ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil
Copyright © 2013 by ABCM

Implementation of heuristic control techniques in power management in hybrid vehicle parallel configuration

Fernanda Cristina Corrêa
UTFPR - Universidade Tecnológica Federal do Paraná Campus Ponta Grossa Av Monteiro Lobato Ponta Grossa - PR
fernandacorrea@utfpr.edu.br

Jony Javorski Eckert
Fabio Mazzariol Santiciolli
Franco Giuseppi Dedini
Faculdade de Engenharia Mecânica - UNICAMP Rua Mendeleyev, 200 Cidade Universitária "Zeferino Vaz" Distrito de Barão Geraldo
13083-860 Campinas SP Brasil
fabio@fem.unicamp.br

Abstract. *The growing number of cars is causing serious effects such as pollution, global warming, and depletion of oil reserves, among others. The high dependence on petroleum products creates a critical situation because these resources have limited availability and exists in specific regions, generating recurring price increases and international conflicts, which encourages research by obtaining new forms of energy-efficient equipment and energy. An example of this is the adoption of hybrid vehicle propulsion technology, and the hybrid electric vehicle (HEV) maintains the characteristics attributed to conventional vehicles such as vehicle performance, safety and reliability. In general, the main reason to use electric hybrid architecture is the additional degree of freedom due to the presence of an additional energy source other than fuel, this means that, at each instant, the power needed by the vehicle can be provided for such a sources, or a combination of both. Thus, there is a demand for a control strategy to manage the operation of these systems obeying aiming at better efficiency performance criteria. This implies meeting the request of power imposed on the vehicle subject to restrictions as possessing a certain autonomy and low emission of pollutants, ie, managing the flow of energy becomes a key factor in HEVs. The classification of HEVs depends on the combination of MCI and ME in the drivetrain and can be given in three different types: Parallel and Parallel-Series Seriously. In this work, the focus is on Parallel configuration where both drive units, MCI and ME, are connected directly to the wheels. In this configuration, the ME can sometimes work as a traction drive, sometimes as power generating unit to meet the needs of the battery. Thus, the aim of this work is the implementation in Matlab / Simulink / Adams a power management algorithm based on heuristic control techniques. This technique is one of the most simple to implement, but which result in considerable fuel savings. The results from this technique allows to observe the changes in the consumption map of the engine for combustion related to fuel economy and the resulting performance, and these results are compared with the results of a conventional vehicle.*

Keywords: *hybrid vehicle, heuristic control, power management, dynamic*

1. INTRODUCTION

The hybrid electric vehicles (HEVs) are becoming, in recent times, an alternative and a solution to the problems faced by urban society. Problems such as high consumption of oil-based fuels and the exhaust of greenhouse gases are reduced with the implementation of the technology used in hybrid vehicles. These factors imply that all manufacturers will, eventually, have a hybrid vehicle in the near future.

Hybrid vehicles have as a main feature the union of two or more power generation systems, such as internal combustion engines coupled with electric motors or fuel cells. Comparing to a classic vehicle, the hybrid one is more complex. The large number of settings allows the division into two main groups: series hybrids and parallel hybrids.

In a series hybrid, a combustion engine turns a generator that powers the batteries and/or directly the electric motor. There is no mechanical coupling between the two types of motors. In a parallel hybrid the combustion engine, the electric motor, propels the vehicle or both together, generally the electric motor also work as a generator when not used for traction, to charge the batteries (Fig. 1).

In order to obtain the maximum efficiency of the hybrid vehicle the main control strategy is to select the propulsion force (engine or electric motor) depending on the load. The engine has a low efficiency at low load, for transient regimes and for idling. For the full loads and high speed, the engine has the maximum efficiency. The control strategy for the hybrid vehicle is trying to avoid these regimes by using the control algorithms to manage the energy sources in order to minimize the fuel consumption and the emissions (Ehsani *et al.*, 2004).

Thus, a hybrid vehicle, with a proper control, will consume less fuel (about a half of a classic vehicle with similar engine characteristics). In this case, the vehicle autonomy will be double and the emissions will be lower because of the transients and idling regimes elimination.

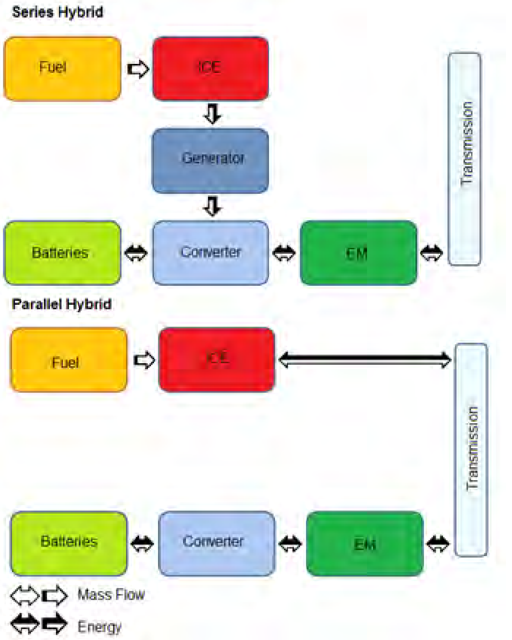

Figure 1. Series and Parallel settings (Souza and Dedini, 2009)

According Serrao and Rizzoni (2008), the hybridization advantages consist essentially in recovering potential and kinetic energy that would otherwise be dissipated in the brakes, and in operating the engine in its highest-efficiency region.

