Robust and Predictive Energy Management Strategy based on Neuro-Fuzzy Approach for Hydraulic-Electric Hybrid Vehicles

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Projet ADEME « BUSINOVA EVOLUTION»

BUSINOVA Project

BUSINOVA is a tri-hybrid electric bus. It consists of three propulsion elements: Electric Motor/Generator (EM/G); Hydraulic Motor (HM); Internal Combustion Engine (ICE).

Minimize Total Energy Consumption while Guaranteeing the Reliability of the Control

OUTLINE

1. System modelling and Control strategy main objectives
2. Robust Energy Management Strategy based on Battery Fault Management
3. Optimal Energy Management Strategy based on the Prediction of Bus' Future States
4. Architecture validation
5. Conclusion and Future work

1. SYSTEM MODELLING AND CONTROL STRATEGY MAIN OBJECTIVES

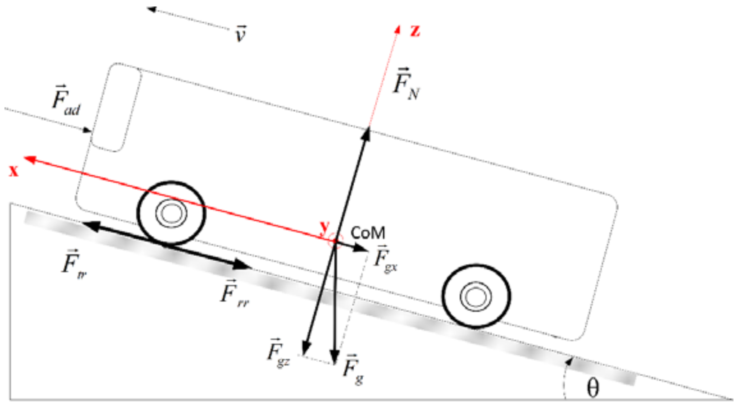
Dynamical model of the bus

$$\vec{F}_{tr} + \vec{F}_{rr} + \vec{F}_{ad} + \vec{F}_{g} + \vec{F}_{br} = (M + M_{eq})\vec{a}$$

With: $\vec{F}_{tr}$ traction force, $\vec{F}_{rr}$ rolling resistance force, $\vec{F}_{ad}$aerodynamic force, $\vec{F}_{g}$ gravity force, $\vec{F}_{br}$ braking force, $\vec{a}$ acceleration, M bus weight and M_{eq} is the equivalent mass given by:

$$M_{eq} = \frac{i_g \eta_{pt} J_{rot}}{r^2}$$

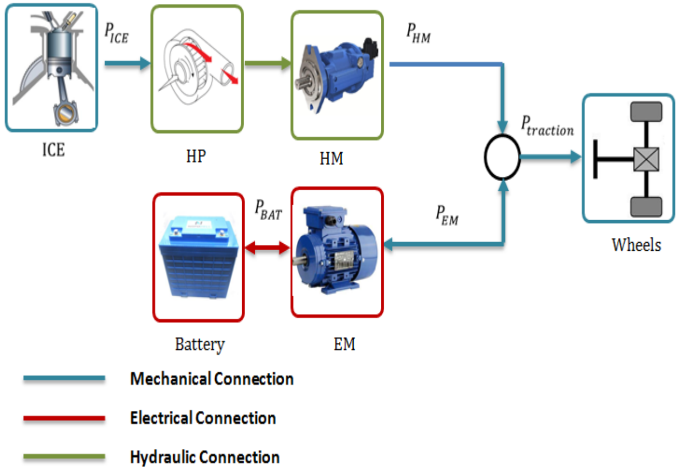
With: i_g gearbox reduction ratio, η_{pt} powertrain efficiency, J_{rot} inertia of the **rotating parts**, r wheels radius.



Distribution of the force components acting on the bus

1. SYSTEM MODELLING AND CONTROL STRATEGY MAIN OBJECTIVES

Hybrid Bus Powertrain Architecture



BUSINOVA powertrain. *HP* – hydraulic pump, P_{ICE}, P_{HM}, P_{BAT}, P_{EM}, $P_{traction}$ respectively ICE, HM, battery, EM, and traction power

BUSINOVA has a parallel-series powertrain configuration. The following main powertrain modes are possible:

- Only EM
- HM via ICE
- EM + HM via ICE
- Regenerative braking (EM as generator)

1. SYSTEM MODELLING AND CONTROL STRATEGY MAIN OBJECTIVES

- **Development of an optimal switching / fusion algorithm dedicated to the control of the propulsion chain**
  - Management of the operating modes of the bus
  - Managing power demand sharing
  - Battery Fault Management
  - Taking into account the intrinsic constraints of the actuators, the constraints of driving and users comfort

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

ISSMBMC (Level 3) Intelligent Supervisory Switching Mode and Battery Management Controller

Manage all of the possible bus operation modes: Compensate the battery faults; Generate the optimal mode and the Healthy SOC set-points for Level 2

IPDOC (Level 2): Intelligent Power Distribution and Optimization Controller based on the neural fuzzy logic

Manage and optimize the power distribution between the two different sources

LFPIDC (Level 1): Local Fuzzy tuning Proportional- Integral-Derivative Controllers

To track the set-points of EM and HM via the ICE

Where:

T_{demand} Torque demand

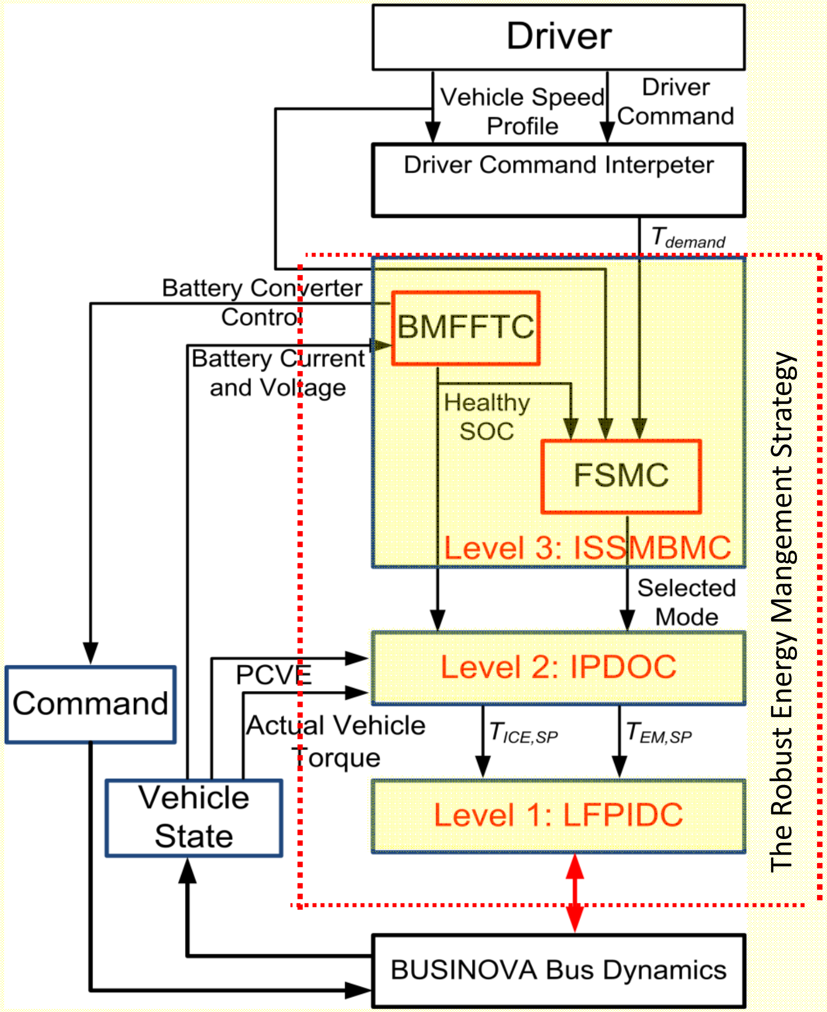
$T_{ICE,SP}$ is the ICE torque set point

$T_{EM,SP}$ is the EM torque set point

BMFFTC Battery Management Fuzzy Fault Tolerant Controller

FSMC Fuzzy Switching Mode Controller

PCVE Produced and Consumed Vehicle Energy



Schematic of the proposed Strategy for BUSINOVA bus

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

ISSMBMC (Level 3): Intelligent Supervisory Switching Mode and Battery Mangament Controller

Level 3 consists of two main blocks

1. BMFFTC (Battery Management Fuzzy Fault Tolerant Controller)

1.1 Fuzzy Observer

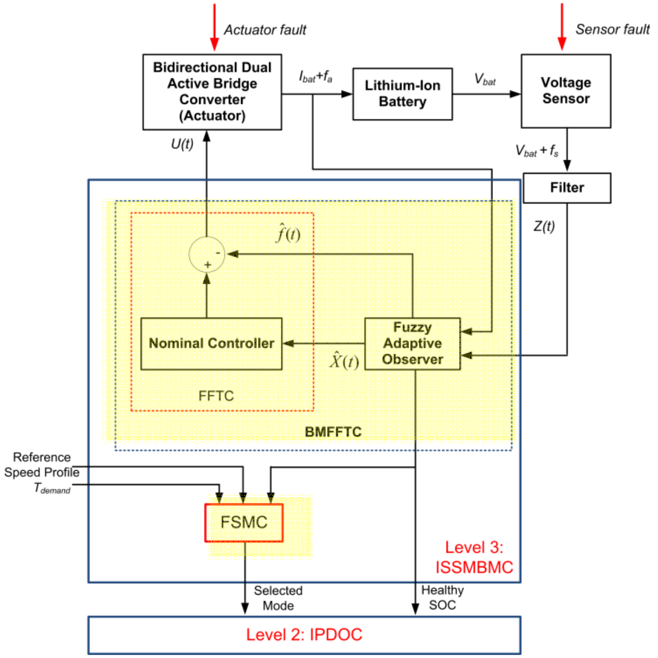
→ Estimate battery states (current, volt and SOC (State Of Charge) and the sensor / actuator faults at the same time

1.2 FFTC (Fuzzy Fault Tolerant Control)

→ Compensate the effect of the sensor/ actuator faults

2. FSMC (Fuzzy Switching Mode Controller)

→ Select all the possible bus operation modes based on fuzzy logic



More details of Level 3

Where:

$Z(t)$ filtered version of the output $V_{bat}(t)$

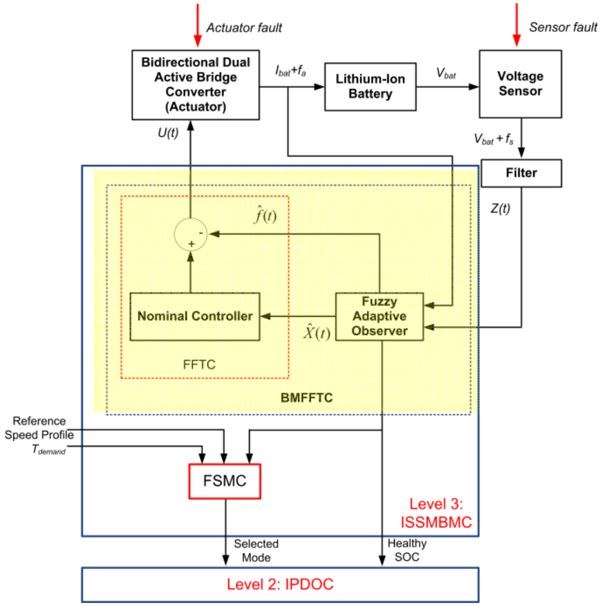
$\hat{X}(t)$ observer state

$\hat{f}(t)$ estimation of the sensor / actuator fault $f(t)$

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

ISSMBMC (Level 3): Intelligent Supervisory Switching Mode and Battery Controller

1. BMFFTC (Battery Management Fuzzy Fault Tolerant Controller)



Takagi-Sugenos Fuzzy Plant Model with Sensor and/or Actuator Faults

$$\dot{x}(t) = \sum_{i=1}^{p} \mu_i(q(t))[A_i x(t) + B_i u(t) + E_{ai} f_a(t)]$$

$$y(t) = \sum_{i=1}^{p} \mu_i(q(t))[C_i x(t) + E_{si} f_s(t)]$$

Where:

$x(t)$ is the state vector, $u(t)$ is the control input vector, $y(t)$ is the output vector

μ_i is the weight (firing strength) of the rules

p is the number of rules of the TS fuzzy model

A_i,B_i and C_i are system input and output matrices, respectively

$q(t)$ are assumed measurable variables and do not depend on the sensor faults the actuator faults

$f_a(t)$ and $f_s(t)$ are actuator and sensor faults vectors

E_{ai} and E_{si} are predefined user matrix

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

ISSMBMC (Level 3): Intelligent Supervisory Switching Mode and Battery Controller

1. BMFFTC (Battery Management Fuzzy Fault Tolerant Controller)

1.1 Fuzzy Observer

$$\dot{\hat{X}}(t) = \sum_{i=1}^{p} \mu_i [\bar{A}_i \hat{X}(t) + \bar{B}_i u(t) + \bar{E}_i \hat{f}(t) + K_i (Y(t) - \hat{Y}(t))]$$

$$\hat{Y}(t) = \sum_{i=1}^{p} \mu_i \bar{C}_i \hat{x}(t)$$

$$\dot{\hat{f}}(t) = \sum_{i=1}^{p} \mu_i L_i (\dot{e}_y(t) + e_y(t)) = \sum_{i=1}^{p} \mu_i L_i \bar{C}_i (\dot{e}_x(t) + e_x(t))$$

$$e_y(t) = Y - \hat{Y} = \bar{C}_i e_x(t)$$

$$e_x(t) = X - \hat{X}$$

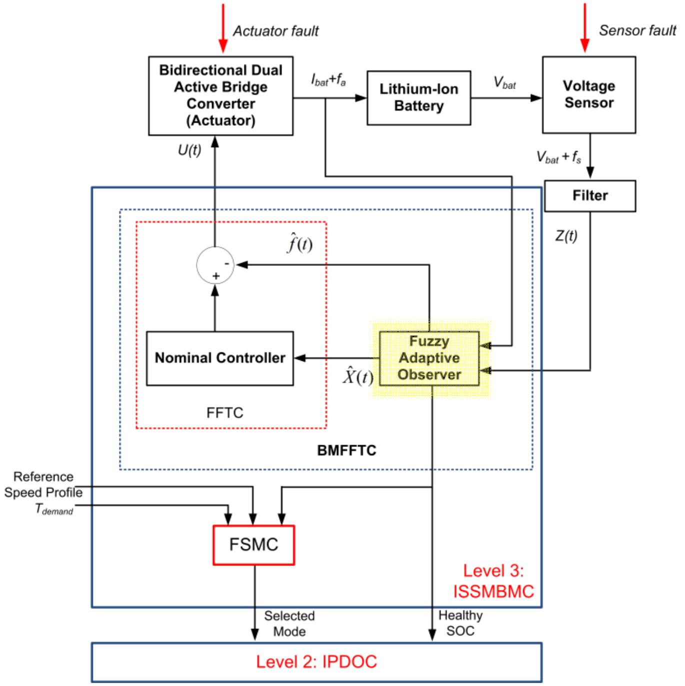
Where:

$\hat{X}(t)$ observer state

$\hat{Y}(t)$ observer output vector

$K_i \; L_i$ observer gains (to be designed)

$\hat{f}(t)$ estimation of the sensor and actuator faults *f(t)*



2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

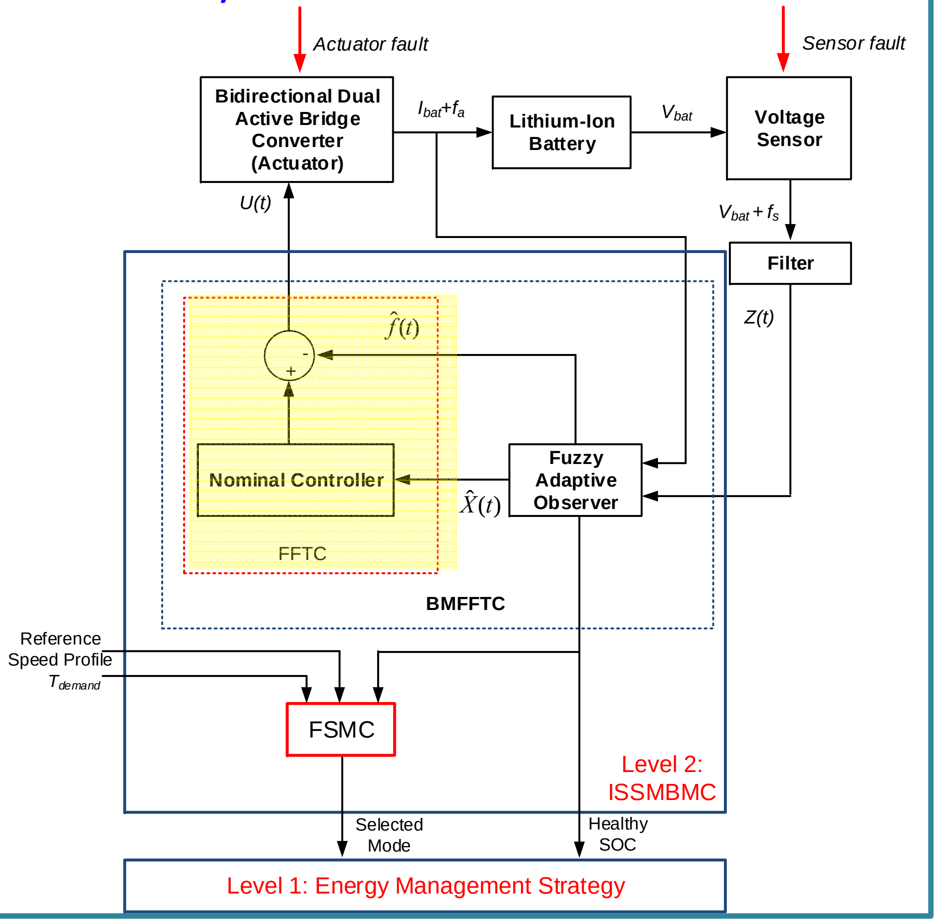
ISSMBMC (Level 3): Intelligent Supervisory Switching Mode and Battery Controller

1. BMFFTC (Battery Management Fuzzy Fault Tolerant Controller)

1.2 Proposed Fuzzy Fault Tolerant Control (FFTC)

$$u(t) = \sum_{i=1}^{p} \mu_j [G_i \hat{X}(t) - \bar{E}_i \hat{f}(t)]$$

Where G_i is the controller gains



2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

ISSMBMC (Level 3): Intelligent Supervisory Switching Mode and Battery Controller

1.3 Controller and Observer gains calculations (G_i, K_i and L_i)

Theorem 1: The TS fuzzy of the battery system is asymptotically stabilizable if there exists symmetric and positive definite matrix P (**P>0**), some matrices G_j, K_i *and* L_i (i=1,2, …,p and j=1,2, …,q), such that the following LMIs are satisfied

$$OA_i^T + A_iO - (B_iW_j)^T - (B_iW_j) < 0$$

$$H_{bi}^T P_2 + P_2 H_{bi} - (D_iC_i)^T - (D_iC_i) < 0$$

Where

$$O = P_1^{-1},\ G_j = W_jO^{-1},\ \bar{K}_i = P_2^{-1}D_i,\ \bar{K}_i = \begin{bmatrix} K_i \\ L_i \end{bmatrix}.$$

A_i is battery system matrix, B_i is the battery system input matrix, K_i and L_i are the observer gains, G_j are the FTC controller gains.

