Dynamic Analysis and Control
Of a Dual Mode Electrically Variable Transmission

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Abstract. This paper focuses on the dynamic analysis and powertrain control of a hybrid electric vehicle equipped with a dual mode electrically variable transmission. The EVT 2-mode is based on a power-split mechanical architecture that can operate in two different configurations, input and compound split, so that the overall efficiency, compared to EVT single-mode, is optimized for different driving conditions, thanks to an additional mechanical point where the power flow path from ICE to wheels is purely mechanical. After a preliminary static and kinematic analysis of the electro-mechanical system, a design method for the powertrain control logic is shown. The model of the system is implemented in a commercial multi-domain 1-D simulation platform. Simulation results prove the efficacy of the proposed control logic to achieve the two opposite targets set in the design phase of the algorithm, full acceleration performance and fuel economy.

Keywords: hybrid electric vehicle (HEV), electric variable transmission (EVT), dual-mode power-split transmission, heuristic control, transmission modelling.

1 Introduction

Hybrid electric vehicles (HEV) are subject of study and experimentation from both academic and industrial community given their great diffusion on the market that has brought to a significant change to the car makers' product portfolio.

Among the several hybrid architectures currently on the market and discussed in literature, most known are represented by Parallel Hybrid configurations, with the electric motor installed in different positions with respect to thermal engine and transmission (P0-P1-P2-P3-P4 [1]), Series Hybrid configuration [2], and Battery Electric Vehicles (BEV) with range extender, Series-Parallel architectures. Within this last category, the so-called Electrically Variable Transmission (EVT) or Electric Continuously Variable Transmission (E-CVT) stands out among the others for both performance and operating efficiency, see e.g. [3]-[5]. Different types of EVT systems have been studied and developed along the years, they vary depending on the number of connected planetary gears and clutches. Articles [6] and [7] present a comparison between EVT 2-modes and EVT 1-mode architectures, reporting the definition of the kinematic and kinetic equations related to the study of mechanical points and the calculation of recirculated electromechanical power and efficiency. In this paper, the reference mechanical model is an EVT 2-mode system, a prototype developed by General Motors [8] as an evolution of the single mode EVT. The control logic in such hybrid vehicles aims at the selection and management of each operating mode so that different targets and objectives can be achieved depending on the specific driving condition. The article [9] describes optimization through Dynamic Programming logic, while other publications propose the ECMS (Equivalent Consumption Minimization Strategy) logic, especially adopted on HEV parallel configurations.

This article proposes a torque split between the actuators through a control logic that focuses on thermal engine efficiency, minimization of power recirculation, battery charge sustaining and achievement of desired car dynamic performance. The paper is structured as follows: after an introductory paragraph with a description of the electromechanical system, the control logic design is discussed; the implementation of the model and its control in LMS Amesim software is shown and finally some simulations results are reported.

1.1 The 2-Mode Electrically Variable Transmission

The stick diagram of the EVT 2-mode system is reported in Fig. 1 [4]. The input is connected to the ICE and the transmission output to the driven wheels via a final drive (not represented in the scheme). The system is composed of two planetary gear set (PG1 and PG2), two electric motors (EM1 and EM2), a thermal engine (ICE) and two clutches (CL1 and CL2).

