Machine Drive System Modelling for HIL Simulation

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HAL Id: hal-00373596
https://hal.science/hal-00373596

Submitted on 2 May 2019

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Abstract: *This paper presents bond-graph models of a parallel hybrid powertrain developed by Volvo Powertrain. It will first focus on bond-graph model of an electrical machine and its characteristic equations. Then a converter representation will be added to the bond-graph to get a complete machine drive system bond-graph model adapted to a HIL application. The closed loop will also be presented and the process of validation based on supplier data will be explained. Finally, we will conclude with an overview of the complete driveline model based on bond graph.*

Keywords*: Hybrid Vehicle, Converter, Electrical Machine, Bond Graph, Simulation, Validation, HIL, Modelling.*

1. Introduction

Current requirements of ecology and mobility are at the basis of the project development of hybrid powertains. The Volvo Group has chosen a parallel hybrid powertrain solution for its buses, trucks and refuse vehicles. This new technology involves new hardware for the control of this complete driveline and requires good software controller verification. The control strategies are implemented in different embedded ECU (Electronic Control Units), whose behaviour has to be first checked in a virtual environment. The HIL (Hardware In the Loop) test bench enables the ECU environment in real time to be simulated and their closed loop behaviour in nominal or critical situations to be studied. In order to obtain a good level of realism for the virtual environment, the models must be as close as possible to the physical phenomena in the limit of the real time requirements. That is why a particular attention must be paid in building physical models and in getting a unique environment. Bond graph language appears to be well dedicated to this objective since this language is a powerful tool for multi-domain modelling. Indeed each element of the bond-graph is related to an elementary physical phenomenon (resistance, storage…). A more complex component will be obtained by assembling each element together. Then each phenomenon of this component will be directly visible on its bond-graph.

The complete driveline is then totally modelled with this bond graph structure. In this paper, we will mainly focus on the electrical part, and more especially on the electrical machine and the power electronic converter. A permanent magnet synchronous machine is used here. The more suitable model is based on the Park transform because it is a physical representation, simple and adapted to the real time constraints. The main advantage of a physical modelling approach is the possibility to analyze the system in order to study the sizing of the components, to build control laws or to propose improvements… Another advantage is that it does not require any information about the machine maps to start this analysis. These maps, once furnished by the supplier, can be used only for the model validation and the adjustments of some Park model parameters. Concerning the converter, the high frequency commutation is not compatible with real time because of its high dynamics. Consequently, the use of a mean model is appropriated to correctly reproduce its global behaviour. At the HIL scale, the behaviour of this component is rightly described without suffering from the time consuming commutation function. In order to minimize the implementation time on the HIL simulation, an off-line control loop has been used for the simulation of the converter actuators and results have been analyzed. Finally a complete validation of the machine drive system has been performed.

2. Electrical Machine

The modelled electrical motor is a three-phase PMSM (Permanent Magnet Synchronous Motor). Indeed, the PMSM is indeed the most used machine in the industry: it has got an important mass and volume torque, the inertia and the rotor losses are low and stator inductances are also small, which enables the machine to answer quickly for a torque demand **[**1**]**.

First will be explained the choice of the park model and then the related bond-graph model and the associated equations will be exposed.

2.1 Choice of the model

Four model categories for an electrical motor can be found in the literature:

- High frequency model: electromagnetism equations, resolution by finite elements.
- Intermediate model: permeance networks (from geometry).
- Model with state variable: Park model, with or without saturation.
- Map model.

The 2 first types of model are not compatible with our purpose to implement a real time model. So, only the 2 last possibilities would be considered. But one stake for this simulator is to integrate the maximum of generic model only affected by their parameters that is why the last solution was not wished by Volvo Powertrain.

However it is interesting to evaluate advantages and drawbacks of these 2 possibilities (*Table 1*):

Table 1: comparison map and state model

Map model	State model
- Simple and quick computation	- Dynamic taken into account
- No need of physical information about the machine	- Longer and more complex computation
- Need an important number of test data	- Need physical information about the machine and its command
- No dynamics taken into account	- Take into account voltage, current, command, flux
- Enable a global evaluation of the electric system	- New parameter configuration easy to implement
	- Enable a complete characterisation of the motor, its losses and its commands.

These 2 types of model are nevertheless developed within Volvo depending of the application. But in our case, ECU test requires a certain level of knowledge of the system state in real time, supporting the choice of a state space model.

