Dual Mode Electric Infinitely Variable Transmission

Arnaud VILLENEUVE, Paulo MENDES
Renault, France

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1. Abstract - Introduction

The development of technologies in order to reduce the green house effect gases emissions is one of the major challenges that the automotive industry must face. Its contribution must be consistent with the threat mankind is now facing: the global warming.

Although the ways to reduce the CO_2 emissions are numerous, all of them are confronted to the same question of their customer value compared to their cost. RENAULT focused first on affordable solutions such as Diesel engine or bio fuels but is working now on solutions involving a technological breakthrough like the hybrid vehicles.

ICE technology combined with electric machines technology is not a novel idea and we can find the first attempts in the early years of the 20th century [1]. However, only the progresses and breakthroughs made essentially during the last 30 years in the electronics, computing, power transistors and electric energy storage technologies, have made the hybridisation possible on automotive applications.

There are many ways to “hybridise” a power train among which the power split transmissions seem to offer an advantageous performance, drivability and fuel economy trade off.
However, this architecture requires an in depth analysis in order to optimize its performance and its cost. A major advantage of power-split architectures stands in the possibility to de-couple ICE and wheels speed as long as the output power demand is met: this gives much more flexibility to choose the ICE working point in order to optimise fuel consumption and reduce exhaust emissions [2].
Another concern is the integration into the tight space of a transversal engine compartment of such a transmission using a variator built-up from 2 electric motors. The reduction of the size of the electric motors is the key condition to succeed to this challenging target.

Since 1999, RENAULT has been developing a dual-mode power split transmission which reduces dramatically the size and needed torque and power characteristics of the electric motors while keeping high performance on both hybrid drive and pure electric drive conditions.
That not only allows an easier packaging of the transmission but also increases the overall efficiency of the power split transmission and therefore the fuel economy.

Vehicle prototypes were manufactured in 2003 in order to assess the potential of such transmissions. We designed a transmission that could be used first as a pure transmission (no energy storage), while improving drivability and performance. The results confirmed the initial expectations and RENAULT demonstrated that power split automatic transmission could give fuel consumption equivalent to Manual transmissions, even with a Diesel engine.
Then transmission has been adapted as a “mild-hybrid” transmission (enabling stop & start and brake & boost features).

This article focuses on the following topics:

- The different types of power split transmissions.
- The solution developed by RENAULT: What is a dual-mode transmission? Why a dual-mode? How mode change works?
- The results obtained so far and the future.

2. Power-split transmission architecture

The figure 1 describes the usual power-split transmission arrangement:

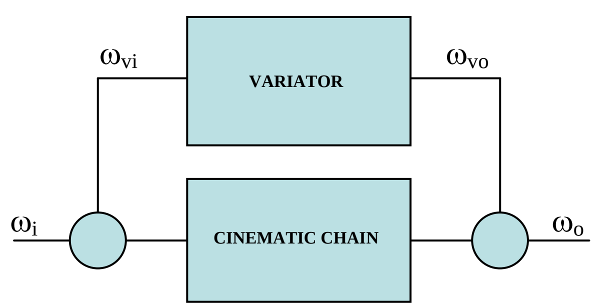

Figure 1: Power split transmission arrangement

2.1. The variator

On a hybrid power split transmission, the variator is made out of two electric machines connected to each other and to an energy storage device, usually batteries.
One electric machine works as generator and delivers the energy to the other one working as a motor.
If the generator produces more energy than the motor uses, the difference is charging the battery. This situation occurs typically is decelerating phases of the vehicle.
On the contrary, if the generator produces less energy than the motor uses, the difference is brought out from the battery which is discharged. This situation typically occurs in accelerating phases in order to supply additional torque to the wheels or to select an optimum working point of the engine for Fuel Economy purpose.

On a so called “pure transmission” design, the energy storage is almost eliminated and the energy produced by the generator is used instantly by the motor. In this case, the two electric machines act as a “true” variator (Figure 2).

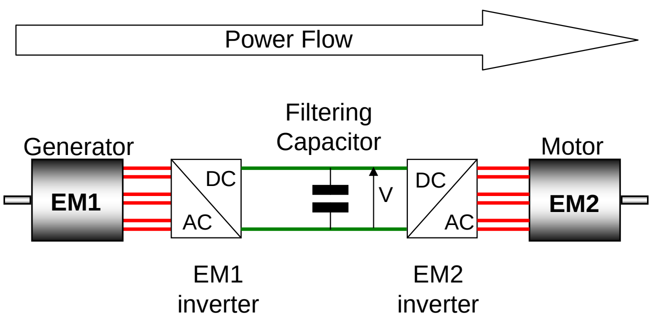

Figure 2: Electric Variator
Input and output powers are theoretically equal; however the efficiency of the machines must be taken into account.

2.2. The mechanical chain

The mechanical chain is usually based on a set of planetary gear sets, from one up to three or four, depending on the constraints the transmission design must address. This matter will be developed in paragraphs 2.3 and 2.4.