In order to realize the benefits of hybrid electric vehicles, HEV models are used as the first step in the design procedure to study and improve fuel economy, top speed and maximum acceleration. Therefore, accurate and flexible simulation tools, which will expedite the design processes for HEVs, are important. The simulation results will enable engineers to compare relative performances and come up with the better designs. In addition, computer modelling and simulation can be used to reduce the expense and length of design cycle of HEVs by testing configurations and energy management strategies before prototype construction begin.

Powell and Pilutti (1994) have used a combination of several controllers, one for each section of the vehicle, due to the highly non-linear system. The fuel consumption was relatively high. Sacks and Cox (1998) have proposed neuro-adaptive controllers; the major advantages are robustness to different driving and road conditions. Lee *et al.* (2000) have used fuzzy systems, a fuzzy predictive controller with nine rules for converting the driver's commands to appropriate torques and another fuzzy controller with 25 rules.

Ippolito and Siano (2003) have used fuzzy c-means, along with genetic algorithms, for power-flow management in different driving cycles of hybrid vehicles. In their method, there is a need for some off-line training for the controller, but they have achieved relatively low fuel consumption and smooth simulation results.

Interest in simulating hybrid electric vehicles began to increase in the 1970's alongside the development of several prototypes that were used to acquire a large amount of test data on the performance of hybrid drivetrains.

Through a search of the relative papers dealing with computer software simulations for HEVs, we found that these simulation tools had varying capabilities in predicting vehicle performance in one or more areas, such as fuel economy, emissions, acceleration, and grade sustainability. Several computer simulations tools have been developed to predict hybrid drivetrain performance (Cole, 1993) and (Butler, 1997).

In this context, this work focuses the study of the control system in a HEV, so who is the best period of work of electric motors and combustion engines. For this, the control system will use as references the urban cycle, verifying that the controller is able to manage the electric motors and combustion engines for this urban cycle.

2. THE DRIVE CYCLE

A driving cycle represents the way the vehicle is driven during a trip and the road characteristics. In the simplest case, it is defined as a sequence of vehicle speed (and therefore acceleration) and road grade. Together with some vehicle characteristics, this completely defines the road load, i.e., the force that the vehicle needs to exchange with the road during the driving cycle. The road load is, in fact, the sum of several terms:

- inertia, i.e. force needed to accelerate the vehicle;

- grade force, needed to overcome the slope of the road;
- rolling resistance, due to the contact between the tire and road, bearing losses etc.;
- aerodynamic drag.

It is important to point out that each term is a function of both the driving cycle (speed, acceleration, grade) and the vehicle (mass, coefficients of aerodynamic and rolling resistance). For this reason, the fuel consumption of a vehicle must always be specified in reference to a specific driving cycle. On the other hand, given a driving cycle, the absolute value of the road load and also the relative magnitude of its components depend on the vehicle characteristics.

These driving cycles are designed to be representative of urban and extra-urban driving conditions, and reproduce measures of vehicle speed in real roads. Some of them and the test procedures have been recently updated to better suit modern vehicles, following criticism towards the previous regulation (Serrao *et al.*, 2011).

Even with the current improvements, the regulatory cycles should be considered a comparison tool rather than a prediction tool. In fact, it is not possible to predict how a vehicle will be driven, since each vehicle has a different usage pattern and each driver his or her own driving style. In order to obtain more realistic estimations of real-world fuel consumption for a specific vehicle, vehicle manufacturers may develop their own testing cycles.

In the case of hybrid vehicles, estimating the actual driving cycles becomes an even more important task, because the actual fuel consumption is affected by the supervisory control strategy implemented, which is tuned using simulations based on the estimated driving cycles.

3. CONTROL STRATEGY BASED ON RULES

The main aspect involved in rule-based energy management approaches is their effectiveness in real-time supervisory control of power flow in a hybrid drive train. The rules are designed based on heuristics, intuition, human expertise, and even mathematical models and, generally, without a priori knowledge of a predefined driving cycle. These strategies can be classified into deterministic and fuzzy rule-based methods.

The main idea of rule-based strategies is commonly based on the concept of “load-leveling”. The introduction of the load leveling idea for energy management in hybrid vehicles found an infrastructure such that many later approaches were based on Hochgraf *et al.* (1996), Guzzella *et al.* (1995), and Baumann *et al.* (2000). The load-leveling strategy is to shift the actual ICE operating point as close as possible to the optimal point of efficiency, fuel economy, or emissions at a particular engine speed. Generally, the best fuel economy for this system is found at a lower torque and a lower engine speed than the best point of efficiency. This means that better fuel economy will be attained by having smaller accelerator commands (Baumann *et al.*, 2000).

The difference between the driver’s commanded power and the power generated by ICE will be compensated by the EM or used in replenishing the battery based on the measured state of the charge (SOC). Obviously, changing the location of the actual operating point on the efficiency map will require a change of engine speed and engine torque. The engine speed is determined by the actual gear ratio and the vehicle speed. Moreover, the amount of fuel injected into the cylinders, or the torque produced by the ICE, is tuned by the engine control unit.

3.0.1 DETERMINISTIC RULE-BASED METHODS

Heuristics based on analysis of power flow in a hybrid drive train, efficiency/fuel or emission maps of an ICE, and human experiences are utilized to design deterministic rules, generally implemented via lookup tables, to spilt requested power between power converters.