2.2 Bond-Graph model

The following assumptions are usually adopted for this kind of model.
- Magnetic circuit is unsaturated. Therefore self-inductance and mutual inductance are independent of the current.
- Hysteresys phenomenon and Foucault currents are neglected
- Air-gap is considered perfect (no irregularities)
- Capacitive coupling between the windings are neglected
- The space distribution of the magneto motive forces is sinusoidal
- The damping effects of the rotor are neglected
- The motor is controlled by voltage
- Internal excitation of the rotor is done by permanent magnets considered as a source of flux ψ_f.

The Bond-Graph model is thus based on the Park model. The use of the Park transform is a good way to simplify computation and understanding. The following figure (*Figure 1*) shows a first bond graph clarifying macroscopic functions of the electrical machine.
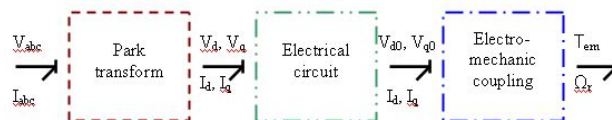

Figure 1: macroscopic bond-graph of the Electrical Machine

An equivalent description of the system applied for Matlab/Simulink would be described from the following way (*Figure 2*).
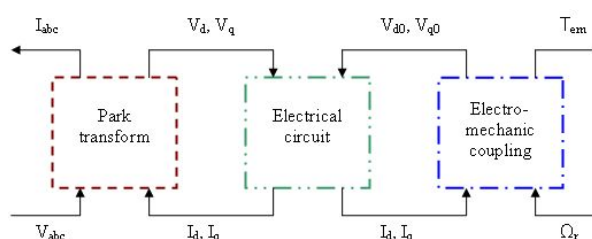

Figure 2: Equivalent simulink model of the Electrical Machine

Finally, the complete description of the system is written in the following bond-graph [2]. (*Figure 3*).
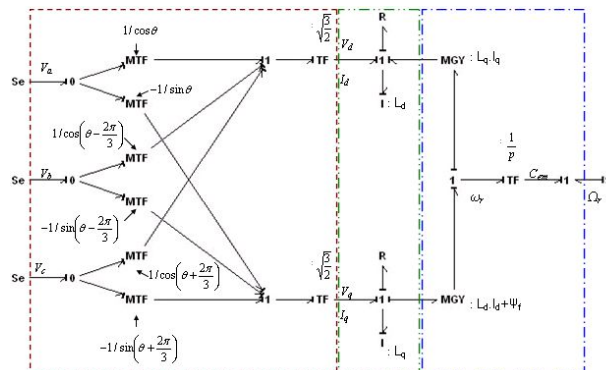

Figure 3: Bond-graph of the Electrical Machine

The park transform block is not a physical phenomenon, but a transformation from a fix 3-dimensionnal to a rotating 2-dimensionnal reference mark.

Only five parameters are needed to configure this model (*Table 2*).

Table 2: parameters of the Electrical Machine

Ψ_f	Wb	Magnetic flux of the permanent magnet
Ld	H	Stator inductance wrt d-axis
Lq	H	Stator inductance wrt q-axis
R	Ω	Stator resistance
p		Number of pole pair

The inputs are the voltages on the three phases and the rotational speed of the motor. The outputs are the currents on the three phases and the torque generated.

2.3 Equations and theory

The equations of this system can be now deduced. For the park transform, the following matrix is used:

$$T_a = T_{dq0/abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ -\sin\theta_r & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$ (1)

with $\begin{cases} \Psi_{abc} = T_a^{-1}.\Psi_{dq0} \\ i_{abc} = T_a^{-1}.i_{dq0} \end{cases}$ (2)

The expression of the machine flux is then (Ld and Lq are only dependant of the temperature):

$$\begin{cases} \Psi_d = L_d.i_d + \Psi_f \\ \Psi_q = L_q.i_q \end{cases}$$ (3)

And the expression of the tension (from generalized ohm law) in the rotating dq reference mark:

$$\begin{cases} v_d = R.i_d + \left(\frac{d}{dt}\Psi_d\right)_{dq} - \omega_r.\Psi_q \\ v_q = R.i_q + \left(\frac{d}{dt}\Psi_q\right)_{dq} + \omega_r.\Psi_d \end{cases}$$ (4)

That gives:

$$\begin{cases} v_d = R.i_d + L_d.\frac{d}{dt}i_d - \omega_r.L_q.i_q \\ v_q = R.i_q + L_q.\frac{d}{dt}i_q + \omega_r.L_d.i_d + \omega_r.\Psi_f \end{cases}$$ (5)

In these equations, mechanical losses and iron losses are not represented, the mechanical losses are taken into account later in the mechanical part of the model and iron losses are too complex to be studied directly from the electrical equations. They are represented as a mechanical loss following a numerical behaviour law [3].

