

A Proposal for the Propulsion System of a Series Hybrid Electric Vehicle

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Abstract- Hybrid Electric Vehicles, HEV, are an attractive opportunity to use new energy sources in road transportation, not only to minimize fuel consumption but also to reduce air pollution.

Efforts are being made to improve the HEV electrical subsystems, such as electric motors, power converters, electronic controllers, energy management units, batteries, and the more important: the system-level integration and optimization. This paper pretends to contribute in the improvement of the hybrid drive-train configuration applying a new motion system, the Joint System, JS.

In this article the authors show the possible application of JS, in a simplified HEV model with series configuration.

An optimized vector control technique is applied to the JS propulsion drive to enhance the HEV performance. The performance of the Series HEV model with JS power-train has been checked by simulation.

I. INTRODUCTION

Hybrid Electric Vehicles, HEV, are offering the best possibility for the use of new energy sources in urban transportation, reducing the overall impact on air pollution while obtaining minimum fuel consumption.

The major challenges for the HEV design are managing multiple energy sources, which is highly dependent on the drive-train configuration and other significant components. Efforts are being made to improve the HEV electrical subsystems, such as electric motors, power converters, electronic controllers, energy management units, batteries, and the more important: the system-level integration and optimization. In this sense, this paper pretends to contribute to the improvement of the hybrid drive-train configuration applying a new motion system developed, the Joint System, JS.

In this paper the authors show the possible application of the particular motion system, the JS, in a simplified HEV model. A special Energy Management Strategy must be applied in order to take into account the operation modes of the JS and the particular constraints linked to the structure and configuration of an HEV.

In the second Section of this paper, a generic HEV with series configuration, is described.

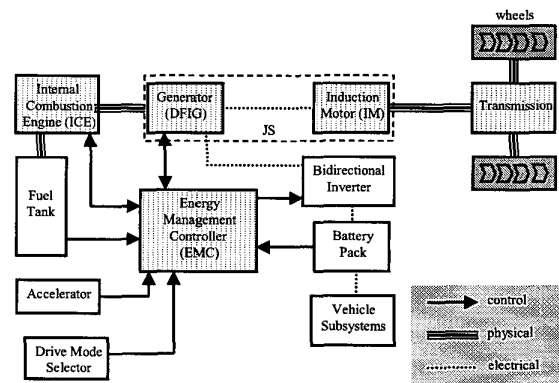


Figure 1: Series HEV System Schematic.

The third Section includes an introduction to the theory and modeling of the JS based in earlier works. In Section IV a vector control technique has been applied to the JS and in Section V optimization of this technique is applied to the JS propulsion drive to enhance the HEV performance. In Section VI the behavior of a Series HEV model with JS power-train has been checked by the simulation with the computer software *ADVISOR2002*[®]. Finally, a brief description of the management of energy flows is established in section VII.

II. HYBRID ELECTRIC VEHICLE

The terminology *Hybrid Vehicle* is generally applied to vehicles that use an internal combustion engine associated to equipment to generate electric energy “on board”. The electric energy is then used to feed a traction electric motor, usually an induction motor, IM, which can operate independently or mechanically associated to the internal combustion engine, ICE, in order to power the wheels of the vehicle [1].

The ICE demonstrates lower specific fuel consumption at only a small region of its ranges of speed and load, and

demonstrates particularly high fuel consumption and high emissions use under transient engine operation.

The IM demonstrates high efficiency over the entire range of its operations, and demonstrates high torque at low speeds.

The HEV combines these features to minimize transient engine operation and to take advantage of the IM suitability to acceleration. For example, one viable solution is the use of an hybridization scheme that decouples the ICE from peak requirements, thus reducing the demands on the engine map.

In a typical series design for an HEV, the ICE mechanical output is first converted into electricity using a generator, commonly a permanent magnet synchronous generator, PMSG.

This integrated subsystem, engine-generator provides the energy to drive the vehicle and to operate on-board accessories. The converted electricity from this subsystem charges the battery and/or can propel the wheels via the IM and mechanical transmission.

A new proposed electric generation scheme consists in replacing the PMSG by a double-fed induction generator, DFIG, like in Fig. 1. With this scheme the DFIG is used as a variable-voltage variable-frequency (VVVF) generator to supply the IM wheels drive with the appropriated power supply. It is possible to consider jointly the DFIG and the IM, giving rise to what we denominate the Joint System, JS.

