Development of an Adaptive Efficient Thermal / Electric Skipping Control Strategy applied to a parallel plug-in hybrid electric vehicle

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Abstract

In recent years automobile manufacturers focused on an increasing degree of electrification of the powertrains with the aim to reduce pollutants and CO₂ emissions. Despite more complex design processes and control strategies, these powertrains offer improved fuel exploitation compared to conventional vehicles thanks to intelligent energy management. A simulation study is here presented aiming at developing a new control strategy for a P3 parallel plug-in hybrid electric vehicle. The simulation model is implemented using vehicle modeling and simulation toolboxes in MATLAB/Simulink. The proposed control strategy is based on an alternative utilization of the electric motor and thermal engine to satisfy the vehicle power demand at the wheels (Efficient Thermal/Electric Skipping Strategy - ETESS). The choice between the two units is realized through a comparison between two equivalent fuel rates, one related to the thermal engine and the other related to the electric consumption. An adaptive function is introduced to develop a charge-blended control strategy. The novel adaptive control strategy (A-ETESS) is applied to estimate fuel consumption along different driving cycles. The control algorithm is implemented on a dedicated microcontroller unit performing a Processor-In-the-Loop (PIL) simulation. To demonstrate the reliability and effectiveness of the A-ETESS, the same adaptive function is built on the Equivalent Consumption Minimization Strategy (ECMS). The PIL results showed that the proposed strategy ensures a fuel economy similar to ECMS (worse of about 2% on average) and a computational effort reduced by 99% on average. This last feature reveals the potential for real-time on-vehicle applications.

Introduction

Electrified powertrains are one of the key technologies for vehicle energy saving. Combining an Internal Combustion Engine (ICE) and one or more high-efficiency electric machines, Hybrid Electric Vehicles (HEVs) have lower fuel consumption than conventional vehicles. However, effective Energy Management Strategies (EMSs) are required to coordinate the energy distribution among powertrain components and, at the same time, respecting their safe working condition.

Zhang et al. [1] proposed to classify EMSs in two main headlines: (1) offline EMSs, categorized according to the information level of the driving conditions utilized, including global optimization based-EMSs and rule-based EMSs; and (2) online EMSs represented as instantaneous optimization-based EMSs, predictive EMSs, and learning-based EMSs.

Offline EMSs are mainly divided into global optimization-based EMSs and rule-based EMSs. Rule-based EMSs are based on the selection of driving modes. They are typically used in real-time applications thanks to their low computational effort. [2,3,4]. Dynamic programming (DP) and Pontryagin Minimization Principle (PMP) are two of the most common offline EMSs. DP is a mathematical technique to find the global optimum solution in managing the energy sources in hybrid power trains [5,6]. Therefore, it is used as a benchmark tool for other EMSs [7]. It requires prior knowledge of the entire driving cycle and has high computational complexity. PMP is an analytical optimization method that transforms a global optimization problem into an instantaneous Hamiltonian optimization problem [8,9]. Its main disadvantage is the requirement of the co-state estimation [10,11]. Kim et al. [12] developed a methodology to calculate the optimal co-state when a driving cycle is given. The simulation results showed that PMP control can achieve near-optimal results compared to DP. The computational time for PMP-based control was a tenth of that for DP-based control.

The Equivalent Consumption Minimization Strategy (ECMS) can be considered a PMP extension for online implementation. It is based on the idea that power is distributed by minimizing the fuel consumption at each instant by converting the electricity consumption into the equivalent fuel consumption. [13,14] The control variable in ECMS is an Equivalent Factor (EF) that relates the electric energy consumption to the power requirement. Wang et al. [15] developed a real-time ECMS for a series-parallel hybrid electric bus. HIL simulations showed that the proposed Adaptive ECMS (A-ECMS) can reduce the fuel consumption of the hybrid bus by 12.75% and 40.57% compared to the hybrid electric bus with a logic-threshold control strategy and the conventional ICE bus, respectively.