The expression of the torque is given by this formula.

$$T_{em} = p.\left(i_q\Psi_d - i_d\Psi_q\right) \text{ with } \Omega_r = \frac{\omega_r}{p}$$ (6)

Therefore, from an dynamic point of view, 2 non-linear state equations define the complete behaviour of the machine.

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d}.i_d + \frac{L_q}{L_d}.p.\Omega_r.i_q + \frac{1}{L_d}.v_d \\ -\frac{R}{L_q}.i_q - \frac{L_d}{L_q}.p.\Omega_r.i_d - \frac{1}{L_q}.p.\Omega_r.\Psi_f + \frac{1}{L_q}.v_q \end{bmatrix}$$

with $T_{em} = p.\left(L_d - L_q\right)i_d.i_q + p.i_q.\Psi_f$ (7)

In section 4, the validation of this model is detailed. But first let us study the behaviour of the converter.

3. Power Electronic Converter

The control of converters is now more and more simple and is no more a difficulty to use a PMSM. Nevertheless, some disadvantages still remains. It presents problems of torque oscillation especially at low speed. The action to deflux the machine is also a delicate operation when increasing the speed, since the flux is fixed by the magnets and demagnetization must remain limited. Moreover, it does not tolerate high temperatures of operation (need of an efficient cooling).

However, its cost of production is quite high because of the price of the permanent magnets.
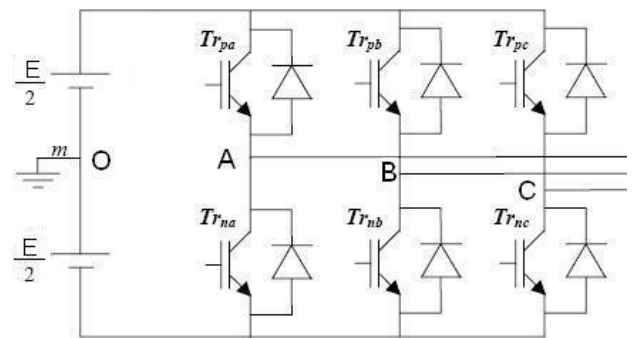
3.1 Choice of the model

Figure 4: electrical schema of the converter

The objective of a power electronic converter (*Figure 4*) is to realize the function "energy conversion", i.e. to adapt the primary energy and to control the transmitted power to the actuator, using components of commutation. These components are characterized by two states, a on-state and a off-state. The modelling of such components uses commutation model with very fast dynamics. Such a precise modelling would take into account IGBT

response time (about the nanosecond), this is however not in agreement with our purpose.

Less precise but still quite realistic, the commutation model (On/Off) does not take into account transient operation of the IGBT and shows the discontinuities in the model. For our application, the knowledge of the state of each switch is not required to study the energy transfer between the electrical components.

On the other hand, to obtain a good appreciation of the converter behaviour on a more global scale without studying the commutation phases, the use of average models [4] is judicious. They make possible to describe the converter behaviour while removing the commutation function and thus reducing considerably the time of computation.

The main hypothesis is to assume that the cycle period of commutation is small compared to the time constants of the system. This is obvious for a good converter operation.

3.2 Bond-Graph model

The following schema (*Figure 5*) describes how the converter is connected to its environment.
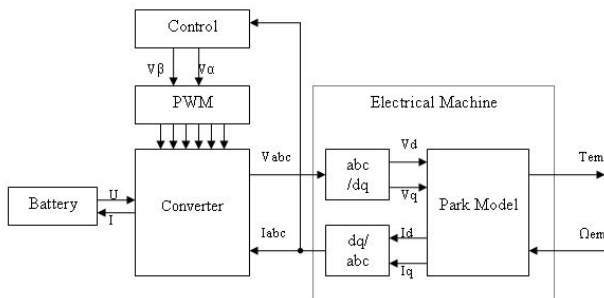