2.3. Simple approach to understand power split transmission work

Step 1: Let’s consider the simplest transmission that could be built-up from a single planetary gear set (Figure 3).

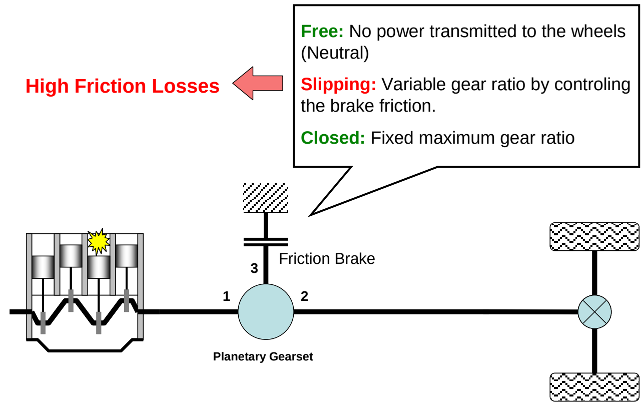

Figure 3: Single planetary gear set transmission

We can see that if the third branch of the planetary gear set is free, no torque can be transmitted to the wheels. This operating condition corresponds to a Neutral position, when the vehicle is stopped.
If we add a friction brake on the third branch and we can control precisely its friction speed, we can control the gear ratio of the transmission which depends directly on the friction speed.
If the brake is blocked, the transmission reaches its maximum gear ratio.

We can easily observe that this transmission is highly impractical as friction losses can be very high! The friction brake would also be subject to wear and would not last very long on a real vehicle.

Step 2: Now let’s replace the friction brake by an electric generator (Figure 4). The friction is replaced by the electric energy generated that can be dispersed or better, stored in a battery.

The difficulty is to manage the electric energy produced by the generator and the overall efficiency of the transmission issue is not solved.

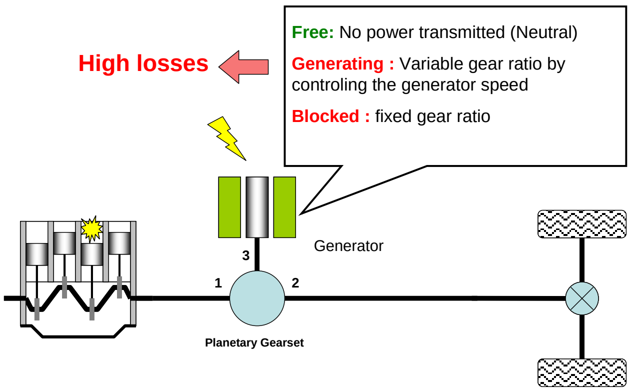

Figure 4: Replacing the friction brake by an electric generator

<u>Step 3</u>: An idea could be to use the energy produced by the generator in order to drive a motor connected to the secondary shaft (Figure 5). The energy is then re-injected into the transmission and increases dramatically its overall efficiency.

This is the principle of the Toyota PRIUS transmission and this simple example describes the basic principle of power split transmission:

- A fraction of the energy passes throughout the electric machines,
- The other part of the energy passes throughout the gears of the planetary gear set.

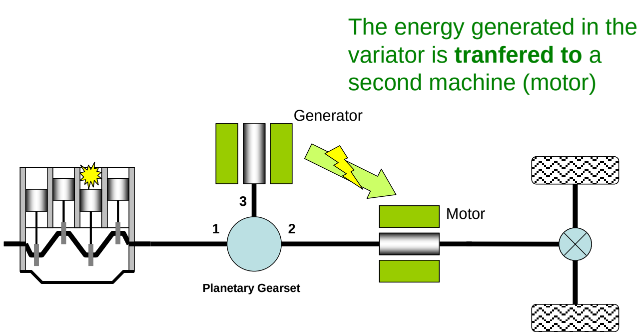

Figure 5: Addition of a second electric machine

<u>Conclusions</u>: It is important to notice that the efficiency of gears is generally much higher that the efficiency of two electric machines connected in series (the extreme case being a series hybrid where there is no mechanical chain at all!).

The power split transmission must therefore be designed in a way to minimize the energy derived in the variator.

We could demonstrate that the ratio between the energy passing throughout the variator and the energy coming from the ICE (named Power Split Ratio - PSR) is only a function of the overall transmission gear ratio.

In the case described above, usually referred as input split transmission, the power split decreases linearly from 1 (Neutral, gear ratio equal to 0) to 0 (maximum gear ratio when the third branch is blocked). In that particular point there is theoretically no energy passing throughout the variator and the corresponding gear ratio is called a node (Figure 6).