State of Charge (SoC) management strategies are classified according to how the SoC of the energy storage system varies with time. Hybrid Electric Vehicles (HEVs) cannot charge the battery from the grid so, Charge-Sustaining (CS) strategies are developed aiming to keep the SoC level around a predefined target. Plug-in HEVs (PHEVs) could have the potential for providing pure electric driving for a longer range (with respect to HEVs) and CS strategies are not appropriate. Charge-Depleting (CD)/Charge-Sustaining strategies consist of a plan that firstly discharges the battery until a certain SoC level and then sustains the SoC around the above level. [16,17]. They are widely implemented in heuristic hybrid control modules of PHEVs [18,19]. Charge Blended
(CB) strategies are similar to CS strategies, but the SoC target decreases linearly with the driven distance [20]. CB strategies are compatible with PHEVs that usually start driving missions with a fully charged battery and aim to arrive with a lower SoC level at the end of the mission. It is widely recognized that, in CB mode, the ICE operates in its most efficient region longer, resulting in lower CO₂ emissions [21].

Several approaches have been proposed in the literature to realize adaptive CB control strategies [22, 23, 24]. In [25] the authors developed an artificial neural network-enhanced ECMS for a PHEV. Results highlight a reduced energy total cost compared to a simple CD-CS strategy for each test case, however computational time is more than 10 times increased. Onori et al. [26, 27] designed a causal controller PMP based to develop a CB strategy. The adaption law was tuned and implemented in a vehicle model in the form of a look-up table, where the optimal value of the co-state is tabulated as a function of total traveled distance and average driving cycle speed. Simulation results were compared to PMP and CD/CS mode, and they showed that the proposed strategy can improve fuel consumption by around 20%. On the other hand, PMP require higher computational effort compared to CD/CS approach, as shown in [25].

To reduce computational time typical of ECMS strategies, in previous work of the authors [28] a simplified control strategy was proposed, based on an alternative utilization of the thermal and electric unit for the vehicle driving (Efficient Thermal Electric Skipping Strategy – ETESS). At each time the choice between the power source depends on the comparison between the actual fuel rate in pure ICE driving and an equivalent fuel rate in pure electric driving. ETESS was demonstrated to perform in a manner similar to ECMS if applied to a HEV operated under charge-sustaining mode in terms of fuel economy, but with a very reduced computational effort [28].

In this work, the ETESS logic is extended to the management of a parallel plugin HEV. To this aim, an adaptive function is introduced, leading to an Adaptive ETESS strategy (named in the following as A-ETESS). The main aim of this work is to demonstrate the feasibility of the above strategy to the control of PHEV under CB mode, maintaining fuel economy levels similar to well-assessed strategies, such as Adaptive-ECMS (A-ECMS), with a computational effort similar to rule-based strategies. To this aim, the A-ETESS is implemented in a vehicle simulation model built on MATLAB/Simulink and tested along different driving cycles. The same adaptive function is introduced in the A-ECMS to benchmark the proposed control strategy in terms of fuel economy and computational effort. To compare the computational time, A-ETESS and A-ECMS are executed on the same MicroController Unit (MCU), ST Microelectronics board NUCLEO-H743ZI2, realizing processor-in-the-loop (PIL) tests, while the vehicle model is simulated on a PC-host.

**Vehicle model and simulation platform**

The investigated vehicle features a parallel P3 PHEV powertrain composed of a 3-cylinder spark ignition engine (ICE), an electric reversible machine (EM), a battery pack (BA), a DC-DC converter, a manual transmission (MT), and a torque coupler (TCP). The powertrain is schematized in Figure 1. Vehicle main characteristics are listed in Table 1.

Three modes, namely pure thermal mode, pure electric mode, and parallel mode are available to satisfy a tractive demand at the wheels. In pure thermal and pure electric mode, the demanded power is entirely provided by the engine and motor, respectively. Concerning the parallel mode, the power demand is provided in a combined manner by the engine and the motor.
Efficient thermal electric skipping strategy

The ETESS strategy is based on an alternative utilization of the thermal engine and of the electric machine to satisfy the power demanded for the traction. Three operating modes can be defined: pure thermal mode, full electric mode, parallel mode. The choice between the thermal engine and electric motor depends, at each time, on the comparison between the actual fuel rate of the thermal engine, operating to fully satisfy the power demand, and an equivalent fuel rate related to the pure electric driving of the vehicle. The main concept behind the equivalent electric fuel rate lies in the idea that the power provided by the electric motor was produced by the thermal engine in an undefined time while working in its minimum brake specific fuel consumption BSFC\text{min}. To take into account power losses along the driveline, power demand is corrected by efficiencies of driveline components. The equivalent fuel consumption is defined as:

\[
\dot{m}_{f,el} = c_0 \cdot \frac{P_{dem} \cdot BSFC_{min}}{\eta_{diff} \cdot \eta_{EM} \cdot \eta_{GB} \cdot \eta_{batt} \cdot \eta_{inv}} \tag{2}
\]

where \(P_{dem}\) is the commanded wheel power, and \(\eta_{diff}, \eta_{EM}, \eta_{GB}, \eta_{batt}, \eta_{inv}\) are respectively the efficiencies of the differential, electric motor, gearbox, battery, and inverter. \(c_0\) is a tuning constant and represents the fuel-equivalent consumption of pure electric driving.

The actual fuel rate of the thermal engine depends on its operating point, defined by torque output and rotational speed:

\[
\dot{m}_{f} = \frac{P_{dem} \cdot BSFC}{\eta_{GB} \cdot \eta_{diff}} \tag{3}
\]

Parallel mode is selected only if the thermal engine is not able to fully satisfy the power demand. In parallel mode, the thermal engine operates at its maximum load point and the electric motor delivers the lacking power to fulfill the demanded one.

Battery recharging is provided only through regenerative braking. In summary, ETESS can be considered as a specialization of ECMS for which the only allowed values for the power-split are either 0 or 1. ETESS advantage consists on reduced computational effort. Implementation of ETESS advantage consists on reduced computational effort.

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Control strategies

In the next paragraphs, a brief description of ECMS and ETESS principles, suitable for HEV operated in charge sustaining mode is introduced. Subsequently, those strategies are extended to managing the PHEV in a charge blended mode. Note that in both ECMS and ETESS implementations a transmission control module is adopted. The desired gear is selected from a vehicle speed–accelerator pedal position lookup table to simplify the control logic and lower the computational effort.

Equivalent consumption minimization strategy

ECMS reduces the global energy minimization problem of HEVs to a local one. Its cost function is formulated as follow:

\[
J = \dot{m}_{f} + \dot{x}_0 \frac{P_{batt}}{LHV} \tag{1}
\]

It consists of an equivalent fuel rate, the sum of the actual fuel rate (\(\dot{m}_f\)) and a contribution related to the electric power, (where LHV is the fuel lower heating value and \(P_{batt}\) is the net electrical power as seen at the battery terminals), through an equivalence factor (\(x_0\)).

The equivalence factor represents the cost of the electric energy stored in the battery and its value for the optimal problem solution highly depends on vehicle characteristics and driving conditions. In the presented model ECMS implementation available in Powertrain Blockset Simulink library is taken as reference, following the formulation proposed by Onori et al. [27].

Table 1. Main characteristics of the tested PHEV

<table>
<thead>
<tr>
<th>Plug-in Hybrid Electric Vehicle Features</th>
<th>Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, kg</td>
<td>1100</td>
</tr>
<tr>
<td>Car aero drag, m^2</td>
<td>2.46</td>
</tr>
<tr>
<td>Wheel diameter, m</td>
<td>0.366</td>
</tr>
<tr>
<td>Axle ratio, -</td>
<td>3.32</td>
</tr>
<tr>
<td>Internal Combustion Engine</td>
<td></td>
</tr>
<tr>
<td>Displacement, cm^3</td>
<td>999</td>
</tr>
<tr>
<td>Max Power, kW</td>
<td>46</td>
</tr>
<tr>
<td>Max Torque, Nm</td>
<td>90</td>
</tr>
<tr>
<td>Electric Machine</td>
<td></td>
</tr>
<tr>
<td>Max Power, kW</td>
<td>60</td>
</tr>
<tr>
<td>Max Torque, Nm</td>
<td>207</td>
</tr>
<tr>
<td>Battery</td>
<td></td>
</tr>
<tr>
<td>Rated Capacity, Ah</td>
<td>6.5</td>
</tr>
<tr>
<td>Gearbox</td>
<td></td>
</tr>
<tr>
<td>Gear 1 Ratio, -</td>
<td>4.212</td>
</tr>
<tr>
<td>Gear 2 Ratio, -</td>
<td>2.637</td>
</tr>
<tr>
<td>Gear 3 Ratio, -</td>
<td>1.8</td>
</tr>
<tr>
<td>Gear 4 Ratio, -</td>
<td>1.386</td>
</tr>
<tr>
<td>Gear 5 Ratio, -</td>
<td>1</td>
</tr>
<tr>
<td>Gear 6 Ratio, -</td>
<td>0.772</td>
</tr>
</tbody>
</table>