Figure 5: The converter in its environment

This component is a power modulator. Energy is available from the battery and depending of the control, the converter will supply or not the electrical machine. The following figures (*Figure 6*) show the macroscopic functions of the converter.
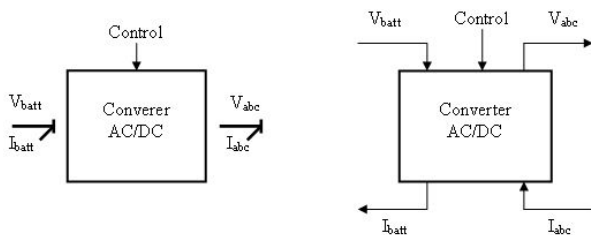

Figure 6: Macroscopic view of the converter

The control is used to generate opening and closing sequence of the IGBT. As shown previously, it operates at a defined frequency whose dynamics is much higher than the rotational machine speed. It computes at each iteration the opening rate of each IGBT. In the case of the mean model, this value is directly transferred to the physical model of the converter. In the case of a more precise model, a binary signal should have been applied, indicating an opening or a closing demand for each switch.
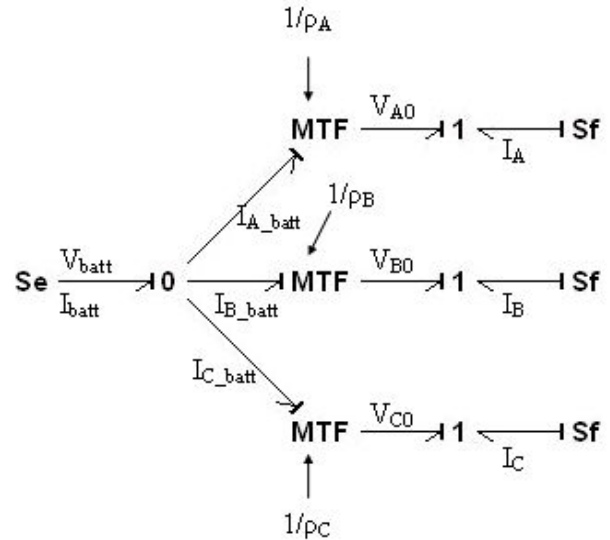

Figure 7: Bond-Graph of the converter

The complete bond-graph of the mean model is given *Figure 7*. The value of the conduction rate of each arm of the converter is not directly deduced from the control. Indeed the two IGBTs of one arm can not switch from the state on/off to the state off/on directly. For safety reason, the state off/off is used during a certain time (called dead time) to be sure not to pass by the state on/on which can damage the converter. Therefore, the obtained result can differ from the control depending of the dead time. This allows a better approximation of control signals during a normal operation:

$$\rho_A = \rho_{A\_PWM} - \rho_{dead}$$

$$\rho_B = \rho_{B\_PWM} - \rho_{dead} \qquad \textbf{(8)}$$

$$\rho_C = \rho_{C\_PWM} - \rho_{dead}$$

3.3 Equations and theory

From the bond-graph, equations can be easily deduced.

$$V_{AO} = \rho_A . V_{batt} \quad \textbf{(9)} \quad \text{and} \quad I_{A\_batt} = \rho_A . I_A \qquad \textbf{(10)}$$

$$I_{batt} = I_{A\_batt} + I_{B\_batt} + I_{C\_batt} \qquad \textbf{(11)}$$

The only difficulty is to determine the value of ρ for each arm, which depends of the control that is applied to the machine. The variable ρ is called the cyclic rate, it defines the rate of opening the first IGBT of one arm. Only three states are possible: First IGBT opened / second IGBT closed, First IGBT opened / second IGBT closed and finally first and second IGBT closed. The last state is defined by the value of the dead rate ρ_{dead}.

To apply a desired magnetic field to the machine, the converter must be controlled in an intelligent way. This calculus does not take into account the dead rate and consider only two states by arm, i.e. there are 8 possible controls of the converter. For each period, the PWM computes the times to apply each of the height vectors with respect to the target field. First, it looks for the vectors that will drive the field in a desired sector (delimited by two vectors). Then, the direction of the field is rebuilt from these two vectors only and the norm is obtained by applying a zero vector during the remaining time. From this result, it is possible to deduce a cyclic rate by arm (**Table 3**).