III. JOINT SYSTEM

The behavior of the JS can be explained as follows: JS is an autonomous motion system that can drive a rotating load with mechanical speed ω_{mM} and torque T_{mM} , delivering an output power P_{mM} to the load.

JS is fed by the prime mover, which can be an ICE or a gas turbine. Prime mover maintains a constant mechanical speed, $\omega_{mG} = K$ where K is chosen to optimize global performance. A bank of batteries is connected to the JS rotor circuit via a bi-directional inverter, delivering slip power P_{rG} , a fraction of total power.

In this system the DFIG is able to operate in two modes delivering leading or lagging stator current to the IM.

Depending on the operating condition, power may flow from the converter to the rotor or in the reverse direction. As the mechanical power delivered from the prime mover is normally larger than the electrical energy required from the converter at the rotor side, the control system has to be rated only for slip power, which is only a fraction of stator power. The resulting reduction in the inverter costs makes this slip recovery system very attractive in all applications where energy saving is an important factor [2].

The JS model is obtained considering the models of the DFIG and the IM, and is represented by a sixth order system of complex ordinary differential equations:

$$M_1 \frac{d}{dt} x = -M_2(\omega)x + v \quad (1)$$

and by two mechanical constrains, these later real:

$$\begin{aligned} \frac{d\omega_G}{dt} &= \frac{1}{J_G} (2M_G \Im m(i_{sG} i_{rG}^*) - T_{Gresist}^c) \\ \frac{d\omega_M}{dt} &= \frac{1}{J_M} (-2M_M^c \Im m(i_{sG} i_{mM}^*) - T_{Mload}) \end{aligned} \quad (2)$$

where

$$M_1 = \begin{pmatrix} L_{GM} & M_G & -M_M^c \\ M_G & L_{rG} & 0 \\ 0 & 0 & L_{rM} \end{pmatrix}$$

$$M_2 = \begin{pmatrix} r_{GM} + j\omega L_{GM} & j\omega M_G & -j\omega M_M^c \\ jg_G \omega M_G & r_{rG} + jg_G \omega L_{rG} & 0 \\ r_{rM} & 0 & r_{rM} + jg_M \omega L_{rM} \end{pmatrix}$$

$$\text{and } x = (i_{sG} \quad i_{rG} \quad i_{mM})^T \quad v = (0 \quad v_{rG} \quad 0)^T$$

State variables i_{sG} and i_{rG} are the stator and rotor currents of the DFIG, and i_{mM} is the magnetizing current of the IM. Control variable v_{rG} is the generator rotor voltage. $T_{Gresist}^c$ is the externally applied mechanical torque from the prime mover, T_{Mload} is the load torque at the IM shaft. (To distinguish among the generator and motor variables, an additional G or M subscript is added).

Its controllability has been also verified and simulation results and experimental validation of the model have been carried out in earlier works [3].

IV. VECTOR CONTROL STRATEGY OF THE JS

In the case of the vector control of the JS, rotor-flux oriented control will be employed. The implementation used to obtain the modulus and space angle of the rotor flux linkage space phasor is the indirect rotor-flux oriented control, where the modulus and space angle of the rotor flux linkage space phasor are obtained by utilizing the monitored stator currents and rotor speed.

From (1) mathematical model of the JS can be represented by a 3-order equation system:

$$\begin{aligned} 0 &= [R_{GM} + L_{GM}(p + j\omega)]i_{sG} + [M_G(p + j\omega)]i_{rG} - [M_M^c(p + j\omega)]i_{mM} \\ v_{rG} &= [M_G(p + jg_G \omega)]i_{sG} + [R_{rG} + L_{rG}(p + jg_G \omega)]i_{rG} \\ 0 &= R_M^c i_{sG} + [R_{rM}^c + M_M^c(p + jg_M \omega)]i_{mM} \end{aligned} \quad (3)$$

Equation system (3) depends on variables i_{rG} , i_{sG} and i_{mM} , rotor current of the DFIG, stator current of the DFIG and magnetizing current of the IM, respectively.

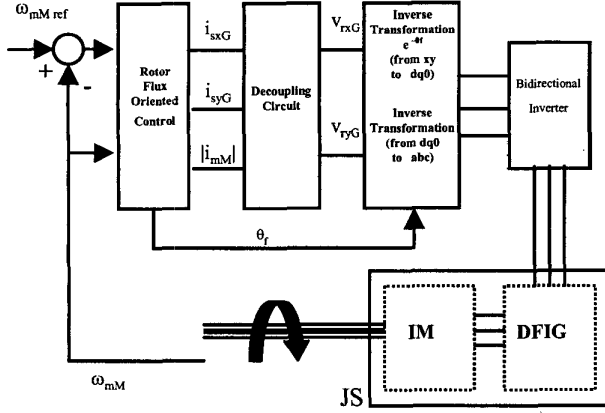


Figure 2: Voltage-source inverter JS drive using rotor-flux-oriented control.