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

ISSMBMC (Level 3): Intelligent Supervisory Switching Mode and Battery Controller

2. Fuzzy Switching Mode Controller (FSMC)

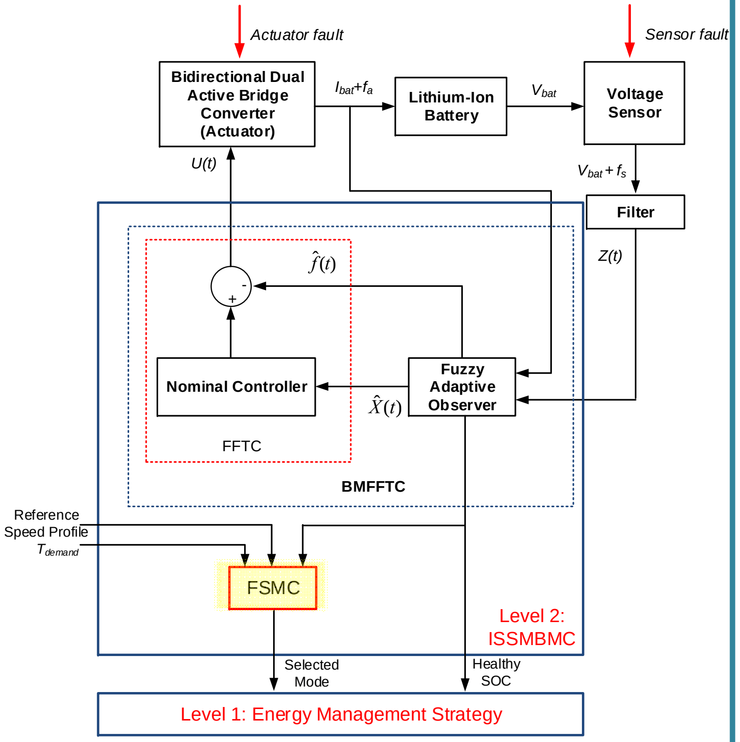
Select operating mode using fuzzy logic

[Kamal et al. IFAC WC 17]*

- Calculation of control signals using the Center of Gravity (CoG) method.

Table1: Some examples of fuzzy rules used by the strategy

Rule number	T_{demand}	SOC	Reference speed profile	Mode of operation
1	Low	High	High	Mode 1
2	High	Low	Low	Mode 2
3	High	medium	High	Mode 3
4	Low	Low	Low	Mode 4
….	…….	…….	……….	………..



*__Elkhatib Kamal__, Lounis Adouane, Nadir Ouddah and Rustem Abdrakhmanov, Hierarchical and Adaptive Neuro-Fuzzy Control for Intelligent Energy Management in Hybrid Electric Vehicles, 20th IFAC World, 9-14 July 2017.

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

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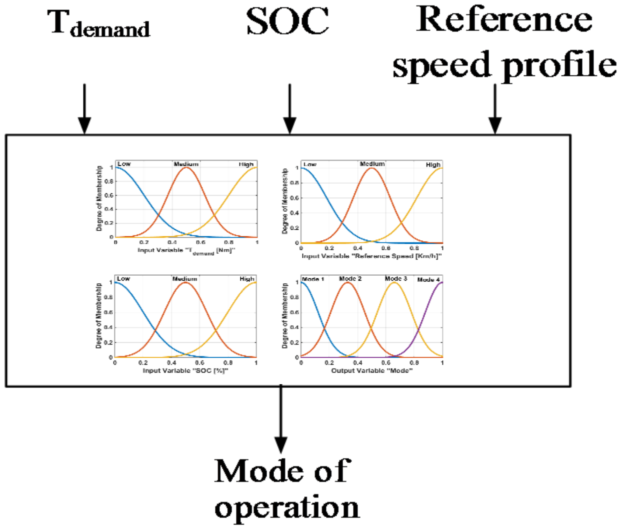


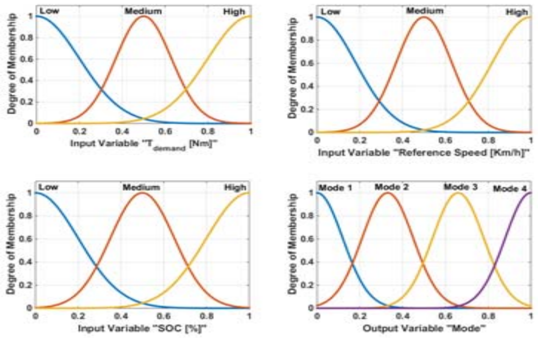
T_{demand}

SOC

Reference speed profile

Mode of operation

Block diagram of the strategy



Input / output variables membership functions

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

IPDOC (Level 2): Intelligent Power Distribution and Optimization

Optimize the energy management

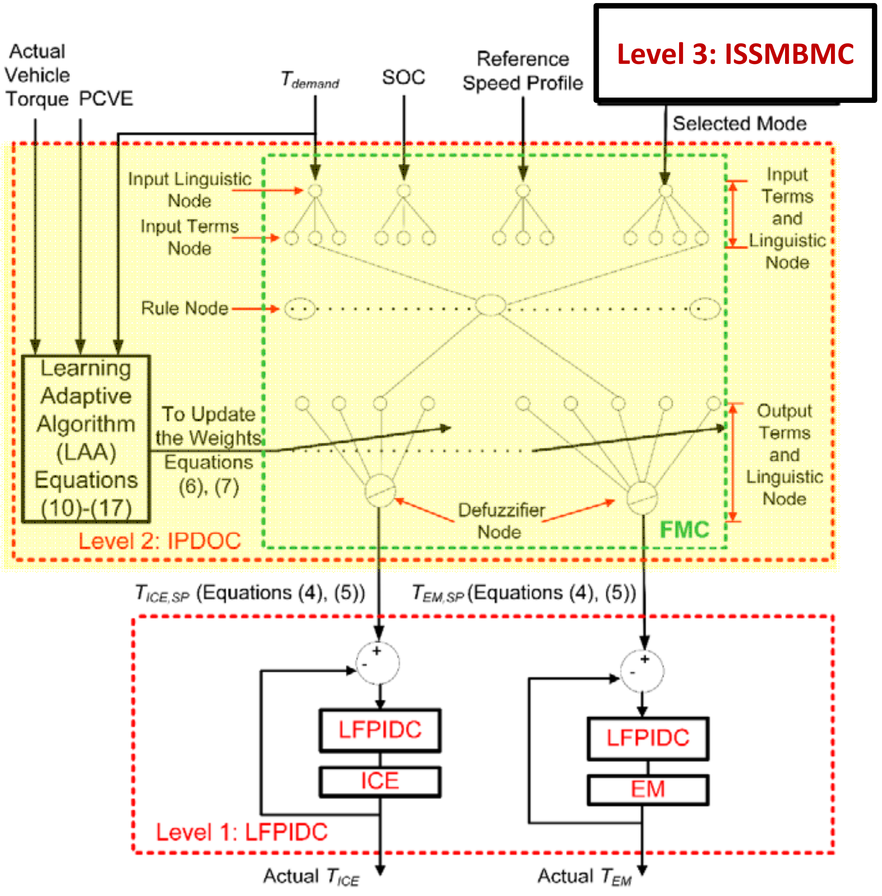
An integrated neuro-fuzzy system is proposed in Level 2 which has the advantages of both: Artificial Neural Network (**ANN**) and **Fuzzy systems**.

- **ANN** are good learning but are generally considered as black boxes
- **Fuzzy system** are:
  - Simple to be implemented in real time
  - Easy to model nonlinearities / uncertainties but as main drawback fuzzy system alone is not adaptive to large modification of the system modelling

Actual Vehicle Torque

Table 2: Some examples of the used fuzzy rules

RN	Mode	T_{demand}	SOC	RS	$T_{EM,SP}$	$T_{ICE,SP}$
1	Mode 1	High	High	High	High	Low
2	Mode 2	High	Low	Low	Low	High
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
27	Mode 3	High	High	High	Medium	Medium



Schematic of the proposed **Level 2**

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

IPDOC (Level 2): Intelligent Power Distribution and Optimization

Proposed Fuzzy management controller inferred T_{ICE} and T_{EM} based on CoG, given by:

$$T_{ICE} = \frac{\sum_{j=1}^{C} m_{ICE,j}\,\sigma_{ICE,j1}\,\sigma_{ICE,j}^{2}}{\sum_{j=1}^{c} m_{ICE,j}\,\sigma_{ICE,j2}} \qquad T_{EM} = \frac{\sum_{j=1}^{c} m_{EM,j}\,\sigma_{EM,j1}\,\sigma_{EM,j}^{2}}{\sum_{j=1}^{c} m_{EM,j}\,\sigma_{EM,j2}}$$

Where: $\sigma_{ICE,j1}$ $\sigma_{ICE,j}$ $\sigma_{ICE,j2}$ $\sigma_{ICE,j}$ are the mean and the standard deviation of the Gaussian Membership Function (GMF) of the output variable for the ICE and the EM, respectively

$m_{ICE,j}$ $m_{EM,j}$ are the inferred weights of the jth and ith output membership function for the ICE and the EM, respectively; C is the number of fuzzy rules.

Average objective function is given by

$$E^k = \frac{1}{2}\sum_{j=1}^{N}(y_j^k - \hat{y}_j^k)^2$$

Where: y_j and $\hat{y}$ are the jth calculated output and desired output, respectively, *N* is the number of training iterations.

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

IPDOC (Level 2): Intelligent Power Distribution and Optimization

Theorem 2: Fuzzy control outputs are optimized by the proposed LAA (Learning Adaptive Algo.), if the mean and the standard deviation of the GMF satisfy the following:

$$\sigma_{ij1}^{k+1} = \sigma_{ij1}^{k} - \zeta^{k} \sum_{k=t+1}^{t+s} \sum_{j=1}^{N} \left(e_{ed}^{k} \mu_{td,ij} + e_{eff}^{k} \mu_{eff,ij} \right)$$

$$\sigma_{ij2}^{k+1} = \sigma_{ij2}^{k} - \zeta^{k} \sum_{k=t+1}^{t+s} \sum_{j=1}^{N} \left(e_{ed}^{k} \mu_{td,ij} + e_{eff}^{k} \mu_{eff,ij} \right)$$

Where:

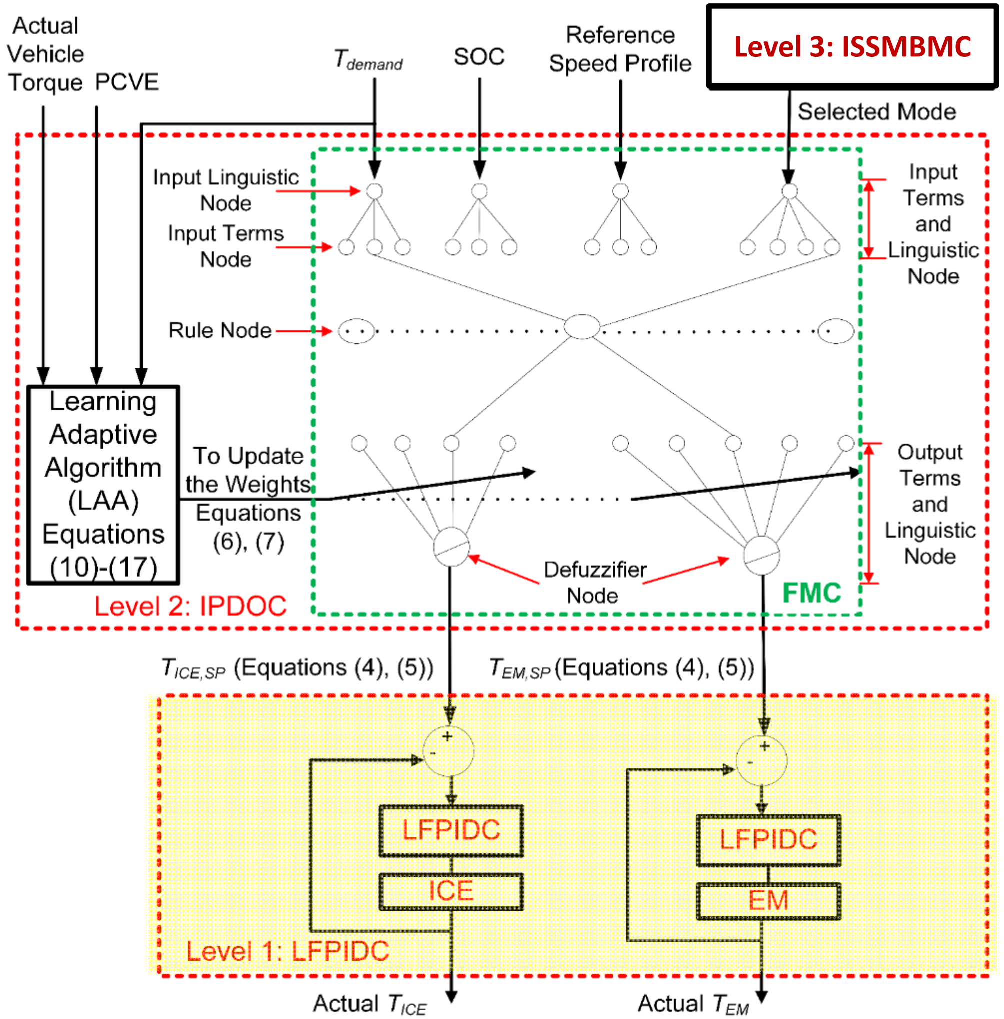
e_{ed} and e_{eff} are the error functions for the **torque demand** and the **vehicle total efficiency**

$\mu_{td,ij}$ $\mu_{eff,ij}$ are the weights of the ith rule for the jth training pattern

ξ is the learningrate

2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

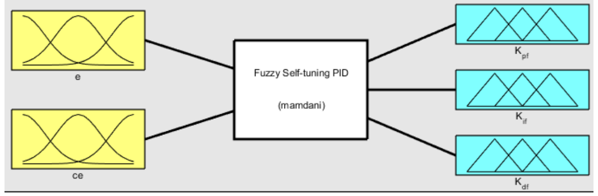
LFPIDC (Level 1): Local Fuzzy tuning Proportional- Integral-Derivative Controllers



2. ROBUST ENERGY MANAGEMENT STRATEGY BASED ON BATTERY FAULT MANAGEMENT

LFPIDC (Level 1): Local Fuzzy tuning Proportional- Integral-Derivative Controllers

To track the set-points of EM and HM via the ICE generated at the second level



- Compared to the works done on fuzzy PID controllers given in [1], the proposed LFPIDC gives better performance for special processes (nonlinear, highly uncertainties and unsteady behavior).
- This level (LFPIDC) corresponds to an adaptive PID controller, based on fuzzy logic inference system to compute its parameters.

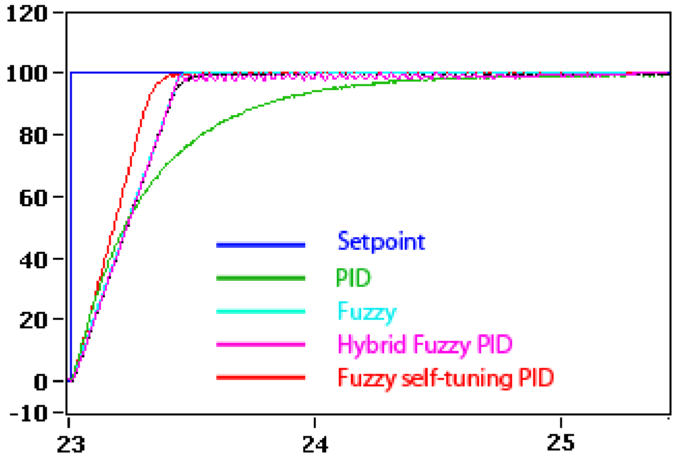


Fig. 7

Controller	% Overshoot	Rise time (s)	Time delay (s)	Settling Time (s)
PID	0	0.675	0.25	2.15
Fuzzy	0	0.325	0.25	0.5
Hybrid Fuzzy PID	0	0.325	0.25	2.6
Fuzzy Selftuning PID	0	0.25	0.2	0.525

[1], J.-X. Xu, C.-C. Hang, C. Liu, Parallel structure and tuning of a fuzzy PID controller, Automatica 36 (2000).

3. Optimal Energy Management Strategy based on the Prediction of Bus' Future States

Prediction Strategy (Level 3): based on ANFIS (Adaptive Neuro Fuzzy Inference System)

To predict SOC of the battery for the whole Driving ($\hat{SOC}_{pred}$) and the power consumption of the vehicle over a given prediction time horizon ($\hat{P}_{hev}$). The prediction optimal efficiencies of EM and ICE are predicted ($\hat{\eta}_{EM,opt}$ and $\hat{\eta}_{ICE,opt}$).

Optimal Energy Management Strategy (Level 2):

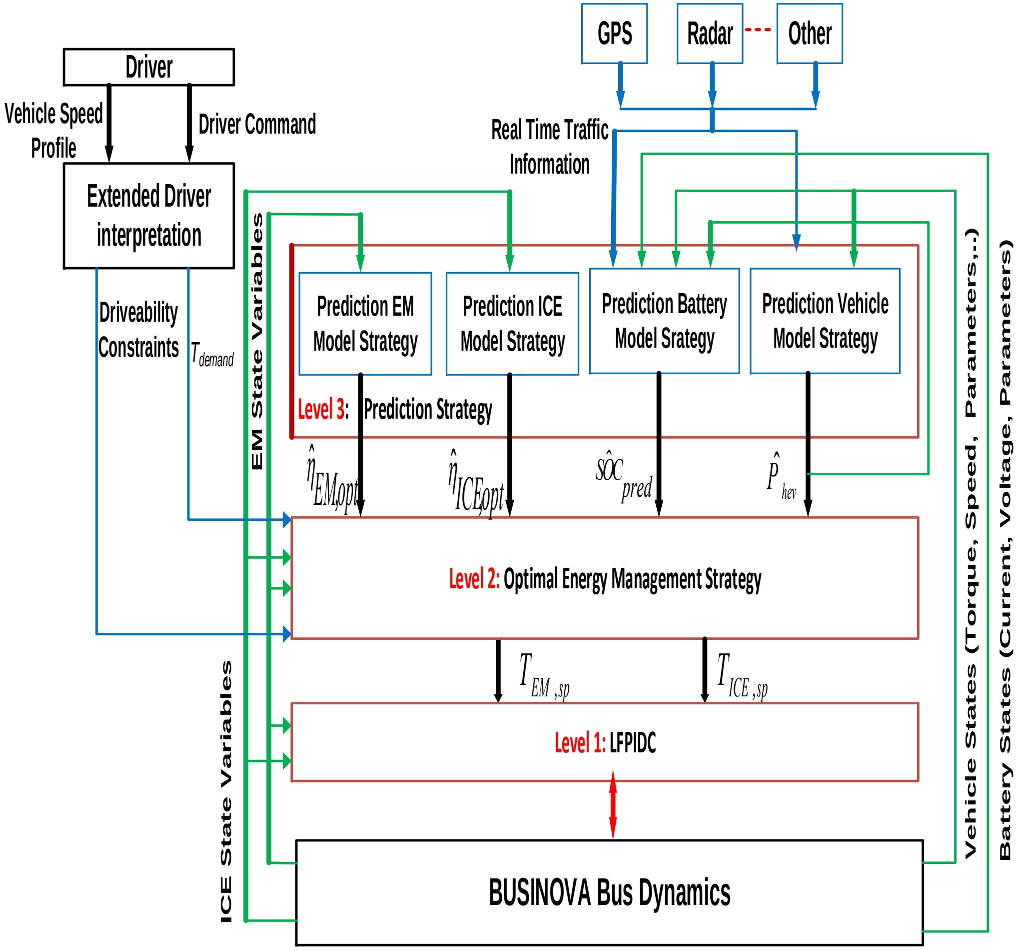
Manage and optimize the power distribution between the two different sources based on new proposed formula.