Table 3: Steps for the PWM calculation

Input	Wished stator field: Vs
Step 1	Compute the characteristic supply vectors (Three phases => height vectors).
Step 2	Apply the Concordia transformation to these vectors (star or delta).
Step 3	Express Vs with respect to its two adjacent vectors.
Step 4	Compute the cyclic rate of these two vectors and the zero vector.
Step 5	Deduce the cyclic rate of each arm.

In conclusion, the mean model takes as input value the cyclic rate of each arm and gives as output the mean value of the voltage of each arm for each period. This voltage takes into account the value of the dead time (due to the commutations) by deducting the dead rate to the cyclic rate just before the computation of the mean voltage *(cf. eq.* (7)*)*.

4. Model Validation

Once the theoretical steps performed, the quality of the model needs to be verified. To measure this quality, two kind of test must be done: static and transient tests in open loop and then in closed loop. As some information is the only propriety of the supplier (control laws, parameters) only the complete system (Power Electronic Converter + Electrical Machine + Controller) can be validated together with the help of static maps.

4.1 Development of a control loop

To get a complete model running, a simple control loop is necessary. From sensor information on the current, a torque control can be determined and the cyclic rates computed.

However the system is non-linear and inputs are linked. To remove the non-linearity, the dynamic of the rotor speed has been considered weak in front of the electrical system response. So it is treated as a constant. For the coupling problem, a small transformation of the state variables enables to obtain a linear formulation of the problem:

From the equations (5), it can be written:

$$\begin{cases} v_d^{'} = v_d + \omega_r.L_q.i_q = R.i_d + L_d.\dfrac{d}{dt}i_d & \textbf{(12)} \\ v_q^{'} = v_q - \omega_r.L_d.i_d - \omega_r.\Psi_f = R.i_q + L_q.\dfrac{d}{dt}i_q \end{cases}$$

By using as new inputs of the problem vd' and vq', we get the two following separate state equations of the first order easy to control with a basic controller.

$$\begin{cases} \dfrac{I_d(p)}{V_d^{'}(p)} = \dfrac{1}{R + L_d.p} \\ \dfrac{I_q(p)}{V_q^{'}(p)} = \dfrac{1}{R + L_q.p} \end{cases} \qquad \textbf{(13)}$$

The simplest and the most common way to control the PMSM is the one called maximum torque [5][6]. It maintains the emf in phase with the stator current; this implies a condition on id: id*=0. The value of Iq will control directly the value of the torque. The main advantage of the method is its simplicity.

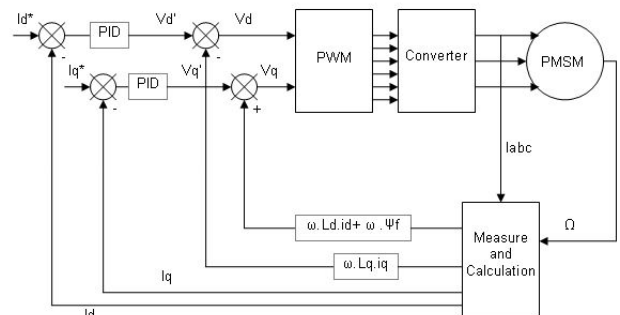*Figure 8: Control of the PMSM*

The previous figure (**Figure 8**) shows the complete control structure of the machine [7]. Only the converter and the PMSM are physical plants. The remaining blocks are part of the controller of the

machine with sensors on the currents and on the rotor position and actuators on the IGBTs of the converter. In our case, the PWM gives to the converter the cyclic rate as computed in the previous section.

4.2 Losses identification

Once the control loop developed, it is possible to make a simulation of the system in a desired operating point and to compare simulation results with test data from the supplier in order to adjust different parameters of the machine. Indeed, a few phenomena of the machine are difficult to evaluate, like the iron losses. A study has evaluated them with interesting numerical laws [3]. This approach has been chosen in our study to minimize the computation time of the model.