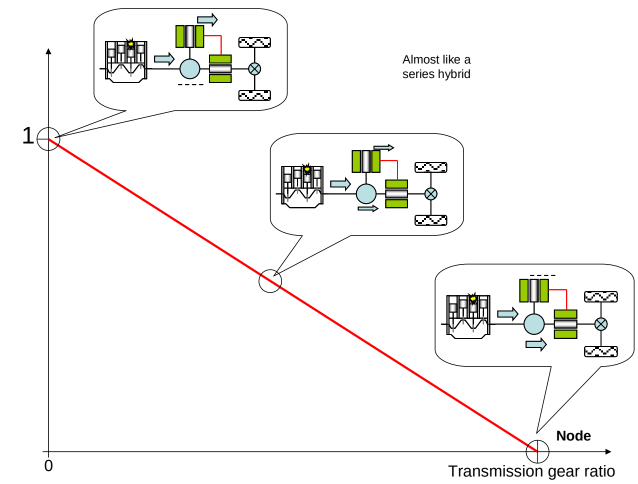

Figure 6: Evolution of Power Split Ratio on an input split transmission

2.4. Advanced power split layouts

A transmission is usually characterised by the range of gear ratio it can achieve. On the input split layout described above, this range is a direct consequence of the power of the electric machines used in the variator. Hopefully, the full power of the engine is not necessary at low gear ratio. This means that even though the PSR can reach up to 1, it is not necessary for the two electric motors to have a power equal to the engine power. That situation would lead to a heavy and rather inefficient transmission.

However, we could demonstrate that for an acceptable transmission, the electric power of the individual electric motors should be close to 50 to 60% of the engine power.
For fuel economy reasons, especially in urban driving conditions, it would be better to minimize the PSR at low gear ratio. Not only the efficiency would be

improved but the size of the electric machines could be reduced, saving weight, space and cost.

Advanced mechanical layouts involving more than one planetary gear set can be used in order to optimize the PSR.

2.4.1. Compound split layout

The Compound split layout uses two planetary gear sets. A typical layout is described in Figure 7.

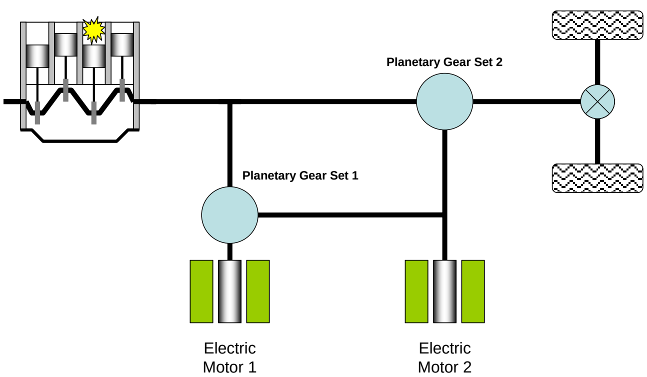

Figure 7: Compound split typical layout involving two planetary gear sets

There are three main consequences to the use of such a layout (Figure 8):

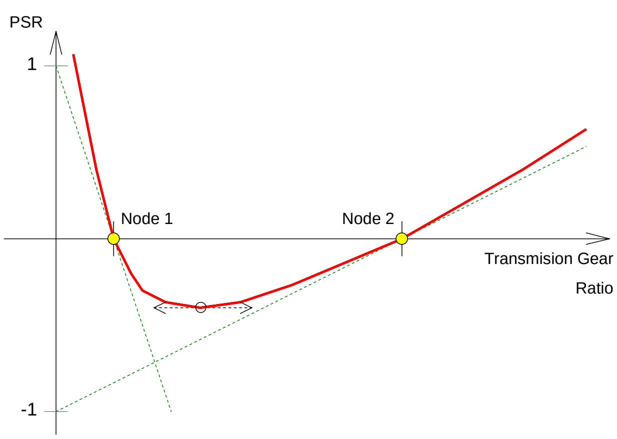

Figure 8: Power Split Ratio as a function of the transmission gear ratio for a compound split layout

1. The PSR curve as a function of the gear ratio is no longer linear,
2. There are two nodes where the PSR is equal to 0,
3. The PSR has an extremum in between the two nodes but diverges quickly to infinite outside of this range. The PSR extremum value depends only on the range (node 2 gear ratio divided by node 1 gear ratio) and increases with it.

This layout allows reducing dramatically the power derived in the electric variator. We could expect, as a consequence, a far better efficiency of the transmission.

Unfortunately, building-up a practical layout for a vehicle, i.e. with an adequate gear ratio range and nodes location, leads to use a very high torque electric motor, requesting a high power / high current inverter which reduce the potential fuel economy that could be expected compared to the Input split layout.

This is the reason why, although the compound split layout could be rather interesting at a first glance, no applications arrived to the market.

2.4.2. Dual-mode layouts

There is a possibility to address this issue along with reducing even more the PSR: the dual-mode transmission.