LFPIDC (Level 1): To track the set-points of EM and HM via the ICE generated at the second level

T_{demand} Torque demand

$T_{ICE,SP}$ is the ICE torque set point

$T_{EM,SP}$ is the EM torque set point



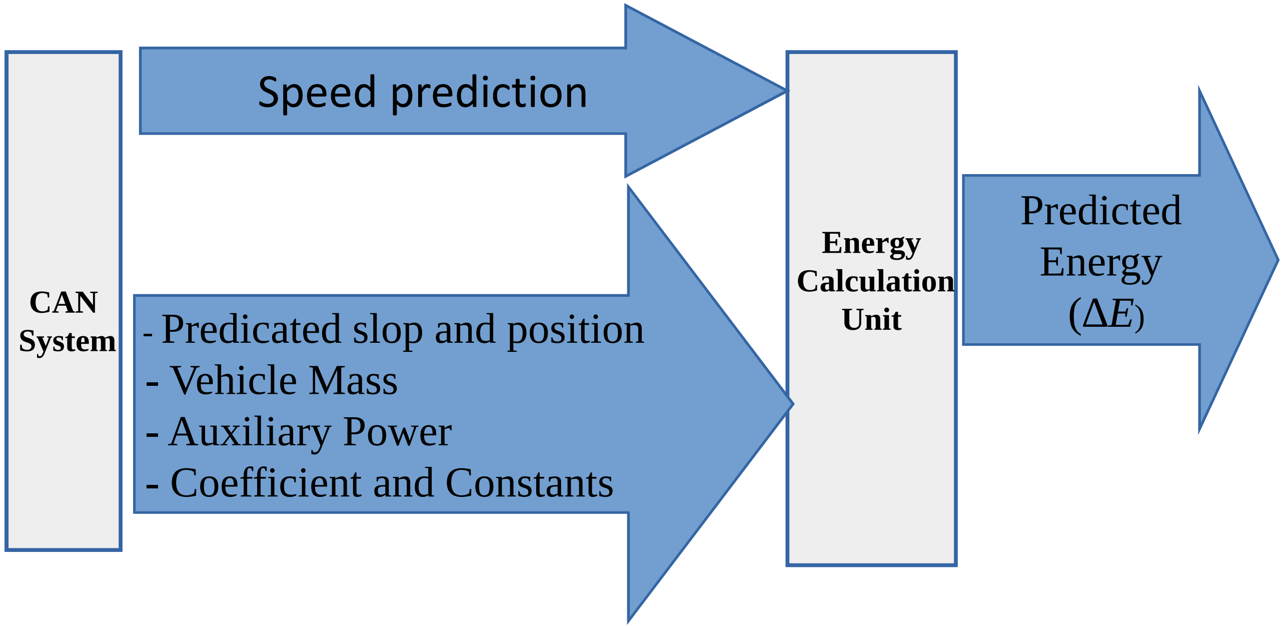
Schematic of the proposed Strategy for BUSINOVA bus.

3. OPTIMAL ENERGY MANAGEMENT STRATEGY BASED ON THE PREDICTION OF BUS' FUTURE STATES

Prediction Strategy (Level 3): Predicted Energy calculation unit

- This unit is used to calculate the energy exchange in the vehicle according to following equation.
- Δ*E* is the amount of energy needed to propel the vehicle at the predicted speed for a given distance around the working day.
- A negative *E* corresponds to where the vehicle is expected to regenerate energy. This energy change is calculated for all prediction samples.
- The calculations include changes in potential energy, air drag, friction and auxiliaries.

$$\Delta E(k) = (mg\Delta h(k).\sin(\theta(k)) - \frac{\rho.v_{mAvg}^{2} C_d A}{2}.\Delta x(k) - mgC_{rr}\cos(\theta(k)).\Delta x(k) - E_{auxilaries}(k))d_{ij}$$



CAN System

Speed prediction

- Predicated slop and position
- Vehicle Mass
- Auxiliary Power
- Coefficient and Constants

Energy Calculation Unit

Predicted Energy (ΔE)

3. OPTIMAL ENERGY MANAGEMENT STRATEGY BASED ON THE PREDICTION OF BUS' FUTURE STATES

Prediction Strategy (Level 3): Predicted Energy calculation unit

$$\Delta E(k) = (mg\Delta h(k).\sin(\theta(k)) - \frac{\rho.v^2 C_d A}{2}.\Delta x(k) - mgC_{rr}\cos(\theta(k)).\Delta x(k) - E_{auxilaries}(k))d_{ij}$$

- *k*: index of predicted samples
- *g:* gravitational acceleration
- *A*: area of vehicle front side

m: vehicle mass

C_d *:* rolling resistance

v : speed prediction

- $C_{rr:}$ Rolling friction coefficient
- *Δh(k)* : Height between each predicted sample
- *Δx(k)* : Distance between each predicted sample
- θ *(k)* : Road slope between each predicted sample
- $\Delta E_{auxiliaries}$ *(k)* : Auxiliary energy demand in the vehicle between each prediction sample
- d_{ij} :Distance driven from point *i* to point *j* [km]
- *ΔE* is the amount of energy needed to propel the vehicle at the predicted speed for a given distance.

3. OPTIMAL ENERGY MANAGEMENT STRATEGY BASED ON THE PREDICTION OF BUS' FUTURE STATES

Prediction Strategy (Level 3): Predicted SOC calculation unit

Regenerative mode

$$SOC_{Reg\_mode}(k) = SOC_{Reg\_mode}(k-1) + \frac{\Delta E(k)}{E_{battery}} . \eta_{whl/bat} . ratio_{sample}$$

k: Index of samples

$\eta_{whl/bat}$: Efficiency of the conversion of energy from wheel to battery

ΔE : Energy change between two prediction samples

$\Delta E_{battery}$: Total capacity of the battery

ratio sample : Ratio of how far the vehicle has passed between two samples.

Pure electric accelerations mode

$$SOC_{EM\_acc} = \frac{\frac{1}{2} m.v^2}{E_{battery}} . \frac{1}{\eta_{whl/bat}}$$

m : The bus mass v : The actual bus speed prediction $\eta_{whl/bat}$: Efficiency of the conversion of energy from the battery to the wheels.

SOC_{EM_acc} : Variation in SOC due to changes in kinetic energy in pure electric mode.

3. OPTIMAL ENERGY MANAGEMENT STRATEGY BASED ON THE PREDICTION OF BUS' FUTURE STATES

Optimal Energy Management Strategy (Level 2):

Theorem: Based on the predicted battery SOC, the power consumption of the vehicle for the whole driving day and the current optimal efficiency of the ICE and EM, the torque split between the ICE and the EM is obtained as following.

$$T_{EM,sp} = \left(\frac{\alpha\hat{\eta}_{EM,opt}}{\alpha\hat{\eta}_{ICE,opt}+\hat{\eta}_{EM,opt}}\right)T_{demand} - \frac{\hat{\eta}_{EM,opt}\hat{\eta}_{ICE,opt}}{\alpha\hat{\eta}_{ICE,opt}+\hat{\eta}_{EM,opt}}\left(\frac{\alpha\hat{P}_{hev}}{\beta\omega}\right)^{1/2}$$

$$T_{ICE,sp} = T_{demand} - T_{EM,sp}$$

Where:

$\hat{\eta}_{EM,opt}$, $\hat{\eta}_{ICE,opt}$ current optimal predictive efficiency for EM and ICE.

α the weight which depend on the current SOC value and the predicted SOC value at the end of the day

$\hat{P}_{hev}$ the current predictive power of the vehicle

T_{demand} (Torque demand) which is required to drive the vehicle and is defined by the global torque set point

ω the speed of the ICE or EM

$\beta = 0.0001$ is constant

3. Optimal Energy Management Strategy based on the Prediction of Bus' Future States

Optimal Energy Management Strategy (Level 2):

Proof. The proof can be given as the following. The overall optimization algorithm consists to maximize the efficiency of the hybrid vehicle which is given by,

$$\eta_{hev} = \frac{P_{hev}}{P_{ICE} + \alpha P_{EM}}$$

Where

The consumed EM and ICE power (P_{EM}, P_{ICE}) are given by,

$$P_{EM} = \alpha P_{elec} = I_{bat} V_{bat} \quad ; \quad P_{ICE} = Q\dot{m}_f$$

Where P_{elec} is battery power I_{bat}, V_{bat} are battery current and voltage

$\dot{m}_f$ Is the fuel flow rate, the lower heating value of the fuel (Q = 43MJ/kg)).

$$\alpha = k\tanh(dSOC + b) - k\tanh(d\hat{SOC}_{pred} + b)$$

$$d = \frac{-\pi}{0.5236}(SOC_{\max} - SOC_{\min}), \qquad b = \frac{-\pi}{0.5236} - SOC_{\min}, \qquad k = \frac{k_p}{d}\cos(d\hat{SOC}_{pred} + b)^2$$

$$k_p = \frac{k_{p,\max} - k_{p,\min}}{15} abs(\hat{SOC}_{pred} - SOC) + k_{p,\min}$$

k_p the controller gains

3. OPTIMAL ENERGY MANAGEMENT STRATEGY BASED ON THE PREDICTION OF BUS' FUTURE STATES

Optimal Energy Management Strategy (Level 2):

If the efficiency of the EM and ICE are given by

$$\eta_{EM} = \frac{T_{EM}\omega_{EM}}{I_{bat}V_{bat}} \quad ; \quad \eta_{ICE} = \frac{T_{ICE}\omega_{ICE}}{Q\dot{m}_f}$$

Where ω_{ICE}, ω_{EM} is the speed of the ICE and EM

The overall efficiency of the hybrid vehicle is given by

$$\eta_{hev} = \frac{P_{hev}}{\frac{T_{ICE}\omega_{ICE}}{\eta_{ICE}} + \alpha\frac{T_{EM}\omega_{EM}}{\eta_{EM}}}$$

Considering that,

$$\eta_{ICE} = \hat{\eta}_{ICE,opt} = C_1 \quad ; \quad \eta_{EM} = \hat{\eta}_{EM,opt} = C_2$$

$$T_{ICE,sp} = XC_1 \quad ; \quad T_{EM,sp} = YC_2$$

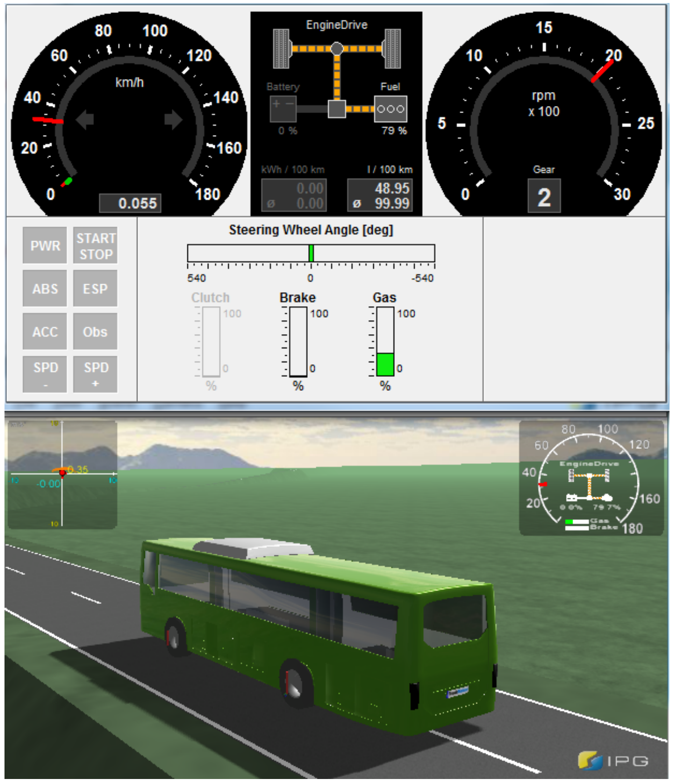
The objective is thus to define how to find X and Y to maximize (optimization) the overall efficiency of the by studied HHEV?