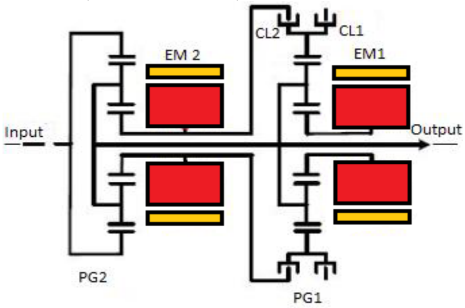

Fig. 1: EVT 2 mode scheme

Table 1: Operating modes

	CL1	CL2
Input split mode	1	0
Compound split mode	0	1

As can be seen from Fig. 1, ICE is connected to the ring (R2) of the first planetary gear set PG2, while the electric motor EM2 to the sun (S2) of the same planetary gear set. The mechanical link between the two planetary gears is made by a rigid connection between their respective carriers (C2 and C1). The second electric motor EM1 is connected to the sun S1. Moreover, thanks to the presence of two clutches CL1 and CL2 that must be operated alternatively, it is possible to select the two operating modes with variable ratio, i.e. “Input split mode” and “Compound split mode”. The two clutches CL2 and CL1 work together but in the opposite way, the closure of one implies the opening of the other. If CL2 is open and CL1 is closed, the input split mode is enabled, the R1 ring is connected to a rigid constraint imposing null speed. Moreover, if CL2 is closed and CL1 open, the R1 ring is connected to the sun S2 that in turn is connected to EM 2 (Table 1). This allows performing a further split of power, even downstream, so in these conditions the compound split mode starts. The input split mode can also be used to realize the vehicle start-up phase in pure electric.

1.2 Power flow analysis and switch point

A preliminary step for control logic design was the kinematic (Eq.1 and 2) and dynamic analysis of the transmission. Regarding the torque equations, for this analysis we consider the static equations (Eq.3 and 4), i.e. assuming unitary efficiency and null mass moment of inertias of the PGs and of the actuators.

Input Split Kinematics Equation

$$\begin{cases} \omega_{out} = \dfrac{1}{N_{S2} + N_{R_2}} \left(\mathrm{N_{R2}}\omega_{ICE} - \mathrm{N_{S2}}\, \omega_{EM2}\right) \\ \omega_{EM1} = \dfrac{N_{S1} + N_{R_1}}{N_{S1}}\, \omega_{out} \end{cases} \quad (1)$$

Compound Split Kinematics Equation

$$\begin{cases} \omega_{out} = \dfrac{1}{N_{S2} + N_{R_2}} \left(\mathrm{N_{R2}}\omega_{ICE} - \mathrm{N_{S2}}\, \omega_{EM2}\right) \\ \omega_{EM1} = \dfrac{N_{S1} + N_{R_1}}{N_{S1}}\, \omega_{out} - \dfrac{N_{R1}}{N_{S1}}\omega_{EM2} \end{cases} \quad (2)$$

Input Split Torque Static Equation

$$\begin{cases} \mathrm{T_{EM1}} = \dfrac{N_{S2}}{N_{S2} + N_{R_2}}\, \mathrm{T}_{out} - \dfrac{\mathrm{N_{S2}}}{N_{R2}}\, \mathrm{T_{ICE}} \\ \mathrm{T_{EM2}} = \dfrac{N_{S2}}{N_{R2}} T_{ICE} \end{cases} \quad (3)$$

Compound Split Torque Static Equation

$$\begin{cases} \mathrm{T_{EM1}} = \dfrac{N_{S2}}{N_{S2} + N_{R_2}}\, \mathrm{T}_{out} - \dfrac{\mathrm{N_{S2}}}{N_{R2}}\, \mathrm{T_{ICE}} \\ \mathrm{T_{EM2}} = \dfrac{N_{S2}}{N_{R2}} T_{ICE} + \dfrac{N_{S1}}{N_{R1}} T_{EM1} \end{cases} \quad (4)$$

N indicates the PG gear teeth number.

As a result, the analytical equations of the Power Ratio (PR), ratio of the power of the electric machine to ICE power, versus the Speed Ratio (SR) are derived, the mechanical points, i.e. when the electric power is null, identified and the efficiency analysis of EVT system was carried out for each power split mode. A detailed description of this procedure can be consulted in [6].

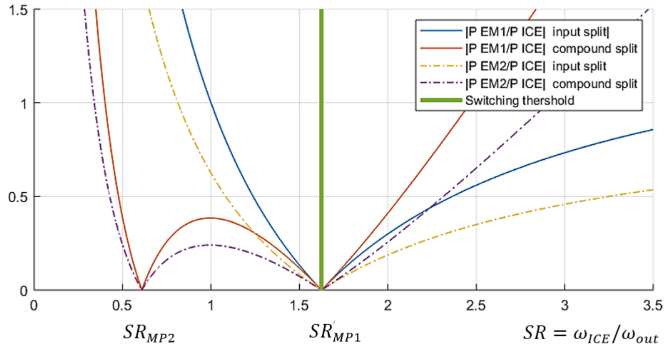

Fig. 2: Power analysis of the two-mode EVT: ratio between electric motor power and internal combustion engine power as a function of the speed ratio, i.e. the ratio between the input and the output speed.