These variables are forward components resulting of application of *Ku Transformation* to the original JS system.

New equations can be obtained in the reference frame fixed to the rotor flux-linkage space vector (that is the same that the rotor magnetizing-current space vector), which rotates at the speed ω_{sM} (defined as the first time derivative of the space angle θ_s , which is the space angle of the rotor magnetizing-current space phasor with respect to the direct axis of the zero reference frame). This quadrature transformation is fundamental for the development of vector control because the objective of field oriented control, FOC, is to establish and maintain an explicit angular relationship between the stator current vector and the rotor flux. This explicit angular relationship may be achieved by regulating the slip of the JS to a particular value which causes the rotor flux vector to become aligned with the *d*-axis component of the stator current vector. Hence, FOC is merely trying to fix the angle $\theta = \theta_s$ between the stator current vector and the rotor flux vector of the JS.

As a result of the special selection of the reference frame, the rotor magnetizing-current space phasor is coaxial with the direct-axis and thus $|i_{mM}| = i_{mxM}$, and $i_{myM} = 0$. Taking into account this conditions and defining motor slip coefficient as $g_M = \omega_{rM} / \omega_s$ and rotor motor time constant as $T_M^c = M_M^c / R_M^c$, three extremely simple equations are obtained which describes the torque control in rotor-flux-oriented reference frame:

$$T_M^c \frac{d\|i_{mM}\|}{dt} + \|i_{mM}\| = -i_{sxG} \quad (4)$$

$$\omega_{rM} = \frac{i_{syG}}{T_M^c \|i_{mM}\|} \quad (5)$$

$$i_{syG} = -\frac{\Gamma_M}{2M_M^c \|i_{mM}\|} \quad (6)$$

It follows that if the parameters of the machines are considered to be constant and $|i_{mM}|$ is constant, then the electromagnetic torque is proportional to the quadrature-axis stator current expressed in the rotor-flux-oriented reference frame and thus the torque will respond instantaneously with i_{syG} .

Fig. 2 shows a simplified scheme for the JS propulsion drive system using rotor-flux-oriented control.

The “rotor-flux-oriented control” block is represented by a cascade control structure: First, the monitored value of the rotor speed ω_{mM} is compared with its reference value $\omega_{mM ref}$ and the resulting error serves as the input of the speed control, which is a PI type controller. The output of this is the reference value of the electromagnetic torque, T_{mM} . Then, to enable field weakening to be performed, the rotor speed ω_{mM} also serves as input of a “Field weakening” block, the output of which is the reference value of the rotor magnetizing current i_{mM} .

The indirect field orientation technique permits that torque can be controlled by regulating i_{sxG} and slip speed ω_{rM} . Rotor magnetizing current can be controlled by regulating i_{syG} .

For the purposes of rotor-flux-oriented control, direct-axis stator current i_{sxG} and quadrature-axis stator current i_{syG} must be independently controlled. However, since the voltage equations are coupled, v_{rxG} and v_{ryG} cannot be considered as decoupled control variables for the rotor flux and electromagnetic torque. The rotor voltage can only be independently controlled if the corresponding equations are decoupled and rotor voltages are indirectly controlled by controlling the stator currents of the JS. The “Decoupling Circuit” block performs that function.

V. JS PROPULSION DRIVE

The electric propulsion system consists of the motor drive, the transmission device, and the wheels. In fact, the motor drive in traditional HEVs comprises the electric motor, the power converter, and the electronic controller.

In the Series HEV, traction motor efficiency is more critical than in other configurations because all the energy of the vehicle is transferred through the motor to the wheels. But, on the other hand, it is important to emphasize that the size of the electric traction drive is minimized in a Series HEV configuration because the electric motor only contributes significant torque and power during transient loading events including periods of major acceleration and deceleration.

In the new Series HEV scheme introduced in this work, the propulsion requirements must be accomplished by the JS propulsion drive using the vector control strategy developed in precedent Section. The design and implementation of the JS drive propulsion control require the definition of a control strategy to meet the principal performance requirement of a vehicle: be able to demonstrate a satisfactory drive range, acceleration and deceleration performance.