Finally, four kinds of losses are taken into account in the model: converter losses, Joule losses, iron losses and mechanical losses. The aim is now to evaluate each loss with the best approximation as possible knowing only the global losses. The following equations have been used:

For the converter losses (losses in conduction and in commutation), an equation of the second order with respect to the input current is a good approximation [3].

$$Pl_{conv} = 2,31.e^{-5}.I_{batt}^2 + 7,3.e^{-3}.I_{batt} + 4,3.e^{-3} \quad \text{(14)}$$

For the Joule losses, the formula is given by the following equation:

$$Pl_{Joule} = R.(Id^2 + Iq^2) \quad \text{(15)}$$

The mechanical losses are modelled with a viscous friction, no dry friction is considered here.

$$Pl_{Meca} = R_{viscous}.\Omega_r \quad \text{(16)}$$

And finally, the iron losses are modelled with the following law with 2 parameters varying with the rotor speed [8].

$$Pl_{Iron} = \alpha(\Omega_r).(v_d^2 + v_q^2) + \beta(\Omega_r) \quad \text{(17)}$$

This method to estimate the loss is really well adapted to real time as the simple losses are calculated from formulae and more complicated ones with numerical model. The main advantages are to keep a reasonable computational time and to have a separate view of the different losses. For example, it is well known that Joule losses will have an important influence on the temperature.

In these equations, three parameters are not given by the supplier and must be identified with the test data: $\alpha(\Omega_r)$, $\beta(\Omega_r)$ and $R_{viscous}$. By using an optimization algorithm, these data have been determined in order to fit as best as possible of the test data (*Figure 9*).
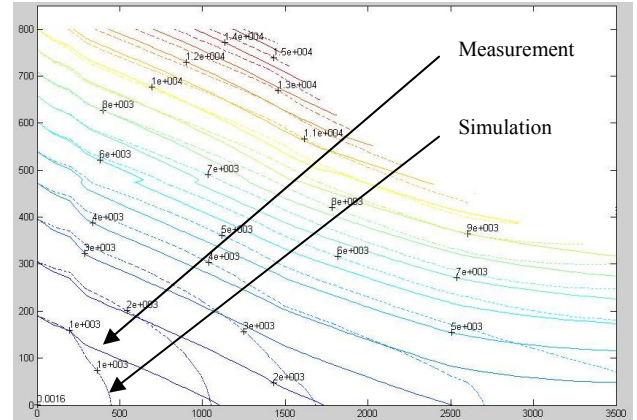

Figure 9: theoritical vs test data losses

4.3 Validation results

The static validation is performed directly from the previous curve (*Figure 9*). For each point, two data are analyzed: the absolute error and the relative error.

$$E_{abs} = Pl_{theoritical} - Pl_{test\_data} \quad \text{(18)}$$

$$E_{rel} = \frac{Pl_{theoritical} - Pl_{test\_data}}{Pl_{theoritical}} \quad \text{(19)}$$

A statistical analysis has then been done and according to several criteria the model can be approved or not. In our case, results are quite good for a torque greater than 100 Nm but they are less concluding for a smaller torque. A possible explanation is that these data have not yet been updated by the supplier whereas parameters have already been supplied. When new test data will be available, a new validation will be performed with an expectation of better result for a torque less than 100Nm.

A transient validation will also be performed when dynamic test data will be available from the supplier. From this study, it is possible to adjust the value of the stator impedance if needed because of their variation with respect to the rotor speed. This correction makes possible to take into account magnetic saturation of the machine and then to have a correct transient behaviour [6][8]. The dynamic in closed loop is defined by the requirements and can be reached with the PID settings. In the scope of the HIL simulation, a requirement is to be able to run the model at a sampling time of 1ms. To avoid numerical oscillations, a minimum of 50ms has been specified to set the step response of the closed loop system. The PID regulator has then been set with respect to this requirement in the global range of operation.

5. Complete model

5.1 Explanation of the need

As explained in the introduction these models are built in order to validate the complete electronic supervision of the hybrid powertrain. The following schema (*Figure 11*) illustrates the part what need to be modelled.
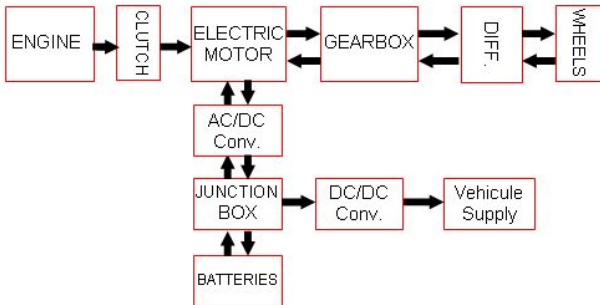

