Modeling of Power Split Device for Heavy-Duty Vehicles

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***Abstract*— Nowadays in the automobile sector, seeking reductions in emission and fuel consumption in Hybrid Electric Vehicles (HEVs) is an increased focus. The series-parallel HEV has an architecture that is more diverse than other types of HEVs as it joins both the advantages of series and parallel HEVs. One of the reasons that series-parallel HEVs are more complicated and complex is due to Power Split Devices (PSDs) such as the Ravigneaux geartrain. This complexity becomes more obvious in heavy-duty applications because of their high weight and power requirements. Modeling such PSDs becomes a vital point because of their role in power distribution, efficiency and enhanced design. In this paper, the modeling of these PSDs is conducted with the assistance of Energetic Macroscopic Representation (EMR) and implemented into MATLAB-Simulink®.**

Keywords-Series-Parallel Hybrid Electric Vehicle (HEV), Ravigneaux Geartrain, Energetic Macroscopic Representation (EMR), Heavy-Duty Vehicle, Modeling

I. INTRODUCTION

In the last few decades, growing attention has been devoted by governments and international agencies to fossil fuel depletion and environmental issues. Because land transportation, specifically those with Internal Combustion Engines (ICEs) contributes greatly to these problems, consistent efforts have been undertaken to reduce both the fuel consumption and the polluting emissions of these ICE vehicles [1]. However, solutions towards efficient and clean land transportation can be achieved with the transition from ICE-based vehicles to ones equipped with electric propulsion or a mix between both thermal and electric vehicles known as Hybrid Electric Vehicle (HEV) [2].

Applied to heavy-duty trucks or buses, hybridization can offer significant advantages in terms of fuel economy. An additional advantage is that the mechanical decoupling of the engine allows it to operate at optimum points with higher efficiency. Also, due to the large weight of these vehicles, the ability to regenerate kinetic and potential energy is highly beneficial in certain conditions (e.g. braking) [3], [4].

HEVs are able to be categorized with respect to their energy flow used for propulsion as either series or parallel. Later, a combination of these two systems, called the series-parallel, was proposed to join the merits of these two basic architectures, although at the price of a more complicated structure. A key role within this series-parallel HEV is played by the PSD that divides the power coming from various power sources into the drivetrain as according to a suitable energy management strategy [5]. These PSDs can be a single planetary gear as used in the Toyota Prius or a compound planetary gear like the Ravigneaux geartrain (Figure 1).

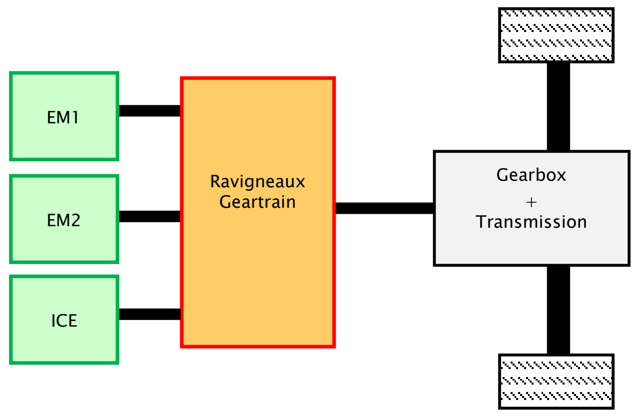

Figure 1- Series-Parallel HEV Configuration with Ravigneaux Geartrain

In this study, the Ravigneaux geartrain is utilized as the PSD [6] because in heavy-duty vehicles the most significant factor is power due to their large weight. This type of PSD ensures that the ICE is available in all conditions. Another significant feature of this geartrain is to start-up the vehicle with the ICE (if needed). This PSD also provides the ability to propel the vehicle at a very low speed (even alone with ICE). However, because of its dynamic behaviour, the modelling of this geartrain is a sensitive issue as it is connected to three power sources and a transmission line [7] - [9].

The aim of this paper is to complete a precise model to understand the critical factors involved in the energy flow study of the PSD for the series-parallel HEV truck. The modelling of these PSDs is essential to exploit the benefits of hybrid powertrains. For this, Energetic Macroscopic Representation (EMR) approach is used because it has the global modelling capabilities for energy flows. This approach is strictly based on the physical causality (integral causality), which shows the graphical representation of energy flows for the system [10] - [12].