1. Thermostat (on/off) Control Strategy: In this primitive method, the battery SOC is always maintained between its pre-set top and bottom lines by turning ON/OFF the engine. Despite its simplicity, this strategy cannot satisfy power demands by the vehicle at all operating conditions (Ehsani *et al.*, 2004). Nevertheless, for a series hybrid electric city bus commuting in prescheduled routes, the thermostat control strategy is applicable.
2. Power Follower (Baseline) Control Strategy: In this rule-base strategy, the engine is the primary source of power, and the EM is used in producing additional power when needed by the vehicle, while sustaining a charge in the batteries. The rule base is set up based on the following heuristics.
   (a) Below a certain minimum vehicle speed, only the EM is used.
   (b) If the demanded power is greater than the maximum engine power at its operating speed, the motor is used to produce excess power.
   (c) The motor charges the batteries by regenerative braking.
   (d) The engine shuts off when the power demand falls below a limit at the operating speed to prevent inefficient operation of the engine.

(e) If the battery SOC is lower than its minimum allowable value, the engine should provide additional power to replenish the battery via the EM.

This is a popular strategy for energy management in hybrid drivetrains. However, the main disadvantage of this method is that the efficiency of the whole drivetrain is not optimized, and improvement in emissions is not directly taken into account. Nevertheless, the control strategies of the Toyota Prius and Honda Insight are developed based on the power follower approach (Burch *et al.*, 1999).

3. Modified Power Follower (Base Line) Strategy: In order to improve the baseline control strategy, Johnson *et al.* (2000) proposed an adaptive rule-based energy management strategy. The main goal of this approach is to optimize both energy usage and emissions by introduction of a cost function representing overall fuel consumption and emissions at all candidate operating points. The control strategy uses a time-averaged speed to find instantaneous energy use and emission targets. The rule base for the proposed control strategy is as follows.

Step 1 Define the range of candidate operating points (distribution of engine and motor torques) represented by the range of acceptable motor torques for the current torque request.

Step 2 For each candidate operating point, calculate the constituent factors for optimization.
  (a) Calculate the fuel energy that would be consumed by the engine.
  (b) Calculate the effective fuel energy that would be consumed by electromechanical energy conversion for a time interval, e.g., a second.
  (c) Calculate total energy that would be consumed by the vehicle.
  (d) Calculate the emissions that would be produced by the engine.

Step 3 Normalize the constituent factors for each candidate operating point

Step 4 Apply user weighting Kuser to results from Step 3.

Step 5 Apply target performance weighting Ktarge = (max of time averaged vehicle performance)/(target performance) to results from Step 4).

Step 6 Compute overall impact factor, which is a composite of results from Steps 3 to 5, for all candidate operating points, i.e.,

The final operating point is the operating point with the minimum impact factor. Although this strategy has improved the problems associated with the former approach, repeating the above steps for all candidates operating points is not desirable for online implementation.

4. State Machine-Based Strategy: Phillips *et al.* (2000) have utilized a state machine for supervisory control of a parallel HEV. The state machine dictates the operating mode of the vehicle such as ENGINE (engine propelling the vehicle), BOOST (engine and motor, both propelling the vehicle), CHARGING (engine propelling the vehicle and charging the battery), etc. The transition between operating modes is decided based on a change in driver demand, a change in vehicle operating condition, or a system or a subsystem fault. Besides, it was claimed that dynamic control algorithms generate output commands to each subsystem, e.g., desired torque from the engine. Implementation of a vehicle controller through state machines facilitates fault resilient supervisory control of the whole system.

Nevertheless, optimization of the performance objectives such as fuel economy or emissions are not guaranteed. Besides, it is not clear how the proclaimed dynamic controllers are designed. Therefore, from an energy management point of view, this approach has no benefit to conventional deterministic rule-based methods.

4. IMPLEMENTATION

The simulation was carried out in Simulink / Matlab due to ease of deployment of vehicle components.

4.1 LONGITUDINAL DYNAMIC VEHICLE

According to the methodology proposed by Gillespie (1992), to a conventional vehicle powered only by the combustion engine, the traction force required is given by Eq. 1. As electric motors are coupled directly to the rear wheels of the vehicle becomes necessary to know the power demand on the wheels and not the combustion engine to one that is the correct management of the two propulsion sources is conducted.

$$F_x = \frac{T_e N_{tf}}{r} - ((I_e + I_t)N_{tf}^2 + I_d N_f^2 + I_w)\frac{a_x}{r^2} \qquad (1)$$

The torque on the wheel of the vehicle due to the torque of the internal combustion engine is given by 2.

$$T_r = T_e N_{tf} \eta_{tf} \tag{2}$$

Replacing the Eq. 2 in the Eq. 1, obtained the Eq. 3.

$$F_x = \frac{T_r}{r} = ((I_e + I_t)N_{tf}^2 + I_d N_f^2 + I_w)\frac{a_x}{r^2} \tag{3}$$

Equation 4 describes the behavior of the vehicle accelerating on a flat track.

$$T_r = r(D_A + R_x + Ma_x + \frac{((I_e + It)N_{tf}^2 + I_d Nf^2 + I_w)a_x}{r^2}) \tag{4}$$

Because of the MEs of the rear wheels are not coupled to the transmission system, the term refers to efficiency is disregarded in calculating the tensile force required at the wheels, which are considered only after the division of power demand between the combustion engine and the electric motors, applied an efficiency factor for each engine.

After calculation of the required torque (T_r) at the wheels of the vehicle, the management system makes decisions on which system to use to propel the vehicle. The portion of the torque allocated to the internal combustion engine to be divided by the efficiency factor of the transmission system and the transmission ratio as shown in Eq.5.

$$T_{MCI} = \frac{Tr_{MCI}}{\eta_{tf} N_{tf}} \tag{5}$$

where:

- T_{MCI} = Portion of the required torque of MCI [Nm];
- Tr_{MCI} = Portion of the required torque of MCI on the wheel of the vehicle [Nm].