Fig. 2 shows the power ratios between engine and electric motors as function of the speed ratio (input speed/output speed) assuming charge sustaining and null energy conversion losses. As can be noted, input split mode has only one mechanical point, when $SR = SR_{MP1}$, while compound split mode has two mechanical points, i.e. SR_{MP1} and SR_{MP2}, one of which is shared with the former mode. As stated in [10], in the presence of a common mechanical point, it is convenient to switch the operating mode exactly at that point to avoid a discontinuous behaviour during mode transition and to minimize the recirculated electromechanical power thus increasing the global efficiency.

2 Mechanical Model

The mechanical model is based on the following assumptions:

- ICE, EM1 and EM2 are ideal torque actuators with maximum and minimum deliverable torque saturation, steady-state efficiency maps and rotors mass moment of inertias;
- Static battery model using maps for internal resistance and open circuit voltage as functions of state of charge (SOC);
- Hyperbolic tangent friction model for the two clutches CL1 and CL2;
- Unitary efficiency and null moment of inertias for the two planetary gear sets (for more detailed models including mesh efficiency, bearing losses and inertias, refer to [11],[12]) ;
- Pure rolling tire model;
- Vehicle model with longitudinal dynamics.

3 Control Logic

Having introduced the mechanical model and the kinematic and static equations in the two different modes, this paragraph defines the transmission control logic aiming at instantaneously calculating the torque demand for each electric and thermal actuator.

Driver Model

Firstly, a Driver Model tracks a desired vehicle mission profile defined through vehicle speed v_{vh} and acceleration time histories. Its output is the amount of required power P_r and torque $T_{r_{WH}}$ to be applied at the drive wheels. The output transmission torque T_{out} is then calculated from the final reduction ratio and the wheels torque $T_{r_{WH}}$.

Charge-Sustaining Logic

A typical goal of hybrid-operating modes is to maximize ICE efficiency while satisfying the driver's power demand and ensuring an optimal SOC. In order to guarantee the charge sustaining mode, the power required from the ICE is set to be equal to the power required by the mission profile multiplied by g_{SOC}, a gain that can be higher or lower than one depending on the value of the SOC, according to Eq.5.

$$P_{ICE} = g_{SOC}\, P_r \qquad g_{SOC} = 1 + K_p \left(\frac{SOC_{ref} - SOC\ (t)}{SOC_{ref}}\right) \tag{5}$$

Assuming to operate in charge-sustaining mode, the aim is to keep the $\boldsymbol{SOC}$ within an acceptable range; thus, an increase (or reduction) in the power demand is triggered by an instantaneous state of charge $\boldsymbol{SOC\ (t)}$ less (or greater) than the target $\boldsymbol{SOC_{ref}}$. Therefore, the internal power recirculation is continuously modulated to achieve the aforementioned objectives.

ICE operating point optimization

As far as ICE control logic is concerned, the focus is to determine the instantaneous operating points, so that the minimum specific fuel consumption, and hence maximum engine efficiency, are obtained. Therefore, given the efficiency map of the ICE, the Economic-line curve (E-line) must be derived, see e.g. Fig. 3. This curve identifies the optimal torque and speed combination able to achieve the lowest specific fuel consumption for every level of engine power required, ranging from the minimum to the maximum engine power. From the E-line maps, the torque T_{ICE} and speed ω_{ICE} can be found according to ICE power. Then, ICE is controlled to work along the respective optimal points. Having determined the torque to be supplied to the ICE and its operating speed, regardless of the type of EVT mode selected, the electric actuators must adapt to comply with the operating conditions of the ICE and to the power required by the driver. Furthermore, ICE activation/deactivation logic allows implementing pure electric mode.