The basic idea is to “split” the gear ratio range of the transmission into two separate power split modes (Figure 9):

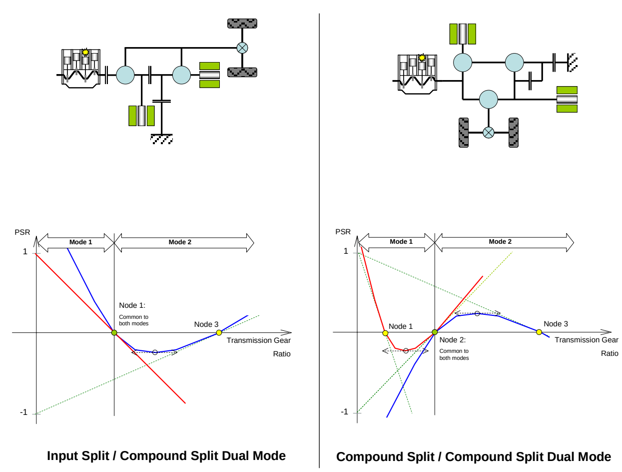

Figure 9: Two dual-mode layouts

1- One input split mode for low gear ratio and one compound split mode for higher gear ratio. This solution was chosen by General Motors (Allison Hybrid System) and is also developed by the consortium General Motors, Daimler-Chrysler and

BMW for their future common hybrid technology [3].

2- Two compound modes, one for low gear ratio and one for higher gear ratio. This solution has been developed by RENAULT since 1999 and will be described in this article.

The key question about dual modes layouts is related to the transition from one mode to the other. Mode change must not be confused with gear change and must be managed and carried automatically in the smoothest way.

The mode change corresponds to the internal change of the mechanical chain with the help of brakes and/or clutches like gear changes in an automatic transmission.

All the technical constraints lead to the following rules for mode change point selection:

1- The two modes have one common node (identical gear ratio where PSR is equal to 0),
2- The mode change occurs when the transmission reaches this common node,
3- The mechanical layout is designed in a way that the brakes and clutches involved in the mode change are near zero torque at the mode change point and preferably even at a zero speed.
4- It is possible and preferable to design a transmission where both modes PSR share the same tangent at the mode change point.

Those conditions allow a very quick and smooth transition between the two modes.

However, the drawback of dual mode layouts is that the mechanical chain is more complex and involves the use of additional actuators. The drastic size reduction of the electric machines of the variator is to be paid by the increase of the mechanical complexity of the transmission.

3. RENAULT Power Split Dual Mode Transmission

RENAULT developed and tested a transmission which uses a variator involving electric machines exhibiting a maximum power of 20% of the engine power.

3.1. Mechanical layout

The mechanical layout is described in figure 10.

This layout includes 4 planetary gear sets allowing a mode change using 2 brakes.
The brakes are at zero speed / zero torque at the mode change point which make the mode change easier and compatible with the use of dog-clutches (see paragraph 3.3.2.).

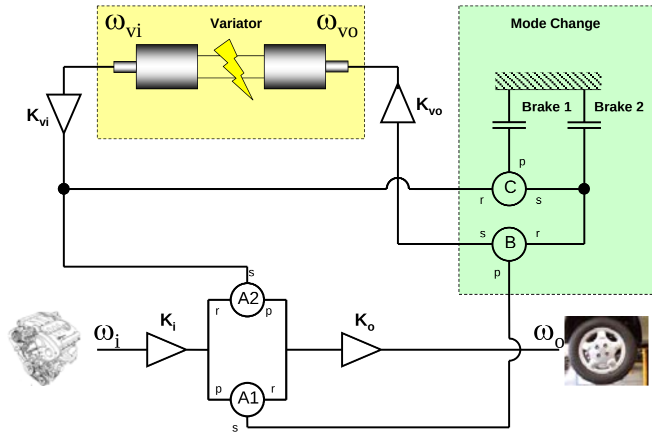

Figure 10: RENAULT dual-mode layout

The resulting mechanical arrangement is detailed in figure 11.

The four planetary gear sets are aligned on the same axis. The two electric machines are located around the planetary gear sets axis and connected to them through silent chains.
The position of the motors allows designing a compact and short transmission which can fit into the tight space of the front wheel drive engine compartment with the engine mounted transversally.

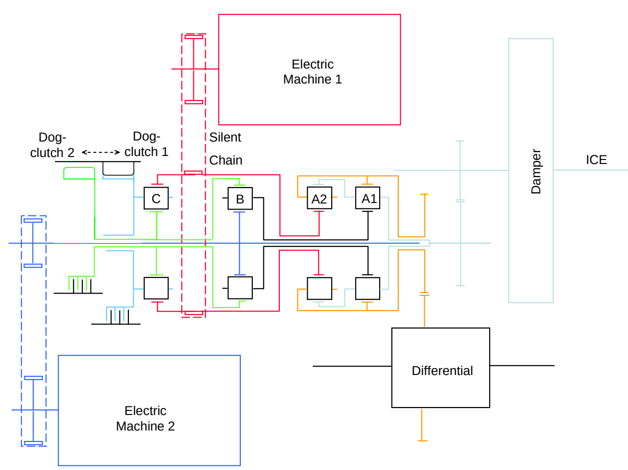

Figure11: Mechanical arrangement of RENAULT dual-mode transmission

3.2. Management of the mode change:

As described above, the mode change occurs at a given gear ratio, which corresponds to a node shared by both low speed and high speed modes.
The decision of mode change is made automatically by the control system of the power train (see paragraph 4). It always occurs when the gear ratio crosses the mode change gear ratio. Gear ratios belonging to mode 1 are never explored in mode 2 and the other way round.

