DC/DC converter picks power on the high voltage battery and brings it at a lower voltage to charge the auxiliary battery.

The motor control unit also contains an optional 6kW onboard charger for charging the main battery from the electric grid.

The motor controller of the *Mogen* provides an integrated solution that packages all power components necessary for the hybrid vehicle. As everything is enclosed into one box, OEM integration is reduced to a minimum.

3.3 Dimensioning of components

The main characteristic of the *Mogen* system is the parallelization of MG1 and MG2 to supplement vehicle accelerations, the ability to reuse MG2 as part of a genset in a series hybrid topology and the ability to connect the combustion engine to the wheels in parallel hybrid operation.

The *Mogen* system is designed to work in a plug-in vehicle that has good EV performance. The battery should be dimensioned to provide full power to the system in its intended EV operating range.

As a first approximation, the components of the *Mogen* 4p should be dimensioned based on the following requirements:

- The combination of MG1 and MG2 must be able to sustain the worst case peak torque demand from the vehicle at lower speed. This requirement often comes from hill climbing requirement.
- MG1 and MG2 must be able to sustain the worst case continuous power demand from the vehicle. This requirement often comes from constant speed hill climbing, high wind conditions or maximum speed.
- The ICE must be able to develop sufficient power for the vehicle to keep the set maximum continuous cruising speed in worst case condition. The worst case condition refers to wind and slope.
- MG2 must be able to provide worst case continuous power in serial operation.
- MG2 must be able must be able to provide the worst case peak torque to start the ICE in cold start conditions.

In the configuration used for this paper, the components have the following sizing:

Table 1: Size of electrical components

	Power		**Torque**
	Nominal	**Peak**	**Peak**
Main motor (MG1)	35kW	44kW	110Nm
Secondary motor (MG2)	15kW	22kW	100Nm
Total electrical	50kW	66kW	210Nm

Table 2: Combustion engine

	Power	**Torque**
ICE @6000rpm	41kW	66Nm

ICE downsizing is one of the key features in consumption reduction [5]. In this case the ICE is reduced by 60% of the original engine size used in the reference vehicle [17].

4 Operating Modes

4.1 Control strategy

As in any complex hybrid, the control strategy of the *Mogen* system requires the development of operation strategies to find the most economical mode. This hybrid propulsion system has two sources of energy: the ICE and the battery. Each power source must be used conforming to the driver's demand, the powertrain state and the specific driving situation. Fuel economy and emission reduction are the main variables to be considered when selecting the source of energy and when applying control strategy.

The main issues involved in energy management of hybrid electric vehicles are [6]

1. **Torque distribution**; distribution of the driver's torque demand into each power source while achieving satisfactory fuel consumption and emissions reductions.
2. **Charge sustenance**; how to accomplish charge sustenance over the entire range of driving conditions that the vehicle may be subjected to.

In the case of the *Mogen* we can also add a third issue that may or may not be considered in the above first issue:

3. **Mode selection;** selection of the best powertrain configuration that would lead to satisfactory fuel consumption, emissions reduction and *performance level*.

With the *Mogen* system, the mode selection to achieve satisfactory performance level is to be considered. As MG1 power and torque level have been reduced by design to a level where additional input from MG2 is needed in certain cases, the controller has to select the right topology to achieve the driver's demand at the right performance level. The topology selection will effectively have to be made to select the right performance level; then the controller will have to optimize fuel consumption and emissions reduction.

Moreover, the vehicle implementation should also allow the use of different driving modes. A typical configuration could be a selection of 3 operating modes, such as:

- EV only,
- Recharge mode,

- Hybrid mode.

The driver’s decision will be based on the distance needed to travel, the type of road taken and, in some cases, the regulations (e.g. EV only city centers).

EV only mode is quite straightforward. In this configuration the powertrain should use only electrical energy from the battery and use MG1 and MG2 as traction power. The recharge mode is to recharge or keep the battery charged in prevision of entering an EV only zone. Hybrid mode is the default mode; it must allow the vehicle to perform as efficiently as possible given the two power sources and unknown road conditions and distance to be traveled.

This powertrain is meant for plug-in electric vehicles. A fully charged battery will allow for EV driving. As for some other plug-in hybrids [14][15], the energy strategy should be to first deplete the battery to a certain level and then go in charge sustaining mode for the remainder of the trip.

The remainder of the control strategy discussion will relate to the hybrid mode as it is the most complex of the user’s selectable modes.

4.2 Mode shifting strategy

The different operating modes of the *Mogen* require governing logic. This logic depends on different variables, such as:

- User’s requests
- Road conditions
- Environmental conditions
- Component state

At powertrain level, these variables must be translated into the best operation mode, given the speed and torque to attain.