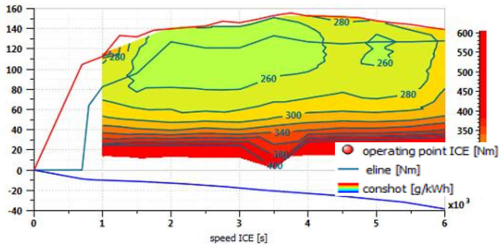

Fig. 3: ICE characteristic map with E line

Pure Electric Mode

It has been assumed that the activation/deactivation of pure electric mode depends on the vehicle forward speed and that vehicle is started in pure electric mode; when the vehicle speed exceeds a reference vehicle speed $v_{VH_{PEM}}$ the ICE activation occurs. In this mode, the same control logic of input split mode is used, whereas ICE torque and speed are zero. The electric mode is enabled by means of the EM2 motor control, which forces ICE speed to stay at zero. ICE is not providing power for vehicle propulsion and battery recharge in this mode, because is switched off. The setpoint for the EM2 speed controller is computed considering the kinematic relationship of the PG2 and imposing that the engine speed is zero while vehicle speed changes according to mission profile. Conversely, the EM1 machine guarantees the vehicle traction and so a speed controller is set up to follow the speed profile imposed by the driving cycle.

Input Split Logic

When Input split mode is activated, EM1 torque is evaluated through the equilibrium equations reported in the static analysis, Eq.3. It corresponds to the linear combination of ICE torque T_{ICE} and output torque T_{out}. EM1 electric machine has the task of managing the total torque required by the wheels. In input split mode, EM1 speed is proportional to the vehicle speed, whereas in compound split mode, it depends on both vehicle speed and EM2 speed.

Concerning EM2, in addition to supplying power intended for vehicle traction and BAT charging, it has mainly the task of controlling the ICE speed during all phases of vehicle operation. ICE starting, acceleration and constant speed operations are obtained by a control action of EM2. This allows the removal of clutches and transmissions with the sole use of an electric variable transmission (EVT). The torque setpoint for EM2

(Eq. 6) is calculated as the sum of two contributions: a feed-forward (open-loop) contribution $T_{EM2_{ff}}$, which is the steady state solution of the torques balance in the transmission system, and a feedback (closed-loop) contribution $T_{EM2_{fb}}$, aiming at minimizing the error between the reference EM2 speed and the actual measured EM2 speed. The reference EM2 speed is obtained by inserting in Eq.1 the ICE optimal speed ω_{ICE} (from E-line) and the measured transmission output speed.

The error compensation is managed through a PID controller, with proportional, integral and derivative gains.

$$\begin{cases} T_{EM2_d} = T_{EM2_{ff}} + T_{EM2_{fb}} = \dfrac{N_{S2}}{N_{R2}} T_{ICE} + PID\left(\omega_{EM2_{ref}} - \omega_{EM2}\right) \\ \omega_{EM2_{ref}} = \dfrac{N_{S2} + N_{R_2}}{N_{S2}} \left(\omega_{out} - \dfrac{N_{R2}}{N_{S2} + N_{R_2}} \omega_{ICE}\right) \end{cases} \tag{6}$$

Compound Split Logic

The Compound split logic has one more mechanical degree of freedom with respect to the Input Split, which can be eliminated with proper adoption of a speed controller for EM1. Indeed, the two PGs work together with a double power split, due to the direct connection of the EM2 with the ring of the PG1. In this way, there is an overall system with 3 degrees of freedom. EM1 depends on both EM2 and the transmission output, so ICE speed is proportional to both EM1 and EM2. Consequently, controlling the ICE speed only by means of EM2 is not sufficient. Indeed, EM1 torque is determined by two contributions (Eq.7), the first $T_{EM1_{ff}}$is the same obtained from the static equations in steady-state conditions. The second is an additional feedback term $T_{EM1_{fb}}$, which has the task of minimizing the error between the reference EM1 speed $\omega_{EM1_{ref}}$ and the actual EM1 speed measured by a sensor, with the use of a PID controller.

$$\begin{cases} T_{EM1_d} = T_{EM1_{ff}} + T_{EM1_{fb}} = \dfrac{N_{S1}}{N_{S1} + N_{R_1}} \left(T_{EM2_{ff}} - T_{out}\right) + PID\left(\omega_{EM1_{ref}} - \omega_{EM1}\right) \\ \omega_{EM1_{ref}} = \dfrac{N_{R1}}{N_{S1}} \dfrac{N_{R2}}{N_{S2}} \omega_{ICE} - \left(\dfrac{N_{R1}}{N_{S1}} \dfrac{N_{R2}}{N_{S2}} - 1\right) \omega_{OUT} \end{cases} \tag{7}$$

The EM2 torque is determined in the same way as Eq. 6, but using the specific equation of Compound split mode (Eq. 4).