In the second part, the modeling of the PSD is presented which will later be implemented in EMR. The third section deals with the modeling of the vehicle in which these equations will be implemented with EMR. Finally, the simulation results are analyzed and compared.

II. Power-Split Device

A. *Architecture of the Ravigneaux Geartrain*

The architecture of the PSD (Ravigneaux geartrain) is shown in Figure 2. There are two layers of pinion gears i.e. outer ③ and inner ② which are meshed with each other. In addition, the outer pinion gears are meshed with a common ring gear ⑤ and a large sun ① with a fixed gear ratio. The inner pinion gear is meshed with the small sun ④ and has a fixed gear ratio. The inner and outer pinion gears are connected independently with the planet-carrier ⑥.

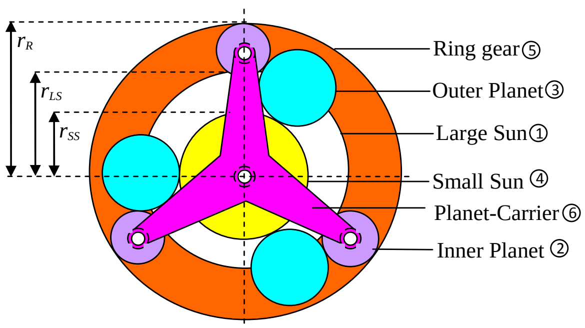

Figure 2- Architecture of the PSD.

Due to both suns, this type of PSD could also be considered as two simple planetary gears meshed with each other. This particular PSD was chosen due its compactness and higher efficiency in comparison to two individual simple planetary gears [6]. By varying arrangements of this type of PSD, different ratios can be achieved. Driving two of these elements simultaneously yields a direct drive. Various combinations of this type of PSD may be used to create the required speeds and torques.

B. *Kinematics of the Ravigneaux Geartrain*

The fundamental equations for this type of complex device are derived from Willis equation. The basic principle of Willis equation is that one gear must rotate so as to maintain a fixed ratio of angular speeds relative to one fixed body (planet-carrier). Keeping this in consideration, the ratio of the relative speeds of the ring gear (Ω_R) and the sun gear (Ω_{LS} and Ω_{SS}) to the speed of the planet-carrier (Ω_{PC}) can be written as:

$$\frac{\Omega_{LS}-\Omega_{PC}}{\Omega_R-\Omega_{PC}} = -\frac{r_R}{r_{LS}} = n_1 \tag{1}$$

$$\frac{\Omega_{SS}-\Omega_{PC}}{\Omega_R-\Omega_{PC}} = \frac{r_R}{r_{SS}} = n_2 \tag{2}$$

where the fixed ratios n_1 and n_2 are defined as the radius of the ring gear r_R to the radius of the large sun gear r_{LS} and small sun gear r_{SS}. The negative sign shows the exterior epicyclic.

After simplification, equation (1) and (2) reduces to the more general form as below:

$$\Omega_{LS} - n_1\Omega_R + (n_1-1)\Omega_{PC} = 0 \tag{3}$$

$$\Omega_{SS} - n_2\Omega_R + (n_2-1)\Omega_{PC} = 0 \tag{4}$$

The above equations show the inherent speed summing the nature of the Ravigneaux geartrain and the reason it is used in the power split. From these relationships, it is possible to deduce the other speed (e.g. Ω_{LS} and Ω_{SS}) if two independent speeds are known (e.g. Ω_R and Ω_{PC}).

If the losses are not considered between the elements of the Ravigneaux geartrain then the torque relationships will be as follows:

$$T_R = -(n_1 T_{LS} + n_2 T_{SS}) \tag{5}$$

$$T_{PC} = T_{LS}(n_1 - 1) + T_{SS}(n_2 - 1) \tag{6}$$

In the above equations (5) and (6), T_R, T_{LS}, T_{SS} and T_{PC} represent the torque of the Ravigneaux geartrain elements such as ring, large sun, small sun and planet-carrier respectively.

III. Modeling of the Vehicle

A. *Studied System*

The studied structure consists of a PSD mounted with shafts connected to two electric machines (EM1 and EM2) through gearboxes, an ICE and transmission through a gearbox as shown in Figure 3.