Figure 10: Complete driveline of the hybrod powertrain

A particular focus has to be taken on the fact that this model is linked to a real network of ECU what controls the system with sensors and actuators (*Figure 11*). Then all sensors and actuators have to be modelled.
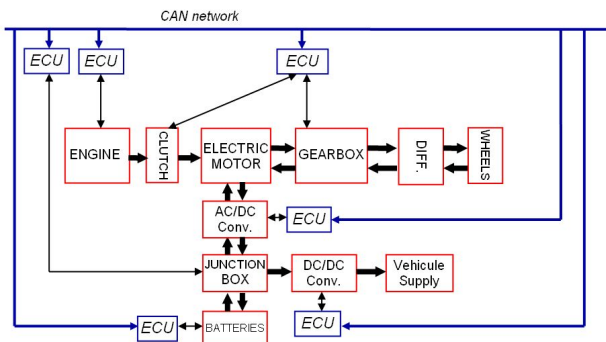

Figure 11: Supervision network of the driveline

5.2 Overview of the complete Bond-Graph model

The bold link in the figure highlights the Energy transfer between components. This transfer is either electric or mechanical. The bond-graph (*Figure 12*) enables a graphic representation of this system without distinction of the nature of the transfer energy.
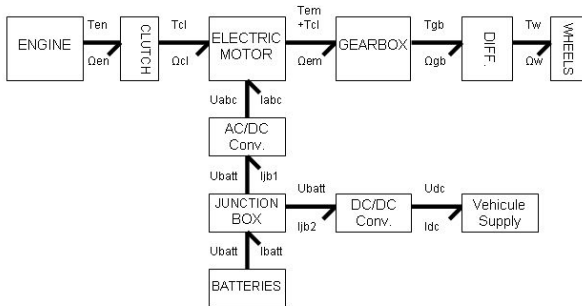

Figure 12: Bond graph of the driveline

Each subsystem is then described using a bond-graph approach. The converter and the electrical machine have been illustrated in previous sections, but the other subsystems have also been developed. Let us focus now on some components which need a good level of modelling because of their interaction with a control unit.

First, the modelling of the engine can be very complex. The air loop needs to be modelled to compute air flow in the engine. The injection system is also necessary; this can take into account the model of injectors and its electrical control. Chemical reactions occur during the injection in cylinders, the crankshaft rotates with a speed depending of the injection and the air flow… Several different physical domains are already mentioned: thermodynamic, electric, mechanic, chemical… The bond-graph differentiates the domain only by the variables that are computed, but power links between components are similar.

In this system, the clutch and the gearbox are robotized. It means that an actuation system has been developed. Depending of the technology, a hydraulic or a pneumatic system is used to shift a gear mechanically. This subsystem has also been modelled with Bond-Graph

The battery is split in lots of cells. Each cell has chemical reactions generating a current. These reactions are strongly dependant of the temperature which has an impact on the tension. Here a thermo-dynamical Bond Graph is used

Finally, this system is a multi-physical modelling problem **[9]**. For an automotive manufacturer, such model problems are very common and the bond-graph is an interesting tool for modelling. The *Figure 12Figure 12* gives the first level of this modelling. To develop the second level, several questions need to be solved before starting: for which application? depth of the modelling?, which phenomena to take into account?, limit of the simulation target?, input and output interface?...

Once the bond-graph model developed, it is a powerful tool of analyze. Modelling problems are easily detected (algebraic loop, causality) and it can be used for sizing problems **[10]** or for conception of control laws.

6. Conclusion

The industrial development of ECU consists of conception phases and validation phases. The process of validation is also divided into several steps; one of these is the HIL validation which focuses on the functional verification. The HIL validation is a tricky problem: it should be able to stimulate the ECU with a really good level of realism and in the same time, it should run in real-time. The

modelling problem is then a constant compromise between these two targets. For some phenomenon a physical law will be necessary, for other a simple law will be sufficient.

We have shown the different choices which have have done for the converter model and for the machine model. With the help of bond-graph approach, electrical and mechanical domains are mixed in the model without distinction to keep a constant look on the energy exchange. This method is also used for the development of the engine model, the transmission model and the battery model. Then, when all components are validated separately, a complete model is then built.

In this industrial context, the future step is to develop suited control laws from the bond-graph analysis. With the help of the concept of bi-causality and model inversion **[11]**, solutions can be developed and studied.

7. Acknowledgement

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9. Gloassary

HIL :   Hardware In the Loop
ECU :   Electronic Control Unit
PWM : Puls With Modulation
IGBT :   Insulated Gate Bipolar Transistor
PMSM : Permanent Magnet Synchronous Motor