Switch Logic

The Switch logic allows the selection of different power split modes, in addition to the pure electric operation of the vehicle. The analytical PR trend study has put in evidence (Fig. 2) that the best condition to switch between the two modes is the mechanical point SR_{MP1}, common for both input and compound split modes. For SR values greater than SR_{MP1}, the absolute value of the PR of the EM1 and EM2 machines in input split mode is lower than the absolute value of the PR of the two machines in compound split mode. Therefore, the electromechanical power recirculated through the electric machines is smaller for the input split than for the compound split, leading to a higher efficiency. It is therefore advisable to select the input split mode. While, for values smaller than SR_{MP1}, compound split mode is favoured to limit the recirculation of electromechanical power. The actual value of SR_i is calculated in real-time and compared with the reference value SR_{MP1}. When SR exceeds the reference value, there is a switch between compound and input split modes, performed by opening and closing the clutches CL1 and CL2.

4 Model implementation

The external layer of Amesim software implemented model is depicted in Fig.4, where the two main subsystems, i.e. Mechanical Model and Control Logic, are reported.

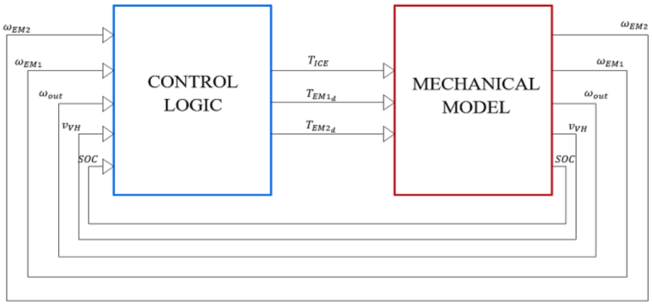

Fig. 4: Block diagram of the implemented model

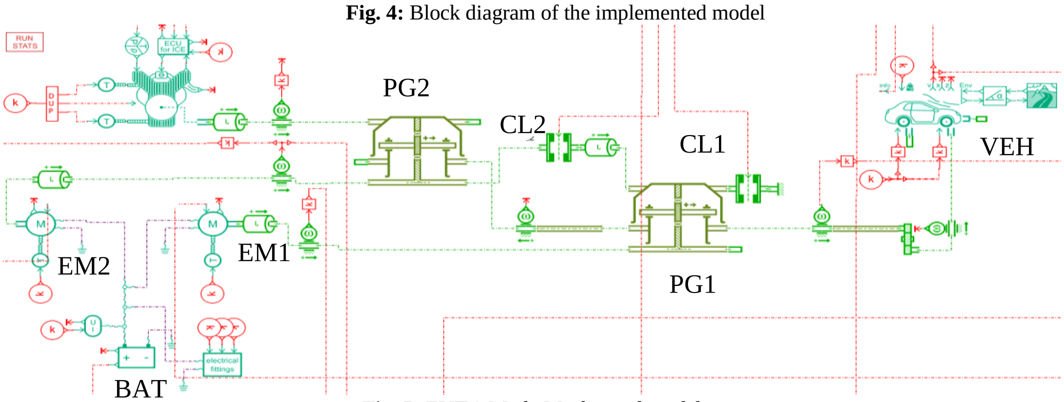

Fig. 5: EVT 2 Mode Mechanical model

Using the software libraries, model of car equipped with a 2-mode EVT has been implemented, as shown in Fig. 5. Note that the mechanical links are shown in green, while the red lines are signal links referring to the control logic.