In the case of the portion of torque provided by the MEs wheel is obtained by dividing the required torque on the wheel the efficiency of MEs (N_{ME}) as shown in the Eq. 6.

$$T_{ME} = \frac{Tr_{ME}}{\eta_{ME}} \tag{6}$$

where:

- T_{ME} = Portion of the required torque of MEs [Nm];
- Tr_{ME} = Portion of the required torque of MCI on the wheel of the vehicle [Nm].

The torque required by the management system T_{MCI} and T_{ME} is compared with the torque available on the respective curves as a function of rotation for each engine type in which the available torque at the wheels of the vehicle (T_D) the sum of the torques provided by the MEs and by the MCI as shown in Eq. 7.

$$T_d = Td_{MCI} N_{tf} \eta_{tf} + Td_{ME} \eta_{ME} \tag{7}$$

where:

- Td_{ME} = Torque given by the curve of the ME [Nm];
- Td_{MCI} = Torque given by the curve of the MCI [Nm].

And the available vehicle acceleration (a_d) is given by Eq. 8.

$$T_d = Td_{MCI} N_{tf} \eta_{tf} + Td_{ME} \eta_{ME} \tag{8}$$

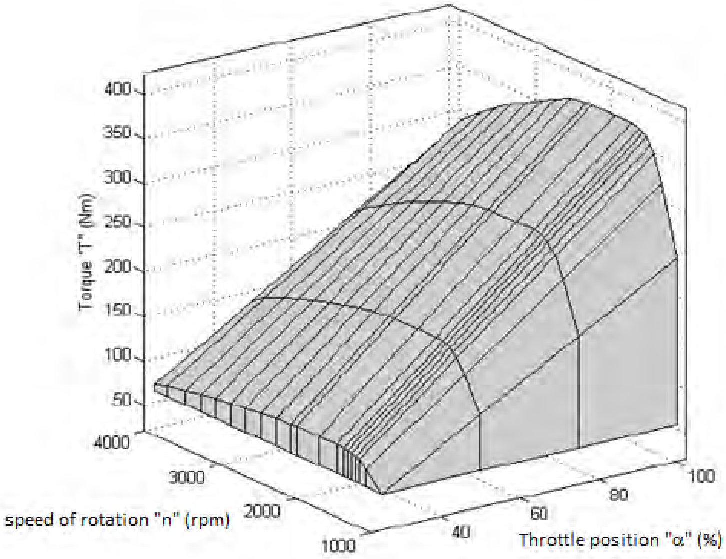

Figure 2. Surface MCI a torque depending on the speed of rotation and position of the throttle

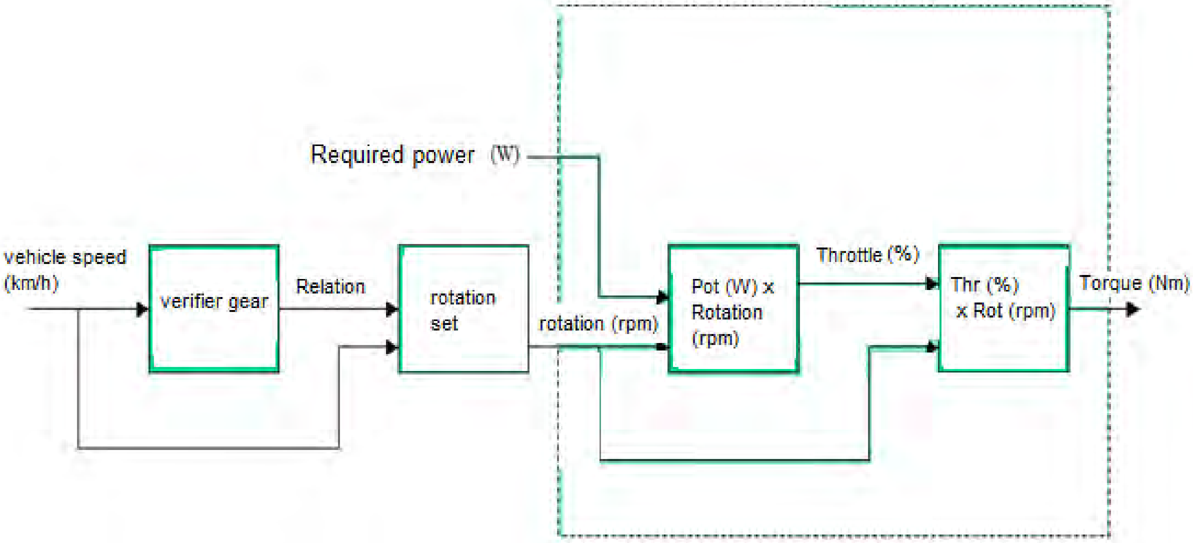

Figure 3. Block diagram representation of the MCI

4.2 COMBUSTION ENGINE

The traction motor on a vehicle is the system responsible for the generation of power through the transmission system originate the driving forces on the driving wheels. For conventional vehicles it is common to find in the literature characterization of MCIs by means of curves of power and torque versus rotation speed as set by Rizoulis *et al.* (2000).

Due to the high complexity of operating a MCI involving control throttle (*throttle*), for example, it was chosen to use a three-dimensional map of the throttle position versus rotational speed versus torque.

The mapping of the graph Fig. 2 was obtained with the rotation speed of the MCI ranging from 1000 to 6400 rpm at intervals of about 200 rpm and the throttle position to an opening from 0 to 100 % in interval of 10%. Thus, for each fixed position of throttle opening sweep up all rotational speeds for which are obtained the torque, the power and the consumption corresponding. These maps are very useful in checking the operation region of the MCI higher performance in VEHs avoiding situations of transitory operation responsible for the poor economy and low emission fuel present in conventional vehicles.