Optimization of the Vector Control Technique. Among the different control schemes for the JS, vector control was chosen to validate the behavior of the JS in the Series HEV system.

Vector control seems one of the most efficient solutions for electrical traction because propulsion drive in an HEV needs fast transient response of torque at standstill. It is necessary to control the motor torque at every moment, that implies a working point in each of the four quadrants of the torque-speed plane (even energy recovering while braking).

Vector control techniques may offer wide speed range up to three to four times of base speed, with the advantage that there are several efficiency optimizing schemes of vector controlled IM drives that are able to control the torque component current and field component current hence to minimize the total losses at any loading condition.

In this sense some modifications have been done to the traditional vector control scheme presented in Section IV in order to optimize the performance of the JS propulsion drive. The special features obtained are: the highest possible starting/braking torque to improve the dynamics performance of the JS drive, and the maximum energy efficiency when the JS operates in steady-state. Both features are achieved by optimizing the exciting current controller.

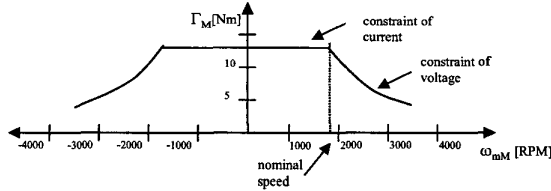


Figure 3. Constrained field weakening region to obtain maximum torque and efficiency.

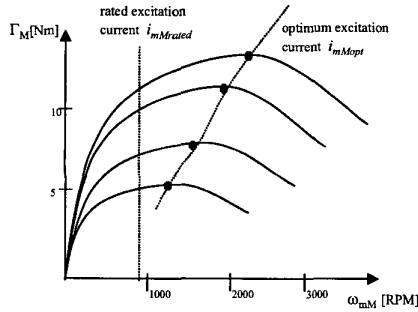


Figure 4. Torque vs. Excitation current.

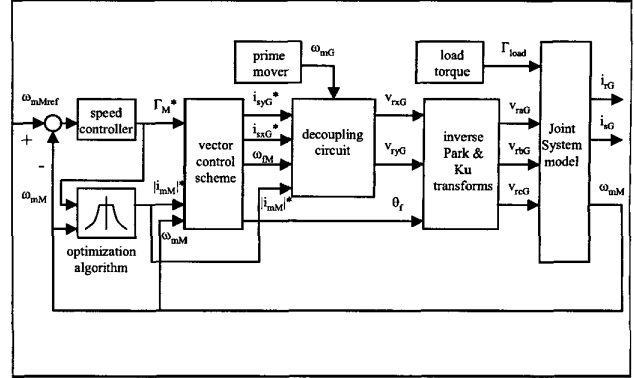


Figure 5. Optimized Vector Control scheme for the JS propulsion drive.

The block that optimizes the exciting current replace the traditional field weakening block. With a traditional Field Weakening block, under peak instantaneous torque demand, properly increasing the rotor flux level to saturation dramatically decrease the torque current since the torque current is much higher than excitation current, so, for the special purpose of a propulsion drive in a vehicle, the better choice is to guarantee a constrained motor operation region taking into account maximum torque and efficiency. Fig. 3 shows the constrained field weakening region.

In vector control strategy can be verified for a given stator current, that the maximum torque is a function of the excitation current i_{mM} . The peak of the torque curve can represent a possible solution of the optimization problem as can be seen in Fig. 4.

The optimization function $OptF(i_{mM})$ must satisfy also the constraint of maximum efficiency. This goal is obtained minimizing the power loss in the motor. Motor loss can be expressed as a function of i_{sxG} and i_{syG} excitation and torque components of the stator currents of the JS,

$$P_{loss\ motor} = P(i_{sxG}, i_{syG}).$$

Taking into account the constraints for the optimization of the maximum stator current, rotor voltage and available torque, a solution can be found for the optimization function $OptF(i_{mM})$. $OptF(i_{mM})$ is implemented in a look-up table through an off-line optimization algorithm.