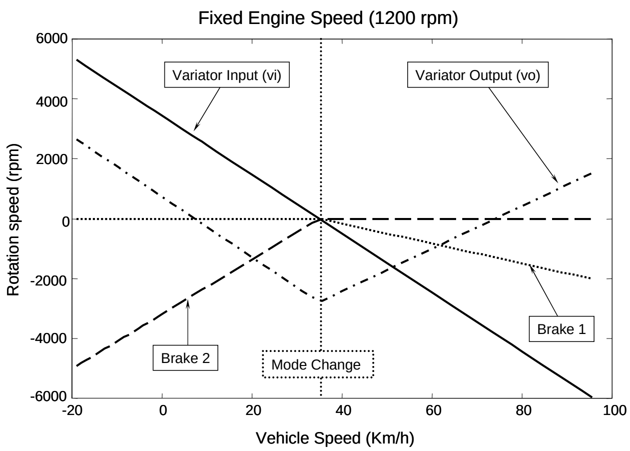

Figure12: Speed diagram

We can see on the preceding graph (figure 12), the speed of various components of the transmission as a function of the vehicle speed, at a fixed engine speed (1200 rpm here).

The mode change occurs when the electric machine 1 is at zero speed. At this point, the transmission is designed in order to have the two brakes speeds and torques near to zero. It is then easy to invert the brakes conditions.
During the mode change sequence, there is a short period when either brakes are on simultaneously (this corresponds to a fixed gear ratio mode). This short period is necessary to keep control of the transmission. If both brakes were off at the same time, the system would be temporarily undetermined and the speed and torques could no longer be controlled.
This short period is referred as mode 3 (Table 1).

	Mode 1	Mode 3	Mode 2
Brake 1	*On*	*On*	*Off*
Brake 2	*Off*	*On*	*On*

Table 1: Mode change configuration.

3.3. Solutions studied by Renault

3.3.1 Multi-discs brakes with hydraulic control

As previously explained, a mode change is comparable to a gear change in an automatic transmission.
Our first priority was to manage a good mode change that was able to respond to all listed constraints. As a consequence, the first prototypes version of the transmission used multi-discs brakes hydraulically controlled (Figure 13):

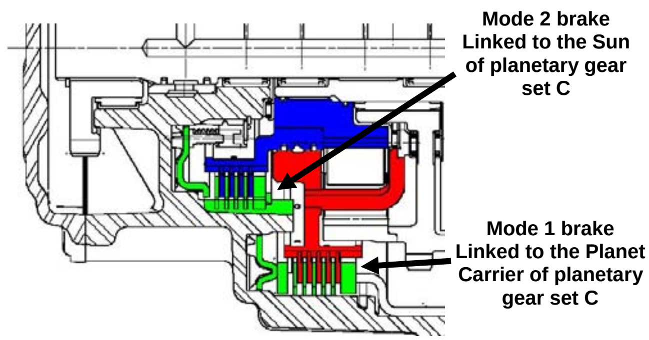

Figure 13: Section cut of the multi-discs brakes mode change system

The hydraulic pump that delivers the oil for the actuation of the brakes is sized in order to allow a mode change in less than 100 ms and to prevent friction even at low engine rpm.

The mode change sequence is as follows, first on a simplified representation (Figure 14), and then with a real record (Figure 15).