Figure 3 has representation in block diagrams for MCI, where entry P_{MCI} corresponds to the request of the required power by MCI, and the rotation of MCI (W_{MCI}) is calculated using the speed of the vehicle in relation to the gear corresponding. Thus, the block Pot (Watt) x rotation (rpm) determines for each input value P_{MCI} and W_{MCI}, the value of the throttle position which in turn is the input of block Thr (%) x rotation(rpm) which results in the torque output of the MCI, referring to the required power.

4.3 MODEL OF THE ELECTRIC MOTOR

ME was modeled according to the dynamic equations for a DC electric machine with independent field. In this context, the electrical transients are disregarded since they are much faster than the transient mechanical and analysis of this work is done in the context of the latter. Thus, the electrical equations will be considered at system.

Through the Eq. 9, which represents the direct relationship between the armature current and the electrical torque developed by the rotor, and the union of this with the Eq. 10 and Eq. 11 is possible to construct a block diagram equivalent for modeling the ME as represented by the 4.

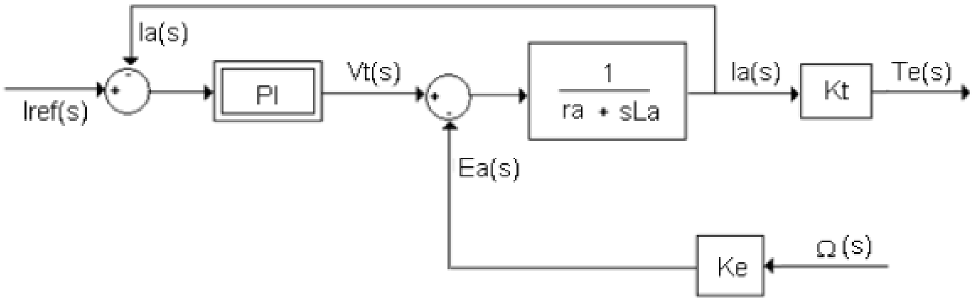

Figure 4. Block diagram of the electrical and dynamic equations for DC motor with independent field.

$$T_{el} = K_T I_a \tag{9}$$

$$I_a(s) = \frac{(V_t(s) - E_a(s))}{(r_a + sL_a)} \tag{10}$$

$$\omega(s) = \frac{(T_{el}(s) - T_{carga}(s))}{(D + sJ)} \tag{11}$$

Based on the study by Waltermann (1996), and as shown in 4, a controller uses proportional and integral (PI) for generating the voltage value of the armature circuit $V_t(s)$ of Eq. 10. The input of this controller is the error obtained from the difference between the current value of the armature current ($I_a(s)$) and its reference value ($I_{ref}(s)$) desired. The current ($I_{ref}(s)$) is defined as the direct demand of the armature current required for the traction motor is able to meet the demand of power required by the driver. This control becomes necessary in the most convenient point for the machine operation, when the $I_a(s)$ is equal to $I_ref(s)$. In this situation, the integrative component of the controller is necessary for the ME error has zero current situations of regime, ie, when $V_t(s)$ is constant.

$$\omega = \frac{(V_{el} N \eta}{r} \tag{12}$$

The torque of ME T_{ME} produced is then used for calculating the longitudinal acceleration and hence the vehicle speed. The vehicle speed and the rotational speed of the traction motor are related by Eq.12. Where: $V_{vel} \cong$ longitudinal velocity of the vehicle. Thus, it was obtained ω calculating *fcem*(back EMF) of the armature circuit.

The ME traction is able to act as a generator during braking the vehicle. In this context, all or a portion limited to the maximum power battery charging, for instant of time, is used to recharge the battery bank. In the model used for the ME, was not considered a maximum value for the armature current, meaning that the ME be able to provide any sign of acceleration or braking torque, that limitation being held by EGP. Another feature of this template is in slight loss coefficient (or drain) by iron and/or copper, for example. That is, the proposed model shows 100% efficiency for electric machine operating as a motor and as a regenerator.

The constants used for solving the ME modeling are:

- $KT = Ke = 1,98$ V.s/rad
- $r_a = 0,082$ ohm
- $L_a = 0,2$ mH

4.4 MODELING BATTERY

The battery used as a source of energy for Parallel HEV is the lead acid type and the model was built for convenience online code. The model inputs are the battery power demand (P_b) of EGP, the depth of discharge (DoD) and the total charge removed (CR_n). DoD and CR_n are fed back to the actual battery model to control the charging and discharging energy at each instant of the simulation. The main output of this model is the power available from battery (Pot) to the traction system. In Fig. 5 illustrated are inputs and outputs of the model proposed battery.

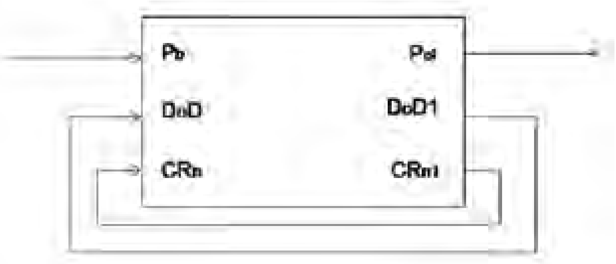

Figure 5. Inputs and Outputs Battery model proposed.