4. SIMULATION AND VALIDATION BASED ON IPG TRUCKMAKER SOFTWARE

High fidelity simulation test design on TruckMaker software

TruckMaker software main features:

- Precise simulation of heavy vehicles and their actual operating conditions,
- Customizable model and powertrain configurations,
- Easy Graphical User Interface (GUI) for model parameters tuning,
- Easy evaluation of power consumption, emissions, and vehicle drivability,
- Simulation of a single component and/or component in the loop,
- Software in the loop, and hardware in the loop validation tests.



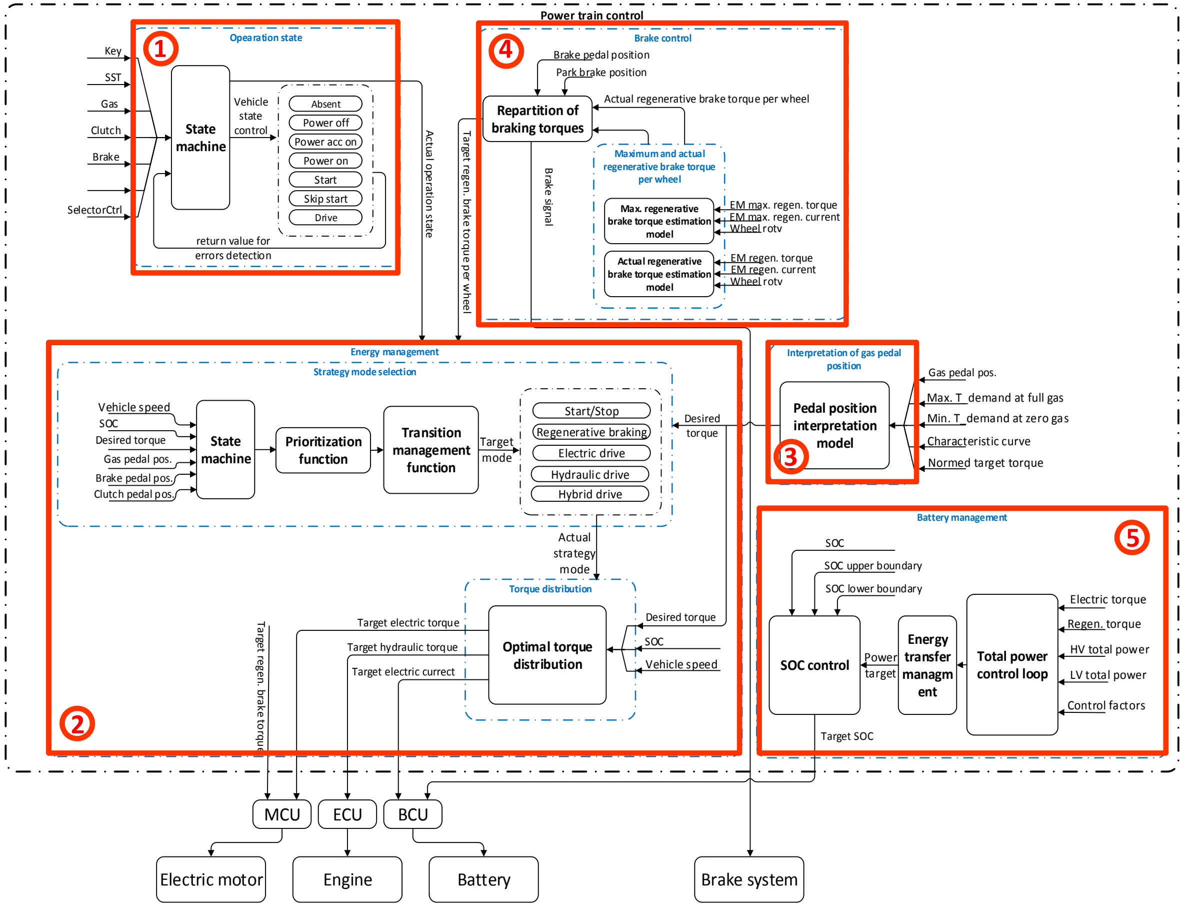
4. SIMULATION AND VALIDATION BASED ON IPG TRUCKMAKER SOFTWARE

High fidelity simulation test design on TruckMaker software

Simulation tool developed under TruckMaker software:

1. Implementation of the drivetrain control functions in C code,

2. Building multiple test scenarios for different operating conditions of the bus (road types, driving cycle, mass of the bus).



4. SIMULATION AND VALIDATION BASED ON IPG TRUCKMAKER SOFTWARE

High fidelity simulation test design on TruckMaker software

Simulation tool developed under TruckMaker software:

- Vehicle operation state management **(block n° 1)**
  - Estimation of the curent operating state
  - transition between the operation states (by executing startup sequences of each state) in order to reach a desired operation state

- Energy management **(block n° 2)**
  - Determination of the current strategy mode of the drivetrain
  - Spliting the torque demand up between the motors

- Interpretation of the gas pedal position **(block n° 3)**
  - Reading in the current gas pedal position and translating it into a desired torque

4. SIMULATION AND VALIDATION BASED ON IPG TRUCKMAKER SOFTWARE

High fidelity simulation test design on TruckMaker software

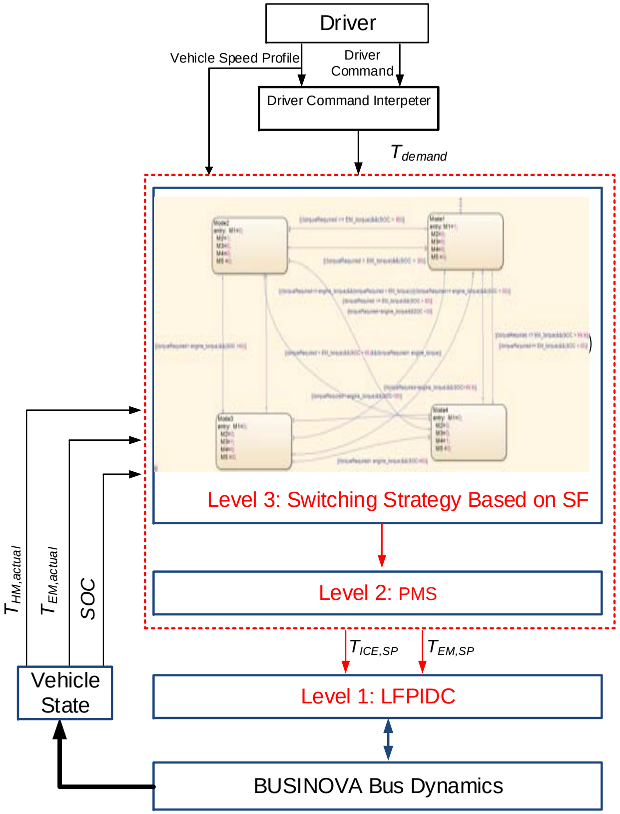
Simulation tool developed under TruckMaker software:

- Regenerative braking management **(block n° 4)**
  - Estimation of the current maximum regenerative braking torque
  - Calculating of a target regenerative braking torque based on maximum regenerative torque
  - Transformation of the target regenerative torque into target torques for the motors

- Drivetrain's elecltric power management **(block n° 5)**
  - Control of the batteries' state of charge
  - Management of the energy transfer between the electric circuits of the power supply model

4. ARCHITECTURE VALIDATION

To show the effective of the proposed Hierarchical strategy we designed PMS based on State Flow (SF) strategy.

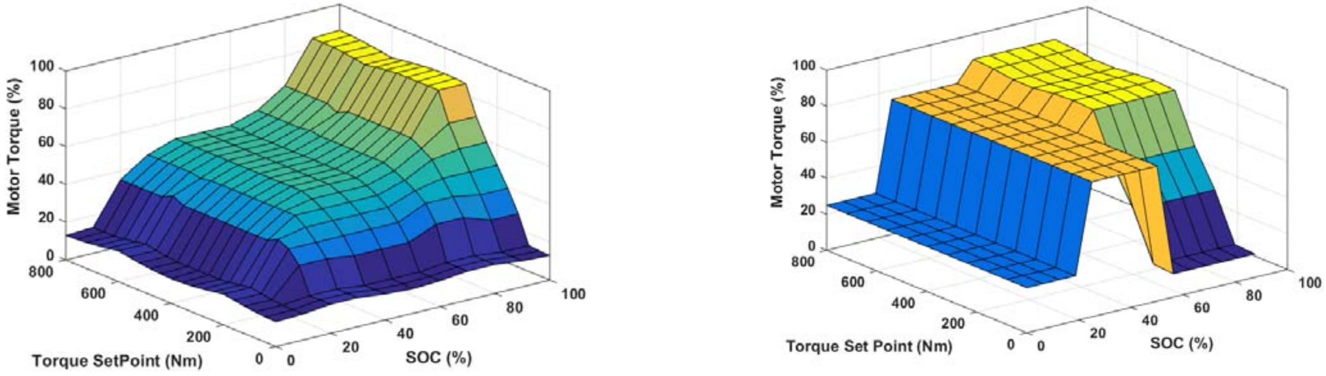


Power Management Strategy (PMS)

T_{demand}	SOC	T_{EM} , T_{ICE}	Mode of operation	Explanation
T_{demand} >0	SOC >60%	T_{demand} <=T_{EM}	Mode 1	When the battery SOC is high (more than 60% as example) and, the torque demand is less than or equal the EM torque. In addition, If T_{demand}>0, this means driver intends to accelerate the vehicle therefore EM can drive the vehicle..
T_{demand} >0	SOC <30%	T_{demand} <= T_{ICE}	Mode 2	
T_{demand} >0	SOC >60%	T_{demand} >T_{EM} or T_{demand} >T_{ICE}	Mode 3	
T_{demand} >0	SOC <30%	T_{demand} <T_{ICE}	Mode 4	
….	….	….	….	