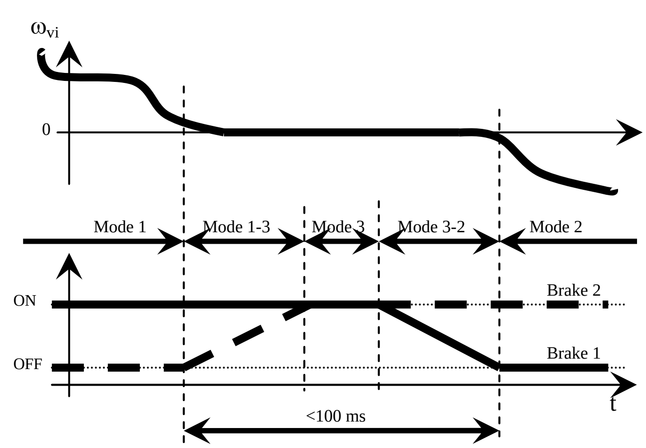

Figure 14: Simplified mode change sequence

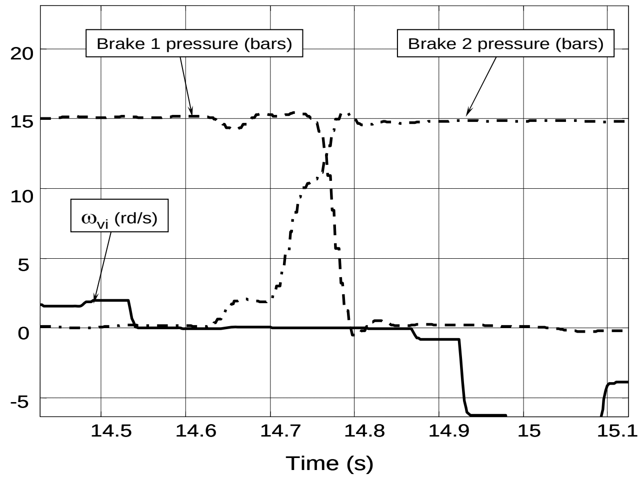

Figure 15: Record of a mode change with multi-discs brakes.

On figure 15, we can notice that the pressure is kept at a high level (~15 bars) after mode change in order to avoid any friction of the brakes.

3.3.2. Dog-clutch brakes with hydraulic control.

As we demonstrated we could manage a mode change in good conditions with hydraulic brakes, when brakes speeds and torques are near zero, we modified the transmission prototypes by replacing the multi-discs brakes by a dog-clutch system (Figure 16).

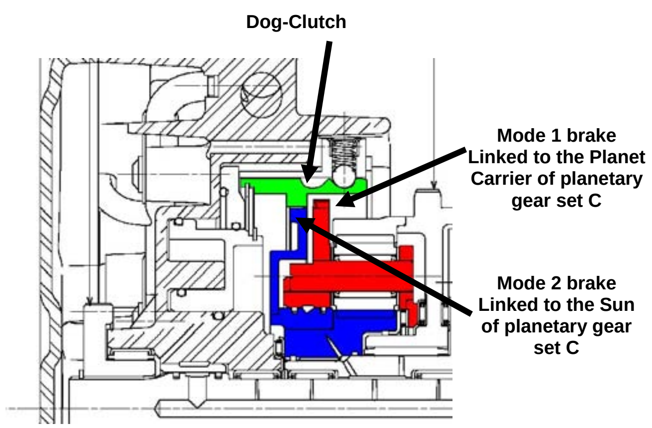

Figure 16: Section cut of the dog-clutches mode change system

We kept the hydraulic actuation system designed for the brakes version, but high pressure is now only requested when mode changes occur (Figure 17). After mode change, the pump only ensures a lubrication pressure, spring loaded balls were used to keep the slider in position

That modification leads to significant improvements in hydraulic losses and as a consequence in vehicle consumption.

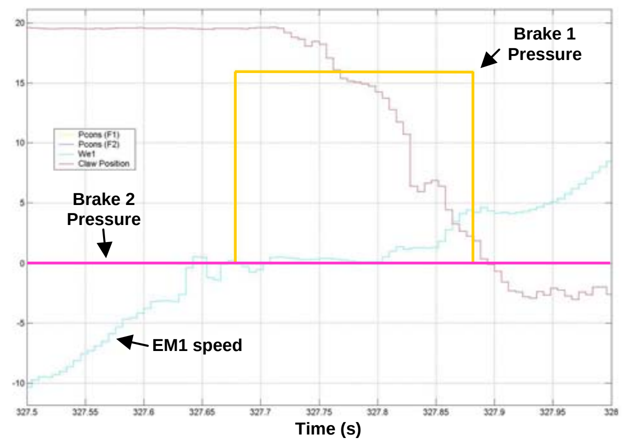

Figure 17: Command signals for a mode change from Mode 1 to Mode 2

3.3.3. Perspectives

In order to further improve the efficiency of the transmission by minimising power losses due to the hydraulic system, next stage would be to test an electric actuation of the dog-clutches.
Then, only a small hydraulic pump, resized accordingly, would be required only for lubrication purposes.

Developments of electric actuated transmissions in the automotive industry (as for double clutch transmissions or automated manual transmissions) are ongoing and could be almost directly applied for mode change actuation on E-iVT.

4. Control strategy

We developed a novel control strategy based upon four different layers (figure 18):

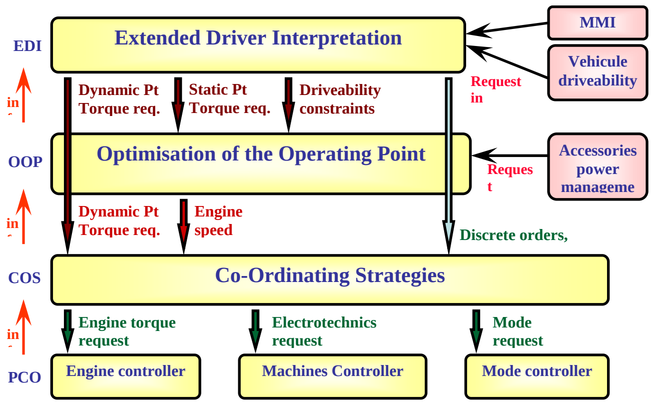

Figure 18: Control strategy

4.1. The EDI (Extended Driver Interpretation)

This layer analyses the driver request (throttle pedal, driver activity through the way the pedal is used by the driver) and the vehicle environment (speed, slope, load…). The EDI produces 2 parameters which are transmitted to the second layer, the OOP (see paragraph 4.2):