For appropriate execution of the request battery power the vehicle in question, chose to a bench composed of two batteries, each of which provides:

Number of cells, Nocells = 10

Capacity = 32 Ah

Coefficient of Peukert, k = 1,2

4.5 MANAGEMENT STRATEGY BASED POWER RULES

In this strategie, the demand power corresponding to the request of the driver to the vehicle, will be called P_dem, the requested power to MCI (P_MCI), the request to ME (P_ME) and the power requested from the battery is P_b. The rules of EGP are determined in accordance with DoD of battery thus, P_dem and also the required torque (T_{req}) which are identified as inputs, and the P_{MCI}, P_{ME}, T_{brake} are the outputs of the EGP.

In this EGP, the ME operates by providing the requested power value (P_{dem}) and operates at maximum capacity when is necessary (P_{MEmax}) until the maximum DoD (DoD_{max}) is reached. Therefore, when the DoD maximum is reached, the ME acts as a generator, recharging the battery. When P_{dem} exceeds the value of P_{MEmax} and DoD is the maximum (DoD_{max}), the MCI is the source responsible for the supplying of surplus power.

MCI also act alone when P_{dem} is greater than P_{MEmax} and less than 35kW, featuring a region of good efficiency for the operation of the MCI. However, if the value of DoD is below of the maximum limit (DoD_max), the MCI will work together with the ME providing the P_{dem} to VEH. Whenever the MCI is actuated the variable *habilitamci* have value 1. However, if the value of P_{dem} is negative denotes that the value of the required torque (T_{req}) is negative, which indicates a deceleration of the vehicle. During braking, when the ME acts as a generator transforming kinetic energy into electricity, you can store this energy, or power, since the battery find yourself above the maximum limit optimal (DoD_{max}). This EGP operates so during braking:

- If the value of P_{dem} is less than the value of maximum load (P_{carga}), the brakes will assist in providing deceleration torque, and the ME operating as a generator;
- If the value of P_{dem} is greater than the value of maximum load (P_{carga}), the ME operating as a generator, will be solely responsible for braking, in which P_{ME} will equal to $P_{d}em$, and therefore will occur charging batteries.

Thus, the amount of power that the battery bank can absorb the charging process is limited by the maximum power value of charge (P_{carga}) that can be absorbed by simulation time step is that the excess amount must be discarded (P_{perda}). The representation of EGP described with regeneration can be seen in Fig. 6 and in Fig. 7.

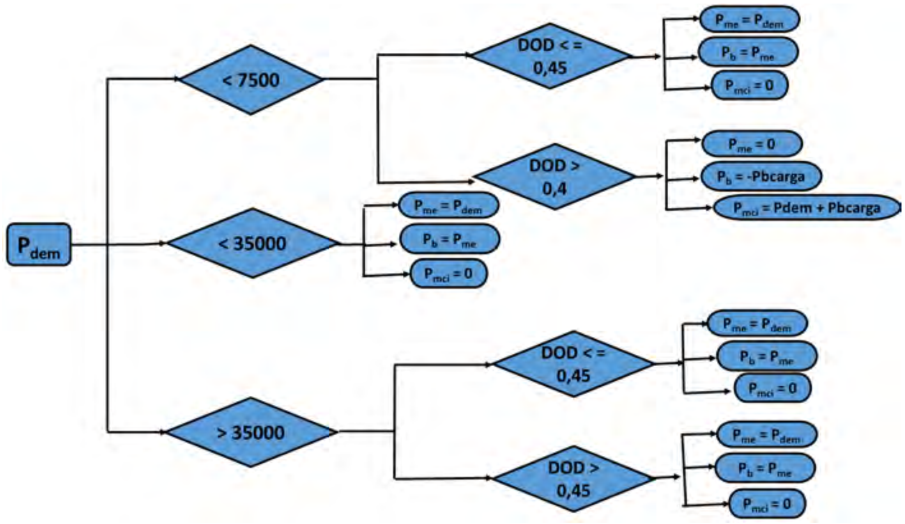

Figure 6. Correlation between the vehicle speed (conventional vehicle) and the urban cycle NBR6601.

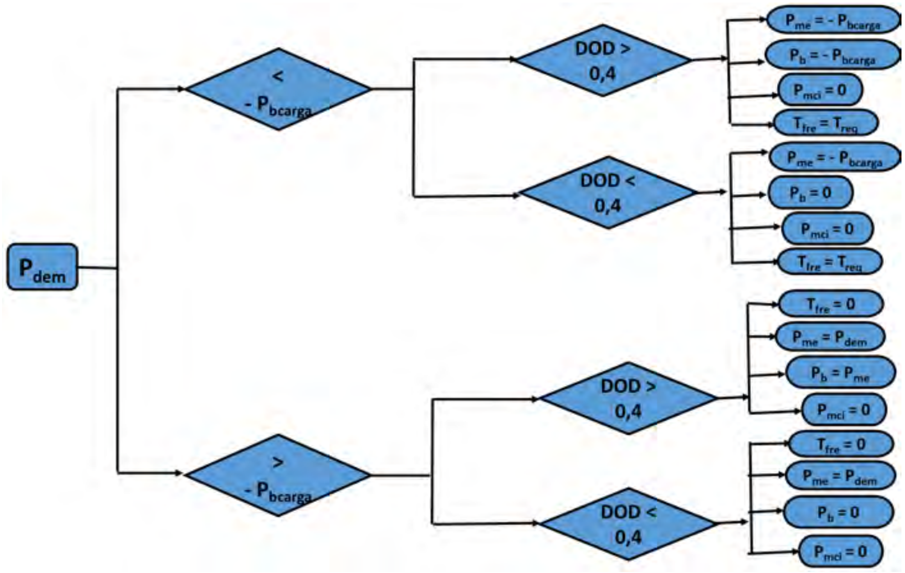

Figure 7. Correlation between the vehicle speed (conventional vehicle) and the urban cycle NBR6601.