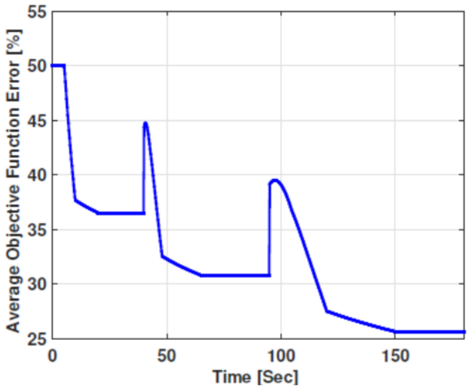
4. ARCHITECTURE VALIDATION

Simulation 1:The Control Surface and the Torque Distribution



(a) Proposed strategy (b) StateFlow strategy

Control surfaces of EM torque set-points with global torque set-point (T_{demand}) and SOC



Average objective function is given by

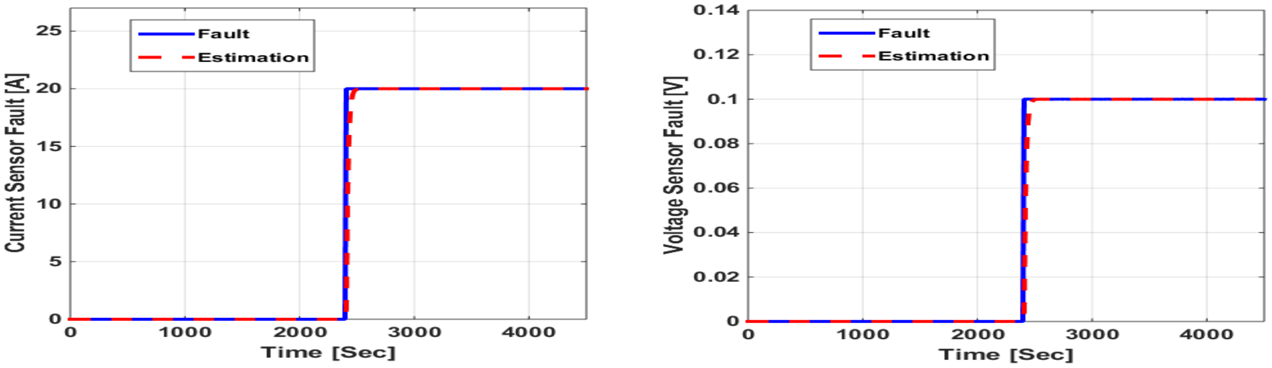
$$E^k = \frac{1}{2}\sum_{j=1}^{N}(y_j^k - \hat{y}_j^k)^2$$

where yj and $\hat{y}$ are the jth calculated output and desired output, respectively, N is the number of training iterations.

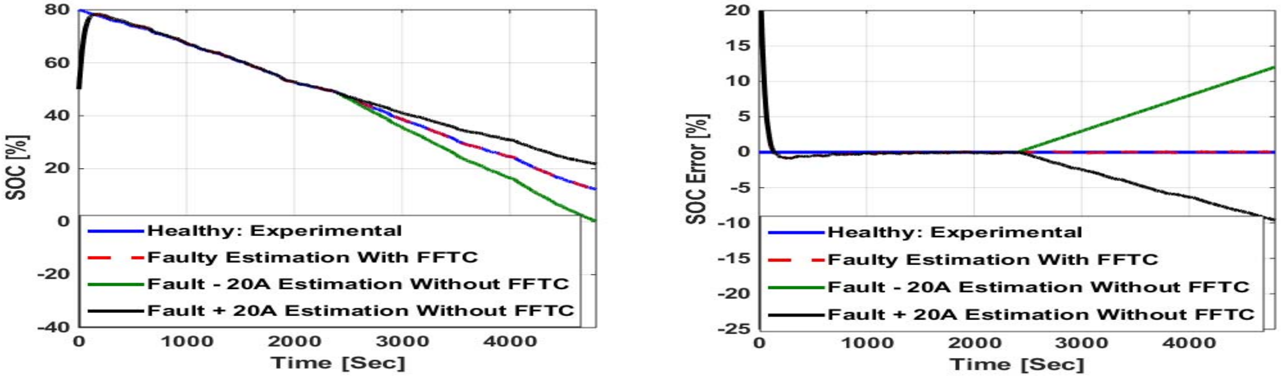
: Average objective function error for the proposed strategy

4. ARCHITECTURE VALIDATION

Simulation 2: Fault Detection and its Effects on Battery SOC Estimation



(Left) battery current sensor fault and its estimation; (right) battery voltage sensor fault and its estimation.



Effects of current fault on battery SOC estimation;
(left) SOC estimation results in the current sensor faulty conditions with FFTC (Fuzzy Fault Tolerant Control) and without FFTC
(right) SOC estimation errors in the current sensor faulty conditions with FFTC and without FFTC

4. ARCHITECTURE VALIDATION

Simulation 3: Proposed Overall Control Architecture For Complete HHEV Simulation

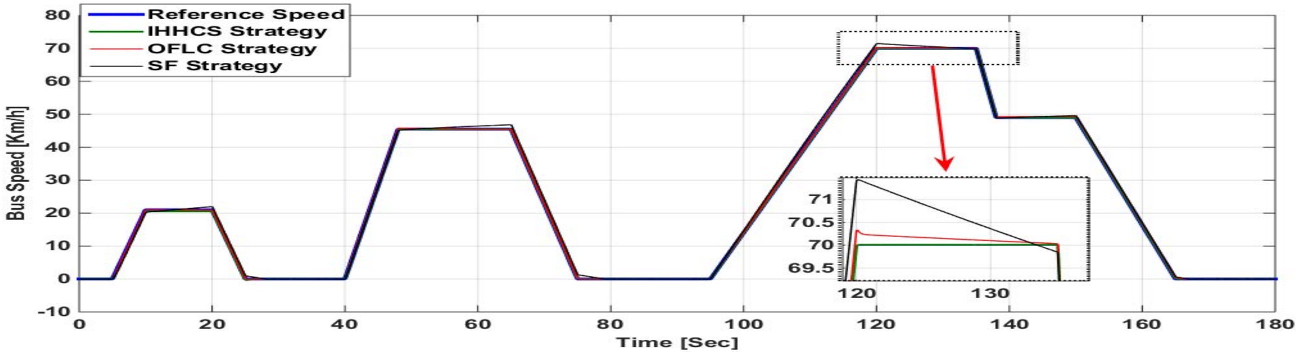
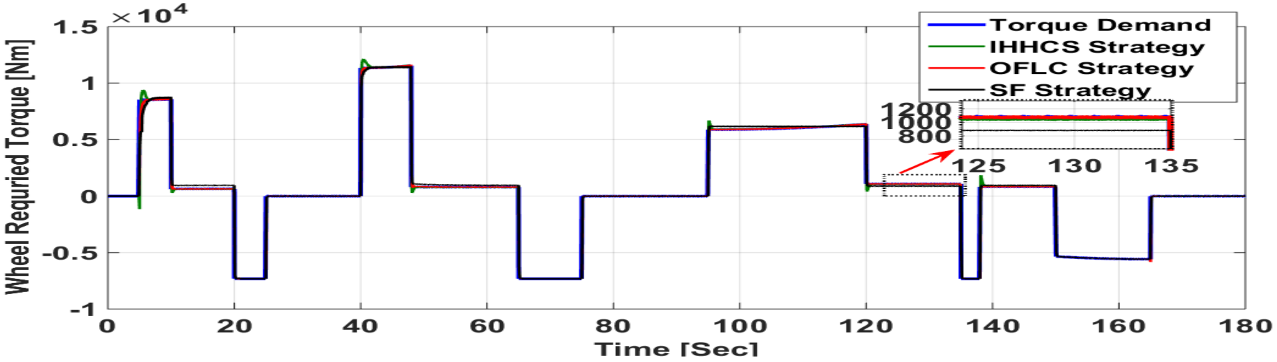


Fig. 11: Reference speed and actual vehicle speed [Km/h] for the proposed IHHCS strategy w.r.t. OFLC and SF.



Reference torque and actual vehicle torque [Nm] for the proposed IHHCS strategy w.r.t. OFLC and SF.

4. ARCHITECTURE VALIDATION

Simulation 3: Proposed Overall Control Architecture For Complete HHEV Simulation

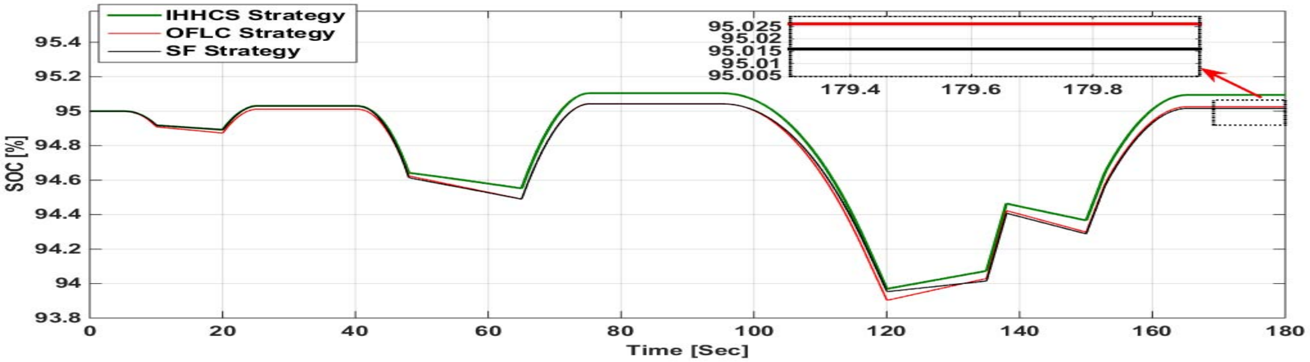
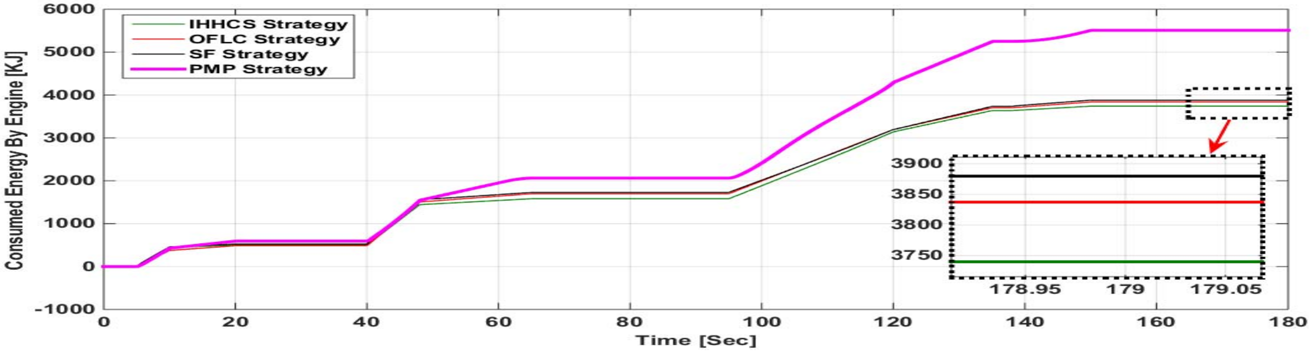