Battery recharging is provided only through regenerative braking. In summary, ECMS can be considered as a specialization of ECMS for which the only allowed values for the power-split are either 0 or 1. ECMS advantage consists on reduced computational effort. In fact, the engine operating point depends only on tractive power demand, and a discrete exploration of power split is not needed.
where SoC and SoCref are respectively the SoC of the battery at the start and the end of the driving mission, x(t) is vehicle position at time instant t and m is the total distance to be covered. It is worthwhile highlighting that the only information needed to evaluate the reference SoC are the initial state of charge of the battery (SoC1), the desired SoC value at the end of the mission (SoCref), and the distance that vehicle must travel (that could be provided by a map service provider in real application on vehicle). In this paper, the ETESS, originally conceived to operate the powertrain in a charge sustaining mode, is extended for a CB strategy through the adoption of the tuning constant c0 related to the weight of pure electric driving cost (Eq 3). The equivalent fuel consumption defined in Eq. (3) is reformulated as:

\[
m_{f,el} = k_{pen} \cdot c_{0} \cdot \frac{P_{dem} \cdot BSFC_{min}}{\eta_{dkg} \cdot \eta_{EM} \cdot \eta_{GB} \cdot \eta_{inv}}
\]

(5)

where the penalization factor \( k_{pen} \) is introduced. During the driving mission two scenarios are possible:

1) The actual SoC is higher than the reference SoC. Pure electric driving must be promoted lowering the cost related to it.

2) The actual SoC is lower than the reference SoC. Pure electric driving must be penalized raising the cost associated with it.

The term \( k_{pen} \) is distinguished for these scenarios. For this reason, two different functions are built depending on the difference between the actual SoC and the reference one SoC. and the normalized distance to travel \( \Delta x = (L_m - x)/L_m \). Logarithmic functions are selected to make the control strategy stable, and the correction of the adaptive cost is assumed to raise with the traveled distance and with the SoC error. For faster model running, the two functions are implemented in the form of a lookup table. Their values are shown in Figure 4 and Figure 5.

\[
J = m_{f} + s_{0} \cdot k_{pen} \cdot \frac{P_{batt}}{LHV}
\]

(6)

Preliminary tests on 5 driving cycles, namely WLTC, HWFET, ARTEMIS URBAN, JC08, and a Real Driving Cycle (RDC), showed that the proper values of \( c_{0} \) and \( s_{0} \) are slightly dependent on the driving mission. In those simulations, the \( c_{0} \) and \( s_{0} \) are selected by a trial-and-error procedure, where the monitored parameter to be minimized is the average difference between actual SoC and SoCtarget. As an example, the SoC trends for optimal (\( c_{opt} \) in black), and sub-optimal values of \( c_{0} \) (0.95 in red and 1.15 in blue), and SoCtarget (green) are depicted in Figure 6 for WLTC.

\[
\text{Figure 4. } k_{pen} \text{ for SoC}(x) < \text{SoC}^{*}(x).
\]

\[
\text{Figure 5. } k_{pen} \text{ for SoC}(x) > \text{SoC}^{*}(x).
\]

\[
\text{Figure 6. SoC along WLTC for: (black) } c_{0}=1.05, \text{ (blue) } c_{0}=1.15, \text{ (red) } c_{0}=0.95, \text{ SoC}^{*} \text{ (green).}
\]

The cycle-dependent optimal values of \( c_{0} \) and \( s_{0} \) are then correlated to the travelled distance of each driving cycle, as shown in Figure 7. The latter also depicts appropriate fitting functions. Those functions will be used in the results presented in the following to assign the initial values of \( c_{0} \) and \( s_{0} \) whatever is the driving cycle, only as a function of the overall distance to be covered.
**Test cases**

A set of 10 driving cycles, listed in Table 2, have been selected for the comparison of A-ETESS and A-ECMS, with the aim of exploring their behavior under various scenarios, highly different in terms of maximum and mean speeds and accelerations, and distance to be covered.

An initial battery SoC of 80% and a final SoC of 30% have been specified, in compliance with typical plug-in hybrid operations.