Table 3: Operation modes attainable with the C1 and C2 clutches

Powertrain operation		**C1**	**C2**
EV Mode	EV1		
EV Mode – high torque	EV2		On
Series hybrid	SH	On	
Parallel hybrid	PH	On	On

As seen in Table 3, the shifting mode strategy can be divided into four different operating modes. Additionally, the two hybrid operation modes (SH and PH) can work at different loading conditions of the generator. To simplify matters only two loading conditions are considered: charge sustaining mode and charge increasing mode. In charge sustaining mode, MG2 will provide just enough power to supply MG1 with zero power going to the battery. In charge increasing mode, the generator MG2 is loaded as much as possible leading to battery charge level increase.

The energy management strategy for the hybrid plug-in should be to deplete the battery to a set level by using EV mode and then to go in charge sustaining mode to keep the battery level within a predetermined range. But to achieve charge sustaining there are more than one method: the battery level can be kept by having a zero power balance from the powertrain; one can also switch between charge increasing and charge depleting by alternating between hybrid mode and EV mode and this can be accomplished using different charging rates. We can call these alternatives the *zero power balance method* and the *charge hysteresis method*. Both methods will render different efficiencies. For simulations in this paper, we have used the full regenerative power available from MG2 when in the charge hysteresis method. We have not looked at partial regeneration that may provide even better efficiencies.

Table 4: Nomenclature of the hybrid modes

Hybrid operation	**SH**	**PH**
Zero power balance	SHA	PHA
Charge hysteresis	SHB	PHB

The mode selection must be done by selecting the most efficient mode to achieve a given torque and speed. Efficiency is calculated for all four operating modes with sustained battery charge. The calculations are made using nominal operation parameters and limitations of the components continuous power and torque. In the charge hysteresis operation case, the efficiency is calculated on one full charging/discharging cycle, insuring that the battery has not accumulated any energy and disturbed the efficiency calculation

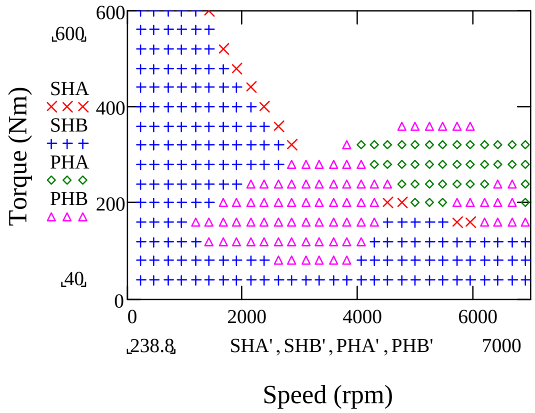

Figure 8 - Mode shift map for hybrid operation

Superimposing the efficiency of the hybrid operation modes and selecting the most efficient one will give the mode shift map shown at Figure 8**Error! Reference source not found.**. As one could expect, at lower speed and lower torque where power output is low the hysteresis operation (SHB) is the most efficient.

At higher power output, the parallel mode with zero power balance (PHA) is predominant. The parallel mode is predominant mainly because the power output cannot be sustained by MG2 being limited to a continuous power of 15kW. Zero power balance is mostly used because either the extra loading of MG2 to bring power into the battery does not displace ICE operation point to an area of higher efficiency or the energy path passing through the battery is not worth it.

4.3 System efficiency

By using the shift mode map to select the most efficient powertrain mode of operation, we can calculate the powertrain efficiency with the ICE consumption for the different operational loads. This calculation gives the efficiency with charge sustaining the battery in hybrid operation mode. As for the mode shift map, when in charge hysteresis operation, the efficiency is calculated on one full charging/discharging cycle, insuring that the battery has not accumulated any energy.

The actual fuel efficiency of the vehicle should consider plug-in operation; this would give better efficiency than what is presented here. The presented efficiency does not consider grid energy contribution.

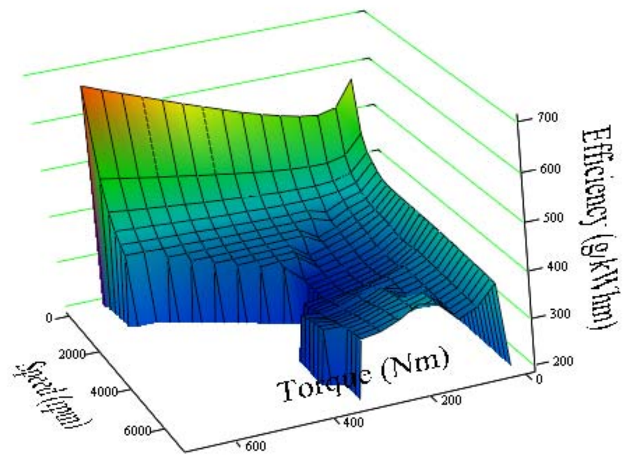

Figure 9 - Efficiency map of *Mogen* operation

5 Simulation Results

This section presents some data on vehicle performances from simulations. The simulations have been done using Simulink/SimDriveline extension, PSAT software and data and other simulation tools developed at TM4.