- $T_{o\ dyn}$ (Dynamic Torque Output): This is the immediate torque output demanded by the driver. The transmission must supply this power as fast as possible.
- $T_{o\ stat}$ (Static Torque Output): This is the maximum torque the transmission could supply immediately if requested (without major change of ω_i). This parameter depends on the driver activity and is defined in order to pre-position the engine at a working point in order to anticipate the driver's demand and satisfy it in the shortest time.

4.2. The OOP (Optimisation of Operating Point)

This layer contains all the optimization algorithms of the transmission. It defines the parameters which are going to be sent to the COS layer. The OOP calculates the most accurate working point that optimizes:

- Fuel consumption and pollutant emissions,
- Electric machines efficiency,
- Engine speed changes ($d\omega_i/dt$).

The OOP calculates the best possible ICE parameters that satisfy the driver demand ($T_{o\ dyn}$, $T_{o\ stat}$). This is a multi-criteria optimization and priorities have been set:

- 1st priority: meet $T_{o\ dyn}$, $T_{o\ stat}$ and $d\omega_i/dt$ criteria,
- 2nd priority: meet both $T_{o\ dyn}$ and $d\omega_i/dt$ criteria,
- 3rd priority: meet both $T_{o\ dyn}$ and $T_{o\ stat}$.

4.3. The COS (Coordinating Strategy)

The COS is controlling all the PCO (Piloting Components – see paragraph 4.5): it sends them all the parameters necessary to meet the EDI and OOP demand. The COS is also in charge of keeping the voltage on the capacitor at the requested voltage (425V).
It manages in real-time all the parameters and the energy flow into the transmission.

There are also some specific parts of the COS managing different transient phases of the vehicle drive: engine stop and start, mode change, speed creeping, torque creeping, neutral position, reverse speed.

4.5. The PCO (Piloting Components)

PCO are the components which are actuated by the COS:

- Electric machine 1,
- Electric machine 2,
- Engine calculator,
- Mode change (hydraulic actuation).

4. Hybridisation

In a pure transmission case, the two electric machines are only used as a variator. The E-IVT calculator controls permanently the power flow into the variator. The two electric machines are kept at a constant voltage. Capacitors are used to keep the voltage of the electric machines: it is storing a small amount of energy that prevents the drop of the voltage as the control system of the E-IVT can not react immediately to all the perturbations. Its capacity is a few mF.

This energy storage can be increased in order to store a higher amount of energy between the two electric machines. In that particular case, input and output powers of the variator can be temporarily de-coupled, enabling new features of the E-IVT:

- Stop and start of the engine: the energy stored in the machine can be used to stop and restart the engine by the electric machines at traffic lights for instance in order to reduce pollutant emissions.
- Regenerative brake: electric machines can be used as generator in decelerating phases in order to charge the energy storage.

- Boost: The electric machines can use the stored energy to boost the vehicle acceleration.
- ZEV (Zero Emission Vehicle): If the energy storage is big enough, the engine can be stopped for a period, and only the electric machines are used to run the vehicle.
- Plug-in: With even higher battery capacity, the battery can be charged using the electricity network, overnight for instance. The vehicle can be driven in electric drive and when the battery is discharged the power train switches automatically to Hybrid drive conditions.

We can use capacitors for small energy storage (transmission mode); super-capacitors are used for "intermediate" energy storage (stop & start, brake & boost).
The original scope of our project was to investigate these two solutions and the transmission design was optimised for this purpose.
In a pure automatic transmission mode, the expectation, based upon simulations, is to reach a fuel consumption / CO_2 emissions equivalent to a manual transmission.
The simulations carried out showed that the addition of the stop & start and break & boost function could save approximately 10% to 15% in fuel consumption.

Fuel consumption could be reduced by 30% on NEDC cycle in full hybrid drive with higher battery capacity and even more if plug-in capability is used.

6. Experiments - results

6.1. Prototype definition

Vehicle: RENAULT LAGUNA II Estate

Internal Combustion Engine: The engine selected for our E-iVT is a turbo-Diesel engine with the following characteristics:

- 1.9L four cylinders
- Max torque: 280N.m at 2500 rpm
- Max power: 95kW at 3750 rpm

Electric Machines:

- Switched-reluctance machines
- Max torque: 135N.m
- Max speed: 11 000rpm
- Max power: 25kW (Generator and Motor)
- Base speed: 1800rpm
- Voltage: 425V
- Water-cooled.

Transmission: pictured in the figure 20.