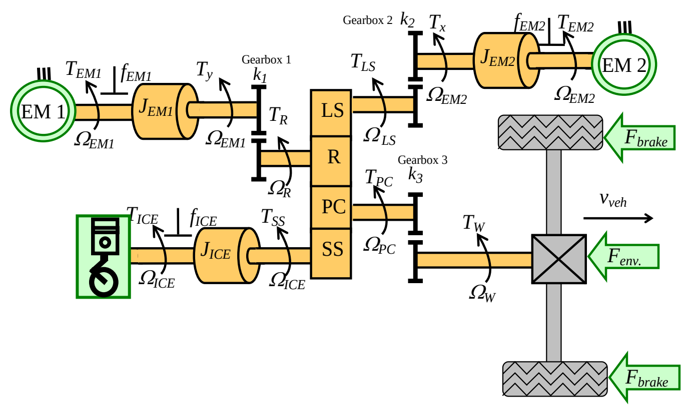

Figure 3- Studied System Layout

The PSDs are the mechanisms of several degrees of freedom. In its composition, one element of the PSD has two rotational movements. In the above system, the ICE drives the small sun wheel (SS), while the large sun gear (LS) is connected to the electric machine EM2 (Motor/Generator) through an additional gearbox of gear ratio (k_2). The ring gear is connected to the other electric machine EM1 (Motor/Generator) through an additional gearbox of gear ratio (k_1), allowing for increased and/or decreased speed. The planet-carrier provides the resultant torque and is connected through the gearbox of gear ratio (k_3) with the wheels of the vehicle. The planet-carrier output shaft transmits the summation power to the vehicle driveline.

The Prius and other architectures do not ensure to start the vehicle with the engine all alone in all circumstances because the operations are combined with engine and electric machines. Also, Prius with simple planetary geartrain has three shafts and has not any clutch on the transmission line. In this architecture, on the transmission line, a gearbox with is installed. Due to this gearbox, the ICE is available in all circumstances even if the failure of batteries and/or electric machines. The vehicle can also reverse with the ICE instead of the electric machines, if needed. In this paper, the simulation of the clutches in between the gears is not considered.

Furthermore, in this architecture the additional gearboxes are provided with electric machines because: to increase the torque in hybrid mode, if only electric traction needed and for rapid recharging of the batteries with high torque.

B. *EMR of the Studied System*

EMR (Energetic Macroscopic Representation) is a synthetic graphical tool based on the principle of action and reaction between connected elements. The principle of EMR is strictly based on only integral causality. It also uses normalized shapes and colors to represent energy sources, conversion elements, storage elements and coupling elements (see Appendix).

The studied system is organized in EMR (Figure 5) and simplified to highlight the exchange variables of the elements of an energetic conversion. The elements used from EMR in figure 5 are described as follows:

Source elements (green oval pictograms) produce state variables (outputs). They can be either generators or receptors. They are disturbed by reactions of other elements.

Conversion elements ensure energy conversion without energy storage. They can have tuning inputs (k_3) to define the conversion between variables. Electrical conversions are depicted by orange square pictograms, electromechanical conversions by orange circular pictograms and mechanical conversions by orange triangular pictograms.

Accumulation elements (orange rectangular pictograms with an oblique bar) connect other elements, thanks to energy storage, which induces at least one state variable (i.e. Ω_{ICE} and Ω_{PC}). All these elements are connected through exchange vectors according to the principle of action and reaction principle. For energy conversion systems specific association rules have been defined to build their EMR.

Coupling elements (overlapped orange pictograms) ensure an energy distribution between several chains of conversion. In Figure 5 the mechanical coupling before accumulation element is used to combine the made up torques T_A and T_B which are associated with sources EM1 and EM2. Similarly, the other mechanical coupling after accumulation element is used to combine the made up torques T_C and T_D associated with ICE and Wheels. These torques are added to get T_1 and T_2 which is discussed in next paragraphs. Later, scalar torques T_1 and T_2 are vectored to apply energy in accumulation element.