5.1 Vehicle data

The reference vehicle is a Ford Focus sedan 4-door 2008. The battery used is a Saft high power 6Ah Lithium-ion cell arranged in a battery pack of four strings of 96 cells. Each cell has 3.6V nominal voltage for a total of 345 Volts. The battery capacity is calculated at about 9kWh. The battery was selected so it would not limit the powertrain performance; its power is higher than 80kW for a state of charge above 40%.

Regeneration torque has been limited to 0.15g. This torque is applied at coast down and when breaking. The efficiency of the gearbox is assumed to be 95%.

Table 5: Vehicle Parameters

Parameter	**Value**	**Notes**
Frontal Area	2.446m^2	
Drag coefficient	0.32	
Tire effective radius	0.2831m	185/65 R 14
Test Weight	1270kg	

Table 6: Powertrain Parameters

Parameter	Value	Notes
Gearbox ratio	5.97	
Gearbox efficiency	95%	
Maximum regen torque	530Nm	0.15g

5.2 Vehicle performance

The simulation focused on the following two interrogations about the new *Mogen* system:
The first was the increased performance that the parallel mode operation can bring to the vehicle. To answer this question, the best exercise is to go through timed acceleration data. The results show that below 70kph the difference is not very noticeable. *Mogen* 4p shifts its operating mode just before reaching 50kph and that adds a delay that is shown in the data.

The results above 70 kph are much different as the parallel mode nearly doubles the available power of the vehicle. The result is especially noticeable in high speed passing.

Table 7: *Mogen* 3p compared to 4p in acceleration

Acceleration	**Original ICE**	***Mogen*4P**	***Mogen*3P**
0-50kph	N/A	5.2 s	5 s
0-70kph	N/A	7.3 s	7.7 s
0-100kph	8.7 s	11.3 s	14.8 s
50-80kph	N/A	3.1 s	4.3 s
80-120kph	N/A	7.4 s	18.2 s

The second interrogation is about efficiency. Table 8 presents the consumption through the Urban Driving Schedule (UDS) and Highway Fuel Efficiency Tests (HWFET). The additional parallel mode does not provide interesting consumption benefits. This is due to the fixed gear ratio selected as a compromise between ICE power and efficiency and motor/generator size.

Table 8: Configuration consumption comparison

Cycle	**Original ICE**	***Mogen*3P**	***Mogen*4P**
UDS	24 MPG	45.9 MPG	46.4 MPG
HWFET	35 MPG	40 MPG	40 MPG

The main reason why the efficiency of the Mogen 4p is not increased by much in comparison to the 3p is that the ICE is not running in its most efficient operating speed. There are different solutions that can increase the efficiency of the system by bringing the ICE in the right operation zone at lower operating speed. The most promising solution is to have two gear ratios in the main gearbox.

6 Conclusion

The *Mogen* 4p system is very promising as it provides high torque and power density in a package that fits European segment B vehicles or North American sub-compact vehicles. The packaging of the motor and generator (MG1 and MG2) into concentric arrangement is the primary feature. But the use of MG2 to complement MG1 torque in accelerations lowers the individual constraints and lowers system cost by reuse of both the power electronics and the motor/generators.

The clutch arrangement that enables system reconfiguration brings flexibility to the system and brings a way to increase fuel economy and increase vehicle performance using controlled logic.

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Authors

Christian Pronovost received the B.S. degree from École Polytechnique de Montréal in Canada in 1992. Mr. Pronovost has been with TM4 since 1998 as senior electrical engineer. He has mainly worked in development of power technologies, in the definition of new products and in the support and planning of new projects. He is currently working as product manager for the *Mogen* powertrain and the TM4 Motive System.

J. Xu obtained B.Eng. degree from Huazhong University of Science and Technology, China, and the DEA and Ph.D from Institut National Polytechnique de Lorraine, France, in 1990 and 1994, respectively. From 1995 to March, 2001 he was with the Université du Québec à Trois-Rivières, Quebec, Canada. Since April, 2001 he works as Electrical Engineer with Technologies M4 inc.