Finally, vector control equations (5) and (6), can be rewritten as:

$$\omega_{rM} = \frac{i_{syG}}{T_M^c OptF(i_{mM})} \quad (7)$$

$$i_{syG} = -\frac{\Gamma_M}{2M_M^c OptF(i_{mM})} \quad (8)$$

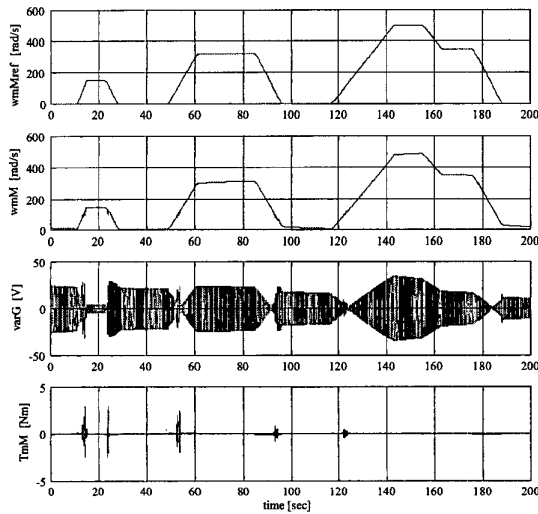


Figure 6. JS dynamics with vector control strategy.

As far as the test of the propulsion drive is concerned, a simulation has been done using the scheme shown in Fig. 5. The control strategy is evaluated using a driving cycle *ECE 15* as speed reference input.

Simulation results are shown in Fig. 6, where speed response ω_{mM} , input voltage v_{raG} and developed torque Γ_M are plotted for a simulation time of 200 seconds. The figure shows that the tested JS propulsion drive is operating at the prescribed speed.

VI. SIMULATION OF A SERIES HEV WITH JS IN THE DRIVETRAIN

A search of the recent literature reveals that a number of computer software simulators are available specifically for HEVs. One of the more prominent tools is *ADVISOR2002*[®], developed by the NREL in 1994. This program is flexible enough to operate in the popular *MATLAB/SIMULINK*[®] programming environment and is used in this work to simulate the behavior of the JS in a Series HEV model. Fig. 7 shows the basic *ADVISOR2002*[®] scheme implemented for the purpose of validate the dynamic behavior of the JS in the power-train of a HEV. The theoretical vehicle used in this work to test the behavior of the JS is a default Series HEV. The vehicle typically operates with an on-board generation system formed by the ICE and the DFIG, which maintains the batteries at an acceptable state of charge, SOC.

Under normal operation, when the ICE/DFIG controller senses a low battery SOC, it executes a start-up procedure for the engine, then maintains the engine speed at the proper level to produce power until the batteries reach a high SOC. It then shuts down the engine and continues to monitor battery SOC.

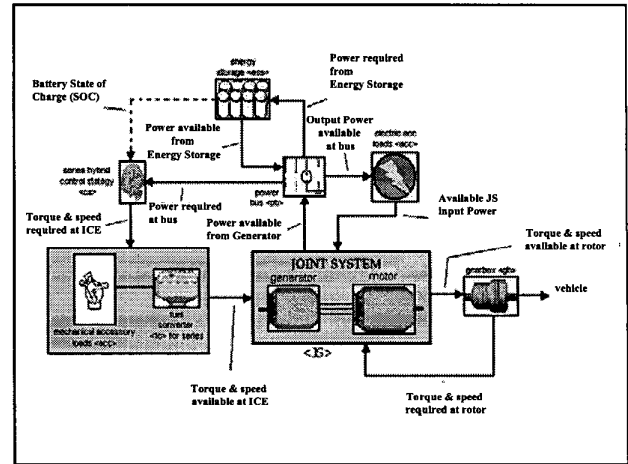


Figure 7. *ADVISOR* scheme with JS.

Next, a brief description of some of the modeled subsystems of the HEV is presented.

Joint System. The JS block translates torque and speed request into electric power requests and convert actual power input to torque and speed output.

RC Battery Model. The Energy Storage System (ESS) block represents the battery pack that stores energy on-board the modeled vehicle. This block accepts the power request and returns available power output from the battery and battery SOC. By convention, positive power is discharge. The RC model uses power as an input and limits the battery operation to the high and low voltage limits.

Series Hybrid Control Strategy. The energy management control strategy described in [5] uses the JS and the ICE (fuel converter) to generate electrical energy for use by the vehicle. The SOC is input into the block, and the required ICE torque and speed are the outputs.

Simulation results. A *CYC_TEST_10sec* driving cycle is used to test the JS performance in a HEV with the *ADVISOR2002*[®] platform. Fig. 8 shows this driving cycle required to the HEV and also shows the effective speed achieved by the vehicle when powered by the JS.

Note the small discrepancy between both curves at the maximum demanded speed. This difference is due to the small rated IM.