The control logic block reported in Fig. 6 includes several subsystems in which the logic described in the dedicated section has been implemented. It receives information about vehicle speed v_{vh}, ICE speed ω_{ICE}, EM1 and EM2 speed (ω_{EM1} and ω_{EM2}), output transmission speed ω_{OUT} and BAT State of Charge SOC. It forwards to the mechanical model block the torques demand for ICE, EM1 and EM2 actuators (T_{ICE}, T_{EM1_d} and T_{EM2_d}).

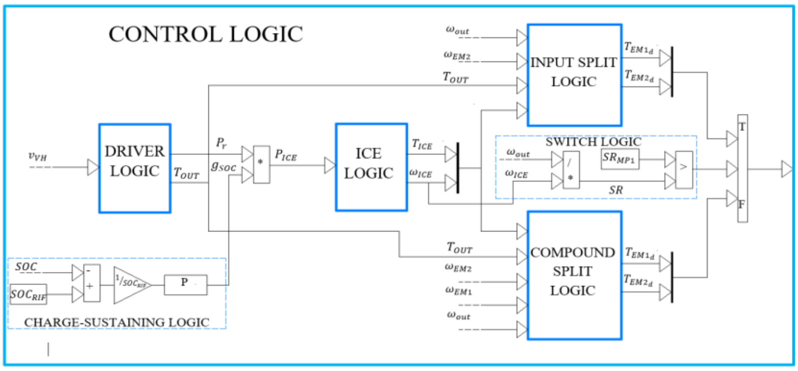

Fig. 6: EVT 2 Mode Control logic

5 Simulations Results

In this chapter, the results of two simulations are reported. The first one requires the driver to perform a very slow vehicle acceleration and involves ICE operation to its optimum points. In the second one, the driver is required to perform a fast acceleration manoeuvre and the engine works at the maximum power point in order to favour the car performance. Subsequently the two simulations are compared, highlighting the use of the two EVT operating modes and analysing the switch point.

5.1 Slow vehicle acceleration (efficiency driven test)

The mission profile is a speed ramp from 0 to 50 m/s (180 km/h) with a constant acceleration of about 0.08 m/s^2, as can be seen in Fig.7. Overall, the vehicle speed required by the driver and the actual vehicle speed are very well superimposed so there is an excellent speed tracking, despite the switch between the operating modes reported in Fig.8.

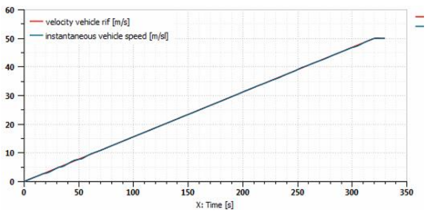

Fig. 7: Comparison of reference and instantaneous vehicle speed trend, sim1

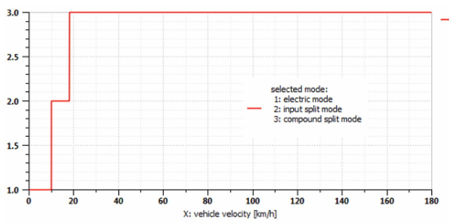

Fig. 8: Selected mode sim 1

The vehicle start-up and acceleration up to 10 km/h are performed in pure electric mode, and traction is delegated to EM1. After, the input split mode is enabled, up to the speed of about 19 km/h, and then the compound split mode is selected up to the end of the test (**Fig. 8**). The Fig. 9shows the clutches signals during the transition from input to compound split mode. The SOC fluctuates around its initial level (65%), thus, charge-sustaining mode is respected. Besides, ICE efficiency is maximized, Fig. 10 shows ICE operating points that are piled on the E-line.