Shafts of the PSD system - The respective equations of the four shafts of the studied system in Figure 3 are represented below from (7) to (10). In this (J_{ICE}, J_{EM1}, J_{EM2} and J_W) and (f_{ICE}, f_{EM1}, f_{EM2} and f_W) represents the moment of inertias and viscous frictions of the ICE, EM1, EM2 and Transmission with chassis respectively.

$$T_{EM1} - \frac{T_R}{k_1} = J_{EM1}\frac{d}{dt}\Omega_{EM1} + f_{EM1}\Omega_{EM1} \tag{7}$$

$$T_{ICE} - T_{SS} = J_{ICE}\frac{d}{dt}\Omega_{ICE} + f_{ICE}\Omega_{ICE} \tag{8}$$

$$T_{EM2} - \frac{T_{LS}}{k_2} = J_{EM2}\frac{d}{dt}\Omega_{EM2} + f_{EM2}\Omega_{EM2} \tag{9}$$

$$T_W - k_3 T_{PC} = J_W\frac{d}{dt}\Omega_W + f_W\Omega_W \tag{10}$$

The system has four made up torques (T_{ICE}, T_{EM1}, T_{EM2}, and T_W) with four speeds (Ω_{ICE}, Ω_{EM1}, Ω_{EM2} and Ω_W). Therefore, for the modeling of the PSD, there are eight different categories of torques and speeds, which are a combination of any three torque and any two speed combinations. Due to these categories of torques and speeds, the system can be modeled in thirty-six different ways. For this modeling of the PSD, a choice was made heuristically by choosing the speeds of the ICE and transmission reflect the function of torques of ICE, EM1, EM2 and transmission as shown below:

$$T_{ICE}, T_{EM1}, T_{EM2} = \mathrm{F}\left(\Omega_{ICE}, \Omega_W\right) \tag{11}$$

$$T_W, T_{EM1}, T_{EM2} = \mathrm{F}\left(\Omega_W, \Omega_{ICE}\right)$$

The speed of transmission directly reflects the speed of the vehicle. The point of operation (torque and speed) of the ICE is already known from the curves which allows for modeling using the speed of ICE instead of EM1 or EM2 [10]. For simplification, the speed of the transmission (Ω_W) is replaced with the speed of the planet-carrier (Ω_{PC}) by multiplying gear ratio of the gearbox (k_3). With the resolution of the equations (7) – (11), without considering the losses, the expression deduced for torques is written in matrix form depicted below:

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} J_1 & -J_2 \\ -J_3 & J_4 \end{bmatrix} \frac{d}{dt}\begin{bmatrix} \Omega_{ICE} \\ \Omega_{PC} \end{bmatrix} + \begin{bmatrix} f_1 & -f_2 \\ -f_3 & f_4 \end{bmatrix}\begin{bmatrix} \Omega_{ICE} \\ \Omega_{PC} \end{bmatrix} \tag{12}$$

$$T_1 = T_A + T_C = T_{ICE} + \frac{1}{n_2}k_1 T_{EM1} + \frac{n_1}{n_2}k_2 T_{EM2} \tag{13}$$

$$T_2 = T_B + T_D = \frac{1}{k_3}T_W + \frac{n_2 - 1}{n_2}k_1 T_{EM1} + \frac{n_2 - n_1}{n_2}k_2 T_{EM2}$$

with

$$\begin{cases} T_C = T_{ICE}, \quad \text{and} \quad T_A = \frac{1}{n_2}k_1 T_{EM1} + \frac{n_1}{n_2}k_2 T_{EM2} \\ T_D = \frac{1}{k_3}T_W \quad \text{and} \quad T_B = \frac{n_2 - 1}{n_2}k_1 T_{EM1} + \frac{n_2 - n_1}{n_2}k_2 T_{EM2} \end{cases}$$

In equation (12), all of the moments of inertia (J_1, J_2, J_3 and J_4) and viscous frictions (f_1, f_2, f_3 and f_4) depend on the gear ratios k_1 and k_2, and the PSD gear ratios n_1 and n_2. The moments of inertia (J_2 and J_3) are equal to each other and dependent on J_{EM1} and J_{EM2}. Similarly, the viscous frictions (f_2 and f_3) are equal to each other and dependent to f_{EM1} and f_{EM2}. J_1 and f_1 depend on the J_{ICE}, and f_{ICE}, and J_4 and f_4 are dependent on J_W and f_W.

Equivalent Shafts of the PSD system - The above expression is illustrated in the following Figure 4, which is also equivalent to Figure 3. This figure shows how the moment of inertia shifts backward to the ICE and transmission shafts.