To reinforce the validity of the comparisons, a Real Driving Emission-compliant cycle (RDE) and a Real Driving cycle, whose data have been collected from a GPS, have been considered (cycles # 9 and #10 in Table 2, respectively, plotted in Figure 8 e Figure 9).

<table>
<thead>
<tr>
<th>TC</th>
<th>Cycle</th>
<th>$L_m$</th>
<th>$V_{\text{mean}}$</th>
<th>$a_{\text{max}}$</th>
<th>$V_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>units</td>
<td>km</td>
<td>m/s²</td>
<td>km/h</td>
</tr>
<tr>
<td>1</td>
<td>WLTC</td>
<td>23.00</td>
<td>46.5</td>
<td>1.75</td>
<td>131.3</td>
</tr>
<tr>
<td>2</td>
<td>FTP75</td>
<td>17.77</td>
<td>25.9</td>
<td>1.48</td>
<td>91.2</td>
</tr>
<tr>
<td>3</td>
<td>HWFET</td>
<td>16.49</td>
<td>77.6</td>
<td>1.43</td>
<td>96.4</td>
</tr>
<tr>
<td>4</td>
<td>LA92</td>
<td>15.80</td>
<td>39.6</td>
<td>3.08</td>
<td>108.1</td>
</tr>
<tr>
<td>5</td>
<td>ARTEMIS URBAN</td>
<td>4.87</td>
<td>17.7</td>
<td>2.86</td>
<td>57.7</td>
</tr>
<tr>
<td>6</td>
<td>ARTEMIS RURAL</td>
<td>17.27</td>
<td>57.5</td>
<td>2.36</td>
<td>111.5</td>
</tr>
<tr>
<td>7</td>
<td>ARTEMIS HIGH 130</td>
<td>28.74</td>
<td>96.9</td>
<td>1.92</td>
<td>131.8</td>
</tr>
<tr>
<td>8</td>
<td>JC08</td>
<td>8.171</td>
<td>24.4</td>
<td>1.69</td>
<td>81.6</td>
</tr>
<tr>
<td>9</td>
<td>RDC</td>
<td>59.02</td>
<td>39.8</td>
<td>3.33</td>
<td>89.9</td>
</tr>
<tr>
<td>10</td>
<td>RDE</td>
<td>78.85</td>
<td>50.7</td>
<td>5.04</td>
<td>128.8</td>
</tr>
</tbody>
</table>

**Fuel consumption correction related to battery discharge**

In order to take into account the energy consumption related to battery discharge, typical of PHEV operations, a correction of the cumulated fuel consumed at the end of the driving mission has to be introduced. To this aim, the electrical energy globally used is converted into an equivalent mass of fuel on the basis of the following hypothesis. The energy taken from the battery ($\Delta E_{\text{batt}}$) is assumed to have been produced by the engine operating at its average efficiency point ($\eta$). The correction of the fuel mass ($\Delta m_{eq}$) can hence be represented as follow:

$$\Delta m_{eq} = \frac{\Delta E_{\text{batt}}}{LHV \cdot \eta}$$  (7)

The total fuel consumed ($m_{tot}$) to cover the driving mission is expressed as:

$$m_{tot} = \Delta m_{eq} + m_{ICE}$$  (8)

where $m_{ICE}$ is the actual mass of fuel consumed by the ICE. The total fuel consumed, normalized by the travelled distance along the driving mission, will be adopted in the following section as an indicator of vehicle fuel economy.
For sake of brevity results for test cases 1, 5, 8, 10, (representative for a high-speed cycle, low-medium speed cycles, and a RDE-compliant cycle) are discussed in detail below.

Starting the discussion from test case 1, both A-ECMS and A-ETESS prove to follow the SoC target profile and almost reach the desired SoC at the end of the mission (Figure 10-b). The adaptive term properly reflects the error between the instantaneous SoC and the instantaneous target SoC (Figure 10-c).

However, ETESS results present more skip between engine ON/OFF, resulting possibly in worse drivability in a real vehicle application (Table 3). Maximum and mean vehicle acceleration rates, and ICE skip number, reported in Table 3, are considered as indicators of vehicle drivability.