VII. SOME BRIEFLY CONSIDERATIONS ABOUT ENERGY MANAGEMENT STRATEGIES IN HEVS

The basic idea of a hybrid vehicle is to decouple the energy generation in the ICE and the energy in the battery, from the energy utilization in the wheels, by an intermediate stage, in our case the JS. The energy contained in the fuel is transformed by the ICE and the DFIG in electric energy, and the conversion process from electric to mechanic energy is performed independently in the IM.

A pack of batteries delivers energy only during the power peaks. The advantages of this generation scheme rely on the reduced size of the batteries and on the constant speed working conditions of the ICE that ensures low gas emission and efficient consumption of fuel.

The rated power of the generating unit in the HEV is predetermined to the estimated required mean power in order to ideally complete a working cycle maintaining the SOC of the battery at a certain level [4].

Fig. 1 also shows that the series hybrid drive train includes an Energy Management Controller, EMC. The EMC in the rotor of the DFIG is becoming the key element for distributing and controlling the electrical energy in energy subsystems, including the battery, for the HEV environment, with the extra advantage that it can be implemented digitally on a low cost processor.

The optimal management of energy flows in a HEV is a difficult task due to the complexity of the system that includes electrical, mechanical, and electrochemical components. EMC adds the capability for all those components to work together in harmony, while at the same time optimizes the operating points of each individual one.

The main objective of the EMC is to satisfy the required power from the propulsion system while keeping fuel consumption and vehicle emissions as low as possible.

The presence of two energy sources and the possibility to recover energy during the braking permits different ways to operate the propulsion system, depending on the flow of energy. The work developed in [5] shows the suitability of rule-based control techniques for the EMC of a Series HEV with a JS power-train.

VIII. CONCLUSIONS

The main objective of this work is to show the use of the specially designed motion system JS in a specific propulsion configuration, such as HEVs, where JS has demonstrated to meet the specific performance requirements.

Vector control has been chosen to validate the behavior of the JS in a Series HEVs simplified model. The control strategy gives rise to an efficient solution for the electrical traction because JS propulsion drive needs fast transient response of torque at standstill.

Modifications have been made to the *ADVISOR2002*[®] code to allow the use of the JS model. Basically the feed-forward model of the JS has been modified to allow its linking with the vehicle model and to integrate vehicle and JS simulations.

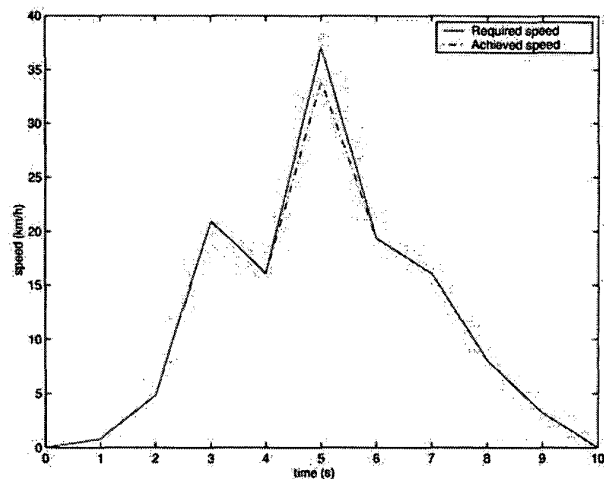


Figure 8. Dynamic performance of the JS with the *CYC_TEST_10sec* driving cycle.

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REFERENCES

- [1] C. Chan. "The state of the art of electric and hybrid vehicles", in *Proceedings of the IEEE*, Vol.90, No.2, pp. 247--275, February 2002.
- [2] Tnani, S., S. Diop, S. Jones, A. Berthon. "Novel Control Strategy of Double-Fed Induction Machines", *Proceedings of EPE'95*, Sevilla, Spain, pp.1553--1558. 1995.
- [3] Caratozzolo, P., Fossas, E., Pedra, J., Riera, J. "Dynamic Modeling of an Isolated Motion System with DFIG", *Proceedings of the CIEP'00*, Acapulco, Mexico, pp. 287--251. 2000.
- [4] Cerruto, E., Consoli, A., Raciti, A., Testa, A. "Fuzzy logic based efficiency improvement of an urban electric vehicle" *Proceedings of 20th IECON '94.*, vol.2, pp. 1304--1309, 1994.
- [5] Caratozzolo, P., Serra, M., Riera, J. "Energy Management Strategies for Hybrid Electric Vehicles", *Proceedings of the IEMDC'03*, Madison, United States, 2003.