5. RESULTS

In this section, the analysis is carried out of the management strategy developed when compared to conventional vehicle. The main analyzes refer to the observance of the behavior of the battery during the driving cycle, fuel consumption and vehicle performance.

The battery behavior is observed through the variable DoD, and this operates between predetermined values ??of loading and unloading (DoD_{max} and DoD_{min}), whose values ??considered seek to expand the life of lead-acid battery.

The fuel consumption is analyzed using an implemented algorithm that performs the estimation by the consumer consumption map, and also by the consumption map dispersion is shown in relation to specific consumption and the rotational torque corresponding MCI.

The performance of the vehicle is checked by the correlation between the driving cycle and test cycle resulting simulation, verifying the capacity of the vehicle to specified conditions in the following imposed cycle.

The EGPs are analyzed by applying the NBR6601 urban driving cycle. Note that all simulations were initiated with the battery initially loaded, in other words, for the DoD initially equal 0, and its maximum and minimum limits were set at 0.4 and 0.45, respectively.

5.1 Conventional vehicle

For comparative purposes analyzed is the first result of the conventional vehicle. According to Fig. 8, the conventional vehicle can follow the urban cycle NBR6601 satisfactorily in which the correlation between the vehicle speed with the speed imposed cycle is 0.99976, which means that MCI could provide alone all the power required to meet the urban cycle.

The amount of fuel used to scroll through the driving cycle has 12 km was 0.6878 l, which corresponds to 17.44 km/l. Figure 9 shows the dispersion of the specific consumption with respect to the rotation torque and the corresponding consumption map MCI. Thus, it can be seen that the consumption map for the conventional vehicle has regions of low efficiency, with the goal of EGP reducing these regions of the map of the graph consumption, which results in fuel economy.

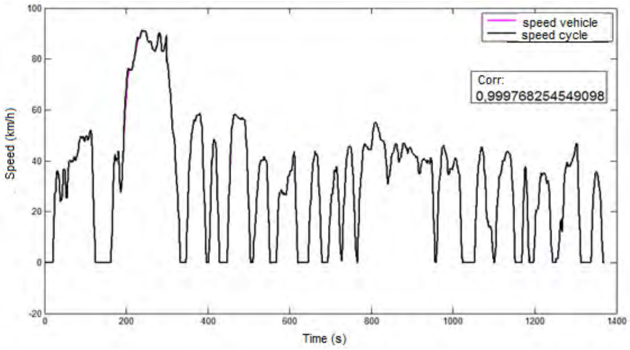

Figure 8. Correlation between the vehicle speed (conventional vehicle) and the urban cycle NBR6601.

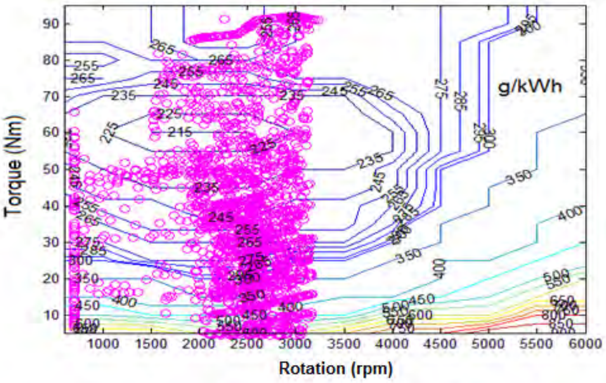

Figure 9. Dispersion of the specific consumption for the conventional vehicle.

5.2 VEH WITH EGP BASED RULES

Using the EGP-based rules, and the ME acting as a principal source of propulsion and rotation MCI limited by changing gears recommended, has the fuel to go through the drive cycle NBR6601 was 0.52 l, which means the VEH did 23.07 km/l. Figure 10 shows the performance of VEH in relation to the cycle followed in which demonstrated a good correlation of velocity profiles (0,999). From Fig. 11 it is possible to observe the dispersion of consumption in specific consumption map, which can be verified that the MCI operates at higher efficiency than the conventional vehicle, a fact that justifies fuel economy.

Already Fig. 12 shows the behavior of the DoD that reaches the maximum discharge in 300 seconds of the driving cycle, and after that oscillates between the maximum and minimum charge and discharge the battery.

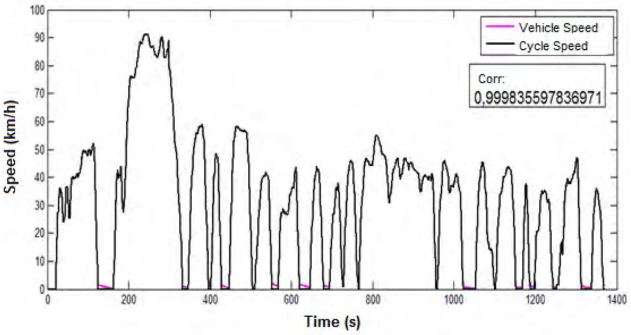

Figure 10. Correlation between the vehicle speed (vehicle with EGP based rules) and the urban cycle NBR6601.

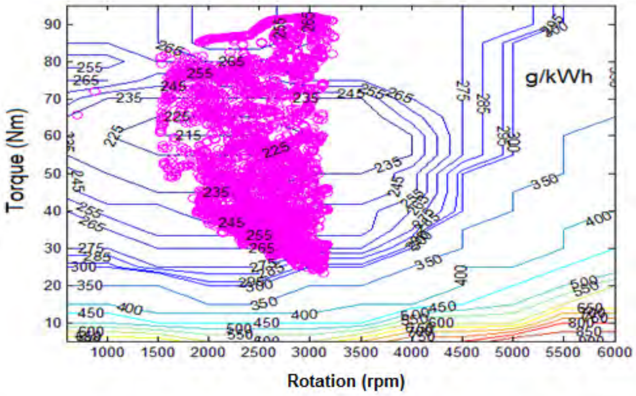

Figure 11. Dispersion of the specific consumption for the vehicle with EGP based rules.