During the high-speed portion of the cycle, between 1400 and 1800s, the EM supports the ICE, which delivers its maximum torque to fulfill the power demand at the wheels both in A-ECMS and A-ETESS. This is also evidenced by similar SoC trends (Figure 11-b). Globally, the considered strategies behave in a very similar manner, leading to analogous levels of consumed fuel (Figure 11-c).

In Figure 12, the instantaneous trends of SoC (Figure 12-b), and the adaptive term (Figure 12-c) along the RDE-compliant cycle are depicted (test case #10 of Table 2). Moreover, the comparisons of ICE and EM powers and consumed fuel are reported in Figure 13. SoC ends and EM powers highlight significant differences in electrical energy usage between the two strategies due to the possibility of A-ECMS exploring intermediate power split. During the low-speed part of the cycle, A-ETESS prefers pure thermal mode more frequently than A-ECMS. In the portion of the cycle between 4400 and 5400s, A-ECMS can recharge the battery keeping ICE mainly on its maximum torque working point. In A-ETESS, instead, battery recharge during traction is not possible and the ICE only delivers the power needed for traction. Consequently, when the EM is forced to fulfill power demand in parallel mode, this leads to a quite deep battery discharge, reaching a 16% SoC at the end of the cycle. Despite those limitations of A-ETESS, the cumulated fuel consumed is lower than the A-ECMS counterpart. On the other hand, a substantially greater electric energy consumption emerges overall. Those results globally compensate each other, leading, as shown in the following, to similar fuel economies. It is worthwhile mentioning that an enhanced gear shifting strategy and a more powerful ICE could significantly improve A-ETESS behavior.
To show the capability of the A-ETESS to deal with slow and short driving cycles, in Figure 14 and Figure 15, comparisons with A-ECMS along the JC08 cycle are depicted (test case #8 of Table 2). The adaptive term is always next to the unit (Figure 14-c) and the trends of the SoC are quite close to the target (Figure 14-b). The final consumed fuels, applying A-ECMS and A-ETESS, are similar but the first involves a greater battery discharge at the cycle end, leading to a worse fuel economy. As better detailed in the following, this is due to some issues in the management of ICE when this is operated with a null-load.

Table 3. Engine ON/OFF number and maximum and mean value of vehicle acceleration derivative for test cases 1,5,8,10.

<table>
<thead>
<tr>
<th>TC</th>
<th>Strategy</th>
<th>Engine ON/OFF, -</th>
<th>max ( \frac{da}{dt} ) m/s²</th>
<th>mean ( \frac{\langle da \rangle}{dt} ) m/s³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A-ETESS</td>
<td>238</td>
<td>1.253</td>
<td>0.145</td>
</tr>
<tr>
<td></td>
<td>A-ECMS</td>
<td>156</td>
<td>1.329</td>
<td>0.133</td>
</tr>
<tr>
<td>5</td>
<td>A-ETESS</td>
<td>120</td>
<td>2.151</td>
<td>0.331</td>
</tr>
<tr>
<td></td>
<td>A-ECMS</td>
<td>152</td>
<td>2.132</td>
<td>0.332</td>
</tr>
<tr>
<td>8</td>
<td>A-ETESS</td>
<td>170</td>
<td>1.008</td>
<td>0.150</td>
</tr>
<tr>
<td></td>
<td>A-ECMS</td>
<td>135</td>
<td>1.354</td>
<td>0.137</td>
</tr>
<tr>
<td>10</td>
<td>A-ETESS</td>
<td>1324</td>
<td>2.363</td>
<td>0.200</td>
</tr>
<tr>
<td></td>
<td>A-ECMS</td>
<td>856</td>
<td>2.385</td>
<td>0.195</td>
</tr>
</tbody>
</table>

Detailed results for Artemis Urban Cycle (test case #8 of Table 2) are depicted in Figure 16 and Figure 17. A-ETESS and A-ECMS differently manage ICE and EM as highlighted in Figure 17-a and Figure 17-b, respectively. In the case of A-ETESS, the EM delivers a greater power when the ICE is operated load-less (null torque request) and the torque converter continues transmitting power (negative) to the driveline. In those circumstances, the battery quickly discharges as shown in Figure 16-b. The ICE works less frequently, even if at higher loads, and hence with higher efficiencies. The overall fuels consumed at the cycle end of A-ETESS and A-ECMS are similar (Figure 17-c), but a lower final SoC level is reached in the first case. This, as shown in the following, will determine a remarkable worsening of fuel economy in the comparison between A-ETESS and A-ECMS.