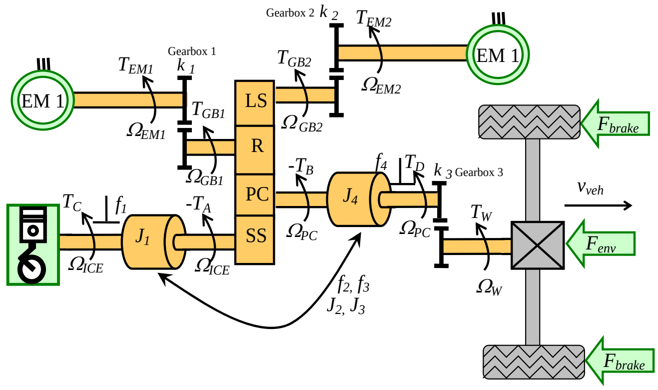

Figure 4- Transmission Scheme after Resolution of Equations

Common Supply – The electric machines EM1 and EM2 are fed by uninterruptible power supplies in parallel by a single DC bus. An electrical coupling is then defined, with the common DC bus voltage:

$$\begin{cases} u_{DC} \quad \text{common} \\ i_{DC} = i_{EM1} + i_{EM2} \end{cases} \tag{14}$$

The DC bus voltage can be considered as the bus which is supplied by the batteries. At this moment, the batteries with choppers and other electrical components are not taken into account.

Machines – The machines EM1, EM2 and ICE delivers machine torques T_{EM1}, T_{EM2} and T_{ICE} and receives their correspondent speeds Ω_{EM1}, Ω_{EM2}.and Ω_{ICE} respectively. The electric machines are modeled by the means of map with the following global equation:

$$u_{DC} i_{EM} = T_{EM} \Omega_{EM} + losses \tag{15}$$

or

$$i_{EM} = \frac{T_{EM}\Omega_{EM} + losses}{u_{DC}}$$

u_{DC} and i_{EM} are the voltage (V) and current (A) respectively.

Gearbox - The gearbox adjusts the output torque to the load torque and it depends on parameters like vehicle weight, desired acceleration, slope, drag coefficient of air, rolling resistance, etc. Here, the gearbox unit chosen in such a way that the torque capacity is always greater than the load torque. There are three gear boxes of gear ratios (k_1, k_2, and k_3) i.e. one with each EM and one on transmission line. The equations associated with gearboxes are:

$$\begin{cases} T_{GB1} = k_1 T_{EM1} \\ \Omega_{EM1} = k_1 \Omega_{GB1} \end{cases} \tag{16}$$

$$\begin{cases} T_{GB2} = k_2 T_{EM2} \\ \Omega_{EM2} = k_2 \Omega_{GB2} \end{cases} \tag{17}$$

$$\begin{cases} T_{GB3} = \dfrac{1}{k_3} T_W \\ \Omega_W = \dfrac{1}{k_3} \Omega_{GB3} \end{cases} \tag{18}$$

Transmission to the Wheels – In this paper the slip phenomena of the wheels and road curves are not taken into consideration. The gearbox has to adapt the rotation speeds between the planet-carrier of the PSD and the wheels. It yields the following torque and speed.

$$\begin{cases} T_W = R_W F_{Tot} \\ v_{veh} = R_W \Omega_W \end{cases} \tag{19}$$

where R_W and F_{Tot} are the radius of wheel and total traction force respectively.

Environment - The environment is a source which delivers the resistive force F_{env} from the vehicle speed v_{veh}:

$$F_{env} = F_0 + a v_{veh} + b v_{veh}^2 + Mg \sin\alpha \tag{20}$$

with F_0 the initial rolling force, a the rolling coefficient, b the drag coefficient, M mass of the vehicle, α slope rate and g acceleration due to gravity.

The resistance forces of environment and braking force (F_{Brake}) summation gives the total forces (F_{Tot}) acting in opposite direction to the vehicle motion. The relationship between these forces is as follows:

$$\begin{cases} v_{veh} \quad \text{common} \\ F_{Tot} = F_{Brake} + F_{env} \end{cases} \tag{21}$$

Brakes - During the transmission of energy to the wheels, the braking element will help to slow down the vehicle. Normally the brake model is always next to each wheel. In Figure 3, a single model of four wheels is considered. In a similar way, single models of brakes are taken into account, shown in Figure 5. In this modeling, it is assumed that there is a uniform braking on all four wheels. Therefore, the brakes are represented by a mechanical source which delivers a braking force to the vehicle chassis. These brakes are controlled by an entry control attached to the source.