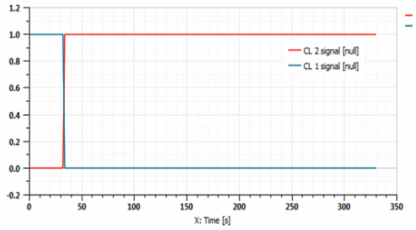

Fig. 9: Clutches signals sim 1

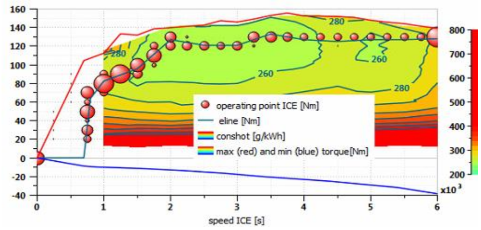

Fig. 10: ICE Operation point in the map, sim 1

5.2 Fast acceleration (performance driven test)

A vehicle full-pedal acceleration manoeuvre is simulated (Fig. 11) with a speed ramp from 0 to 50m/s (180 km/h) with 4 different slopes, starting from 4 m/s^2 and decreasing up to 0 m/s^2. The reference speed and vehicle speed curves are quite overlapping indicating a good speed tracking, as shown in (Fig. 11). The initial vehicle acceleration up to a speed of about 40 km/h is performed in pure electric mode (Fig. 12). Then the input split mode is selected, up to a speed of about 90 km /h, after, compound split mode is active up to 180 km/h. Fig. 13 shows the CLs signal during the mode change, later with respect to the previous case. Compared to the previous case, input split mode persists for a longer period of time and higher vehicle speeds, the value SR_i slowly decreases till it becomes equal to SR_{Mp1}. This is due to a higher ICE speed than before. Therefore, if a more performance and/or torque demanding manoeuvre is requested, input split mode is preferable. When SR_i becomes equal to SR_{Mp1} to avoid the recirculation of power and substantial reduction in the efficiency of the EVT system, the compound split mode switch must be activated. The charge-sustaining objective is respected up to half simulation, then, due to increased power demand, power is drained from the BAT, a final SOC reduction of 10% is obtained at the end of the test. Fig. 14 shows the ICE operating points thickened at the maximum engine power point.

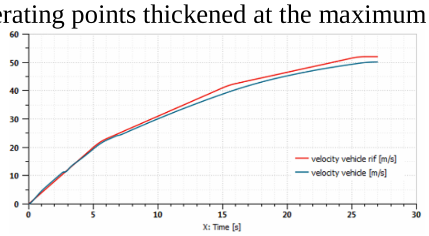

Fig. 11: Comparison of reference and instantaneous vehicle speed trend, sim 2

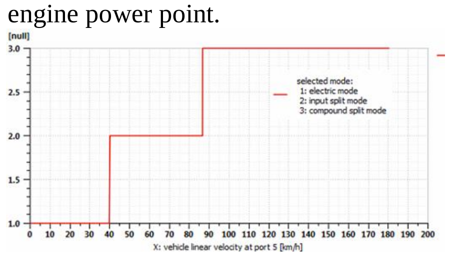

Fig. 12: Selected mode sim 2

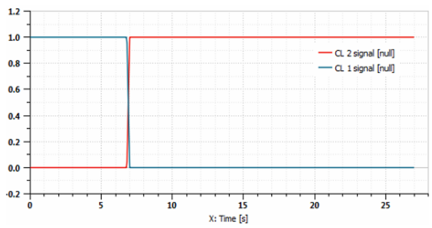

Fig. 13: Clutch signal sim 2

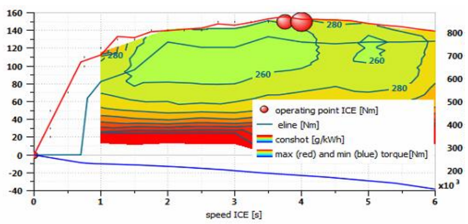

Fig. 14: ICE Operation point in the map, sim 2

6 Conclusion

The results of the simulations indicate that the vehicle model discussed in the paper can be proficiently used for the design and testing of control logics focused on torque management in Dual-Mode EVTs. The proposed control strategy allowed to achieve: engine maximum efficiency, vehicle dynamic performance and battery charge sustaining, which were set as the objectives during the control design phase.

In addition, it has been observed that input split mode remains active for a longer period if more dynamic performance is required to the vehicle, whereas the compound split mode selection is mainly adopted in order to maximize the system efficiency, thus limiting the electro-mechanical power recirculated through the electric components, as well as the double energy conversion. The switching point must not be fixed to a predefined vehicle speed, but let it to depend on the instantaneous speed ratio, thus occurring at different vehicle speeds according to the specific driving conditions.

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