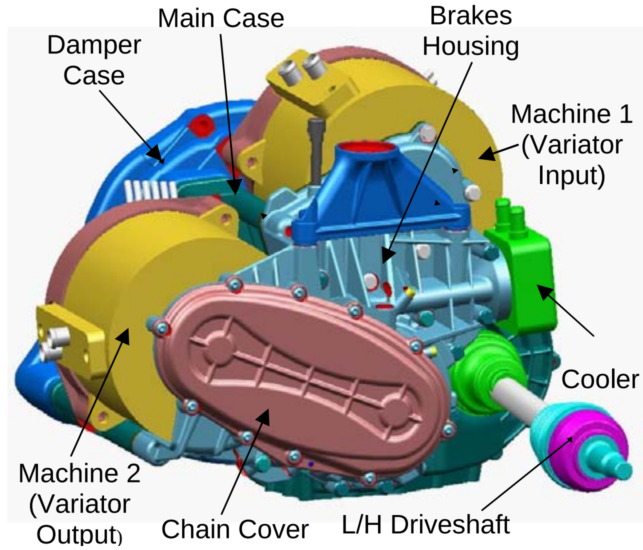

Figure 20: Renault's E-IVT 3D view

6.2. Features

The mode change strategy performs exactly as expected and mode changes are almost not noticeable by the driver, on both brake and dog-clutches version.

We could emulate a discrete gear ratio gearbox (6 speeds) with an impulse manual command. The mode change occurs at the 3rd / 4th gear ratio change.
Speed and torque creeping have been successfully implemented.

As there is no clutch, the neutral position is emulated with a zero torque output at the wheels. In drive mode, a small torque is applied to the wheels (~50N.m). Transitions between P-R-N-D are soft, without any shock or vibration.

6.3. Fuel consumption

The results shown in figure 21 are actual measurements carried out with the prototypes vehicles.

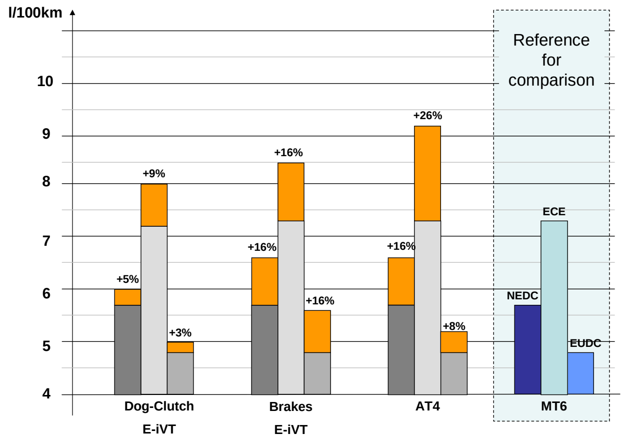

Figure 21: NEDC fuel consumption measurements

The fuel consumption on NEDC cycle is close to a 6 speeds manual transmission in the dog-clutch version. We emphasize on the fact that those measurements were carried out without using any energy storage (pure transmission).

We can clearly observe the impact of the elimination of the hydraulic brakes in favor of the dog clutches. Using an electric actuation for the dog clutch combined with a resizing of the hydraulic pump only for lubrication purposes could lead to fuel consumption even lower than a MT6.

7. Conclusion

Developing a power split transmission is a very challenging opportunity. This architecture is fully depending on the performance of the electric variator and its control strategy that require a novel approach in their development.

Almost all the features that can be expected from a hybrid vehicle are possible on an E-iVT and only depend on the control strategy and the energy storage capacity.

The dual mode RENAULT layout uses smaller electric machines: this offers the double advantage of easier packaging in transversal engine front wheel drive vehicle as well as reducing the cost of the power electronics.

Dual mode E-iVT is potentially a very effective candidate as a base for a range of transmissions starting from an advanced AT (elimination of the hydraulic torque converter) to full hybrid power trains including plug-in capacity, while using the same mechanical and electro-mechanical components.

That would increase the potential market for such transmissions as well as making them a more robust business case when confronted to the cost of batteries.

This project leads to more than 92 patents, on both mechanical architectures and control strategies.

8. References

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9. Abbreviations

EM: Electric Machine
PSR: Power Split Ratio
ω_i, ω_o, ω_{vi}, ω_{vo}: Input (ICE), Output (Wheels), Variator Input and Output Speed (rd/s)
p, s, r: Planet carrier, Sun gear and Ring gear
$T_{o\ dyn}$, $T_{o\ stat}$: Dynamic and Static Output Torque
EDI: Extended Driver Interpretation
OOP: Optimisation of Operating Point
COS: Coordinating Strategy
PCO: piloting Components
E-iVT: Electric-infinitely Variable Transmission
ZEV: Zero Emission Vehicles
AT4: 4 gear ratios Automatic Transmission
MT6: 6 gear ratios Manual Transmission
ECE: also known as UDC – Urban Driving Cycle
EUDC: Extra Urban Driving Cycle
NEDC: New European Driving Cycle (ECE+EUDC)