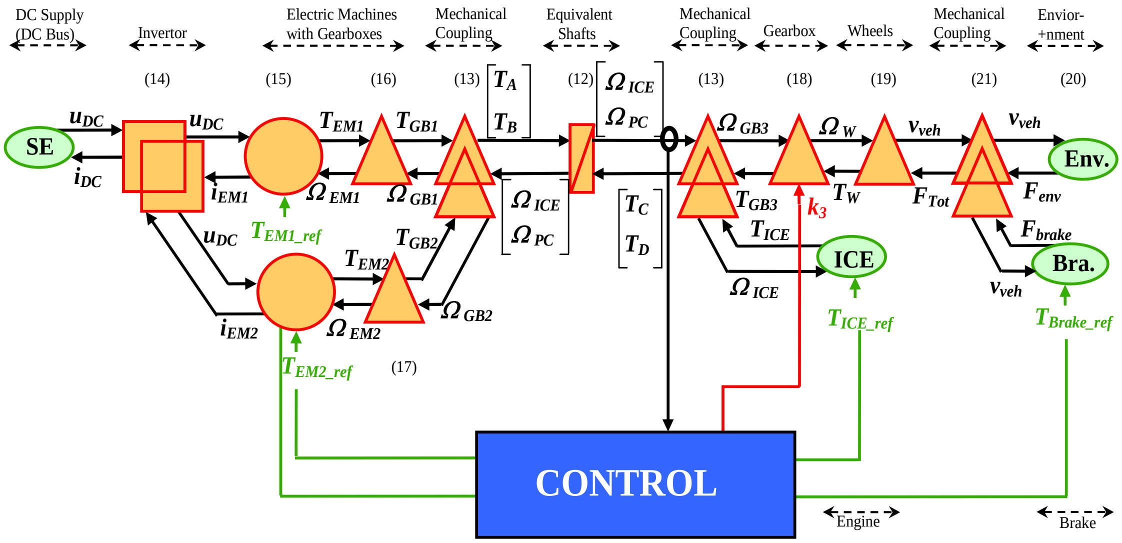

Figure 5- Modeling of the studied system by EMR approach

IV. Simulation Results

Simulation is carried out on Matlab-Simulink® and the results are taken by imposing the reference torque and speed of the ICE. In this simulation, the urban Standard On-Road Test (SORT) driving cycle has been used as a reference to reflect the speed of the wheels [13]. The result shown in Figure 7.a verifies that the simulated speed is the same as the reference speed. The power of the electric machines EM1 and EM2 are shown in Figure 7.b and 7.c. At this point, to avoid discontinuities in the simulated curve, the clutches between the gears are not considered, just the fourth gear has been used.

A. *Operating Modes for HEV*

There are seven operation modes for HEVs, based on their energy sources and traction powers. The seven total modes consist of four basic and three combination modes (Figure 6) [5].

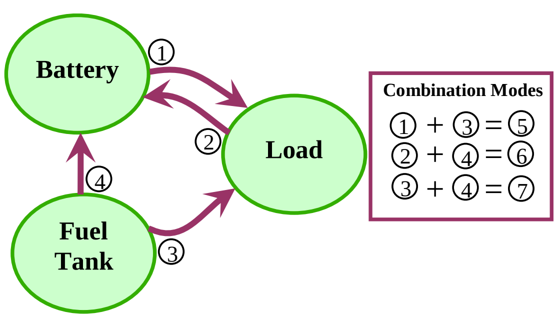

Figure 6- Operating Modes

The first of the basic modes is pure electric traction①, the second is a regenerative braking② where the batteries are recharged during braking, the third is pure ICE③, and the fourth is ICE charging the battery④. When the fuel tank and batteries⑤ worked together to run the vehicle, the fifth mode is created. The sixth mode is when the batteries are charged by both braking and the ICE⑥. The last mode is when the ICE supplies the power as well as charges the battery⑦. In this study, only four operating modes are taken into consideration to follow the SORT cycle.

B. *Simulation results*

From the derived equation in Section II, the EMR has been implemented in MATLAB-Simulink® for optimizing the PSD as according to the operating modes.