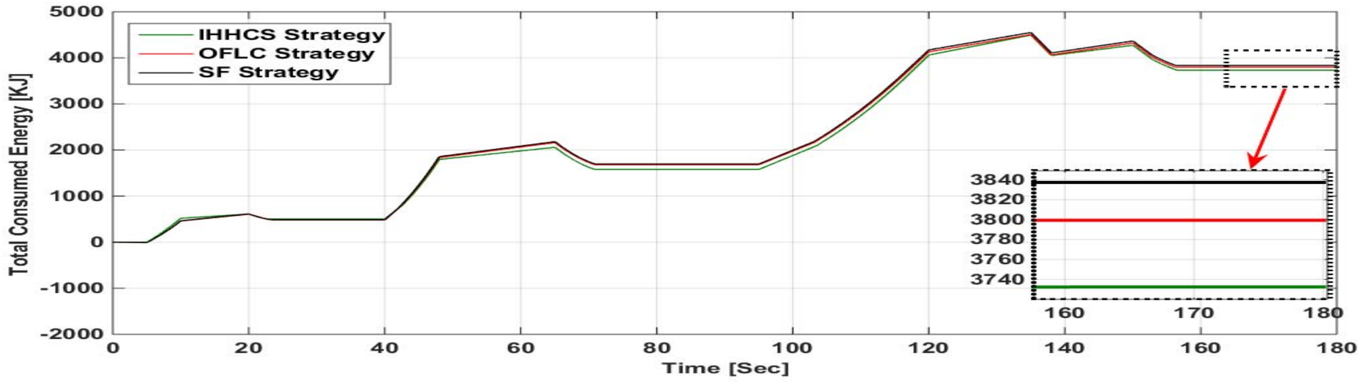
Fig. 13: SOC [%] profile for the proposed IHHCS strategy w.r.t. OFLC and SF.



Consumed energy by ICE [KJ] for the proposed IHHCS strategy w.r.t. OFLC and SF.

4. ARCHITECTURE VALIDATION

Simulation 3: Proposed Overall Control Architecture For Complete HHEV Simulation



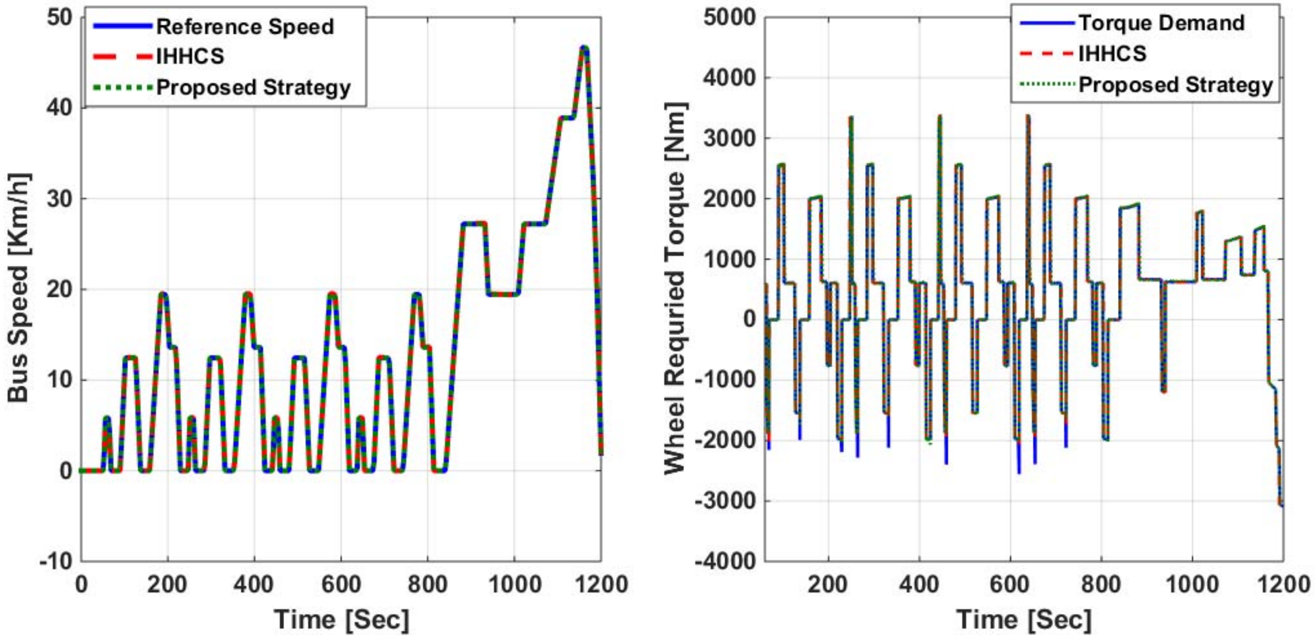
Total energy consumed by the vehicle [KJ] for the proposed IHHCS strategy w.r.t. OFLC and SF.

Table: Comparison of results for proposed IHHCS, OFLC and SF strategies.

Control Strategy	Fuel Energy consumption by ICE (KJ)	SOC (100%)
SF	**3835**	**95~95.015**
OFLC	**3800**	**95~95.03**
IHHCS	**3732**	**95~95.1**

4. ARCHITECTURE VALIDATION

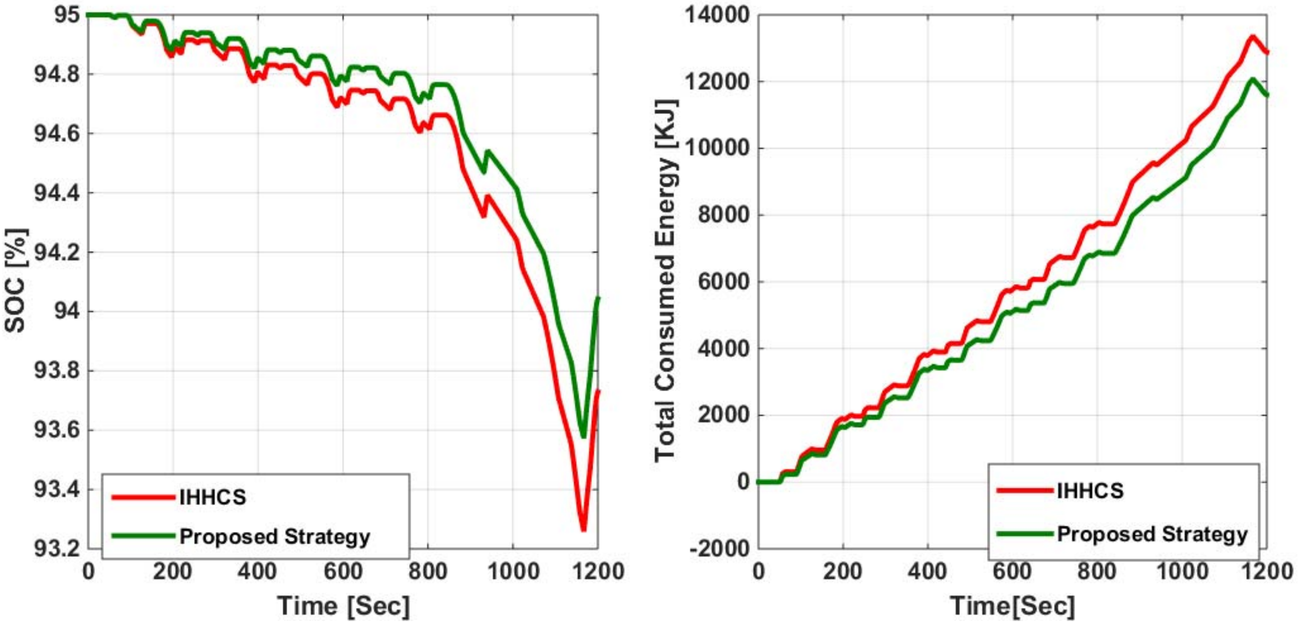
Simulation 4: Proposed Optimal Energy Management Strategy znf IHHCS Control Architecture For Complete HHEV Simulation



Output vehicle speed [Km/h] (left) and actual wheel required torque [Nm] (right) for proposed energy management strategy and IHHCS.

4. ARCHITECTURE VALIDATION

Simulation 4: Proposed Optimal Energy Management Strategy znf IHHCS Control Architecture For Complete HHEV Simulation



SOC profiles (left) and total energy consumed [KJ] (right) for proposed energy management strategy and IHHCS.

4. ARCHITECTURE VALIDATION

Validation based on precise simulation using IPG TruckMaker software

Construction of several test scenarios (standardized or not) for different bus operating conditions (road type, speed cycle, bus mass, etc.)

IPG TruckMaker Software User Interface

5. CONCLUSION AND FUTURE WORK

Conclusion

- ✓ Proposition of robust and online energy management strategy for the studied hydraulic-electric hybrid vehicle
- ✓ Appropriate design of systematic BMFFTC (Battery Management Fuzzy Fault Tolerant Controller) scheme is proposed to estimate and compensate the battery faults
- ✓ Sufficient conditions for robust stabilization of the TS fuzzy model were derived for a Lithium-ion battery and were formulated as an LMI (Linear Matrix Inequalities) format
- ✓ Proposition of global energy consumption minimization (increasing thus the total distance traversed between refueling of the studied hybrid vehicle)
- ✓ Design of Real-Time Energy Management based on the Prediction of Hybrid Vehicle’s Futures States

Future Work

- ➢ Implement the overall proposed control strategy on the actual BUSINOVA platform (work under progress)

Thank you for your attention!

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