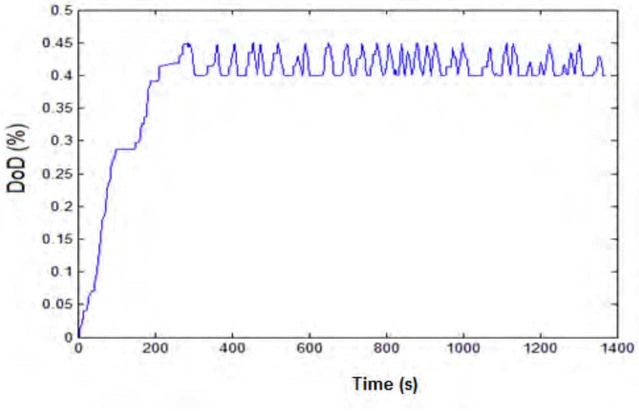

Figure 12. Behavior of the battery during the urban cycle NBR6601.

6. CONCLUSIONS

The power management strategies proposals have been prepared and adjusted by means of a series of preliminary tests on level ground, in order to maintain the battery at every simulation time's with state of charge within predetermined limits.

This work was performed modelling the VEH and one EGP proposed in order to obtain a lower fuel consumption. Through the presented results, we can conclude that with the proposed EGP was possible increased fuel economy when compared to conventional vehicle, because the specific consumption of MCI is in a region of low consumption.

7. REFERENCES

Baumann, B.M., Washington, G., Glenn, B.C. and Rizzoni, G., 2000. "Mechatronic design and control of hybrid electric vehicles". *Mechatronics, IEEE/ASME Transactions on*, Vol. 5, No. 1, pp. 58–72.

Burch, S., Cuddy, M. and Markel, T., 1999. "Advisor 2.1 documentation". *National Renewable Energy Laboratory*.

Butler, K. L., S.K.M.E.M., 1997. "A versatile computer simulation tool for design and analysus of electric and hybrid drive trains". In *SAE Technical Paper*. pp. 19–25.

Cole, G.H., 1993. "Simplev: A simple electric vehicle simulation program version 2.0". In *EG&G Idaho*, Idaho.

Ehsani, M., Gao, Y., Gay, S. and Emadi, A., 2004. "Modern electric, hybrid electric, and fuel cell vehicles: Fundamentals, theory, and design, 2004".

Gillespie, T.D., 1992. *Fundamentals of Vehicle Dynamics*. Society of Automotive Engineers.

Guzzella, L., Amstutz, A. and Grob, F., 1995. "Optimal operation strategies for hybrid powertrains". In *Proc. 1st Int. Federation of Automatic Control Workshop*. pp. 93–98.

Hochgraf, C.G., Ryan, M.J. and Wiegman, H.L., 1996. "Engine control strategy for a series hybrid electric vehicle incorporating load-leveling and computer controlled energy management". *SAE*, Vol. 960230, pp. 11–24.

Ippolito, L., L.V. and Siano, P., 2003. "Extended fuzzy cmeans and genetic algorithms to optimize power flow management in hybrid electric vehicles". In *IEEE Conference on Control Applications*. Vol. 1, pp. 115–119.

Johnson, V.H., Wipke, K.B. and Rausen, D.J., 2000. "Hev control strategy for real-time optimization of fuel economy and emissions". *SAE transactions*, Vol. 109, No. 3, pp. 1677–1690.

Lee, H., Koo, E., Sul, S., Kim, J., Kamiya, M., Ikeda, H., Shinohara, S. and Yoshida, H., 2000. "Torque control strategy for a parallel-hybrid vehicle using fuzzy logic". *Industry Applications Magazine, IEEE*, Vol. 6, No. 6, pp. 33–38.

Phillips, A., Jankovic, M. and Bailey, K., 2000. "Vehicle system controller design for a hybrid electric vehicle". In *Control Applications, 2000. Proceedings of the 2000 IEEE International Conference on*. IEEE, pp. 297–302.

Powell, B.K. and Pilutti, T.E., 1994. "A range extender hybrid electric vehicle dynamic model". In *Decision and Control, Proceedings of the 33rd IEEE Conference on*. Vol. 3, p. 2736 Ű 2741.

Rizoulis, D., Burl, J. and Beard, J., 2000. *Control strategies for a series-parallel hybrid electric vehicle*. Master's thesis, Michigan Technological University.

Sacks, R. and Cox, 1998. "Design of an adaptive control system for a hybrid electric vehicle". In *IEEE SMC Conference*. Vol. 6, pp. 1000–1005.

Serrao, L., Onori, S. and Rizzoni, G., 2011. "A comparative analysis of energy management strategies for hybrid electric vehicles". *Journal of Dynamic Systems, Measurement, and Control*, Vol. 133, p. 031012.

Serrao, L. and Rizzoni, G., 2008. "Optimal control of power split for a hybrid electric refuse vehicle". In *American Control Conference, 2008*. IEEE, pp. 4498–4503.

Waltermann, P., 1996. "Modelling and control of the longitudinal and lateral dynamics of a series hybrid vehicle". In *Control Applications, 1996., Proceedings of the 1996 IEEE International Conference on*. IEEE, pp. 191–198.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.