In this simulation, the urban SORT driving cycle has been used as a reference to reflect the speed of the wheels whereas the ICE reference speed has been taken by calculating the reference torques and power through curves.

The simulation results are shown in Figure 7 where it is easy to identify the considered four operating modes (three basic and one combined).

Mode* ① *(Only Electric) - 0 to 16 seconds - The vehicle is starting up and the ICE is not running. The EM1 and EM2 power is positive (see Figure 7.b and 7.c). The powers of both EMs are declining after certain time (see Figure 7.d) due to decline in power of DC bus. In this mode, only the battery is working to accelerate the vehicle.

Mode* ② *(Regenerative braking) - 120 to 130 seconds - The vehicle decelerates and the ICE is not operating. The battery is being recharged due to regenerative braking where the EM2 and EM1 acts as a generator which gives power back to the battery (see Figure 7.f).

Mode* ③ *(Only Engine) - 52 to 73 seconds - In this mode, the vehicle speed is constant. For this, the ICE will run alone and directly supply the power through transmission to the wheels (see Figure 7.b, 7.c and 7.d). The distribution ratio for braking force between mechanical brake and EMs are 0.5.

Mode* ⑤ *(Hybrid traction) - 101 to 115 seconds - The vehicle accelerates and the ICE is helping to run the vehicle. In this case, the EM1 and EM2 speed is also helping to accelerate the vehicle. In this case, the ICE power is positive (see Figure 7.e) and the EM power is positive (see Figure 7.b and 7.c). The traction power is drawn from both the Fuel tank and the batteries.

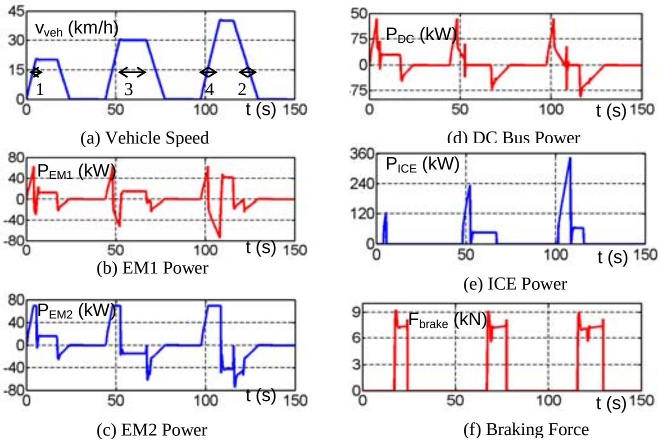

Figure 7- Simulation Results

V. Conclusion

This paper illustrates the modelling of the PSD for application to heavy-duty series-parallel HEVs. Due to the complexity of this device, it is advantageous to model the system with the help of EMR. The goal of this paper was to obtain a complete and simple understanding of PSDs, such as the Ravigneaux geartrain. It has proven to be beneficial to model with EMR as it is able to provide information regarding the PSD in complete and functional perspectives. Using this medium, an improved design which increases the efficiency of the Ravigneaux geartrain with application to series-parallel HEVs will be able to be recognized. The simulation results are made under the SORT cycle. In the simulation results, the reference speed of the vehicle is same as the simulated speed.

As the aim of this paper was not to compare the efficiency of heavy-duty HEVs with conventional HEVs, therefore some basic assumptions such as neglecting the losses, simple gearboxes etc. are taken into consideration. In the future, these considerations could be considered and compared with the conventional heavy-duty vehicle.

Acknowledgment

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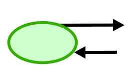
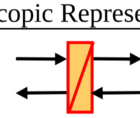
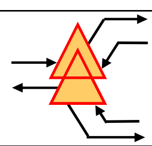
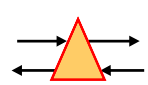
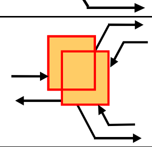
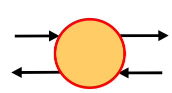
Appendix: Synoptic of Energetic Macroscopic Representation (EMR)

	Source of energy		Element with energy accumulation
	Mechanical coupling (distribution of mechanical energy)		Mechanical converter (without energy accumulation)
	Electrical coupling (distribution of electrical energy)		Electromechanical converter (without energy accumulation)