In the future development of this activity, the adoption of detailed clutch control, combined with the removal of the torque converter, is expected to speed-up the ICE engagement / disengagement, and to nullify the dissipations related to ICE load-less operations. This is expected to align fuel economy performance of A-ETESS with respect to A-ECMS one.

A global synthetic comparison between the results of the two strategies is realized through the bar charts in Figure 18. They represent the total fuel consumed per kilometer, for A-ETESS and A-ECMS, and over each couple of bars is shown the percentage difference, evaluated as:

\[
\Delta m_{\text{tot}} = \frac{m_{\text{tot}}^{A-ECMS} - m_{\text{tot}}^{A-ETESS}}{m_{\text{tot}}^{A-ECMS}} \times 100
\]
As it can be observed, the average total fuel consumed difference between A-ETESS and A-ECMS is below 2% and in most cases of about 1% or lower. Greater differences emerge only for test cases #5 and #8, for the issues related to load-less ICE operations above mentioned. From the viewpoint of vehicle drivability, no relevant difference emerges between A-ETESS and A-ECMS, as evidenced by maximum and averaged values of vehicle acceleration derivative reported in Table 3. As expected, A-ETESS involves a greater number of engine ON/OFF than A-ECMS in most of the test cases of Table 3, even if for case # 5 the opposite situation verified. The consequences of such circumstance of course would require some verification in a real on-vehicle application, especially in terms of thermal management and effectiveness of aftertreatment devices of the ICE.

**PIL Test**

In this section PIL tests' results are presented. The execution of A-ETESS and A-ECMS are tested on the NUCLEO-H743 [29]. It is a high-performance board for optimized control, equipped with an ARM Cortex-M7 running up to 480 MHz, 424 CoreMark / 1027 DMIPS executing from Flash memory. The objective of the PIL test is to evaluate the execution time and computational effort of the C-Code generated for running on the NUCLEO-H743. The PIL testing procedure is based on asynchronous serial communication between the NUCLEO board and PC-Host. To this aim, Simulink Coder for STMicroelectronics NUCLEO board is used. At the end of the simulation in PIL mode, Simulink generates the code execution profiling report. Results are similar for each test case in Table 2, so for sake of brevity, only WLTC results are reported in Table 4. The latter shows that A-ETESS is two orders of magnitude faster than A-ECMS, with a maximum CPU Utilization of 0.015% in the place of 22.95%. For both strategies, the average execution time is lower than the typical cycle time of a CAN message for an updated engine torque request (10 ms), but A-ETESS reduced computational effort confirm the possibility to run multiple control strategy on the same micro-controller optimizing its utilization.

**Table 4. PIL testing results for WLTC**

<table>
<thead>
<tr>
<th>Task</th>
<th>A-ETESS</th>
<th>A-ECMS</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum CPU Utilization, %</td>
<td>0.015</td>
<td>22.95</td>
<td>-99.93</td>
</tr>
<tr>
<td>Average CPU Utilization, %</td>
<td>0.005</td>
<td>14.31</td>
<td>-99.96</td>
</tr>
<tr>
<td>Maximum Execution Time, ms</td>
<td>0.030</td>
<td>2.29</td>
<td>-98.68</td>
</tr>
<tr>
<td>Average Execution Time, ms</td>
<td>0.011</td>
<td>1.43</td>
<td>-99.22</td>
</tr>
</tbody>
</table>

**Contact Information**

**References**


**Acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-ECMS</td>
<td>Adaptive - ECMS</td>
</tr>
<tr>
<td>BA</td>
<td>Battery pack</td>
</tr>
<tr>
<td>BSFC</td>
<td>Brake Specific Fuel Consumption</td>
</tr>
<tr>
<td>CB</td>
<td>Charge Blended</td>
</tr>
<tr>
<td>CD</td>
<td>Charge Depleting</td>
</tr>
<tr>
<td>CS</td>
<td>Charge Sustaining</td>
</tr>
<tr>
<td>DP</td>
<td>Dynamic Programming</td>
</tr>
<tr>
<td>ECMS</td>
<td>Equivalent Consumption Minimization Strategy</td>
</tr>
<tr>
<td>EM</td>
<td>Electric motor</td>
</tr>
<tr>
<td>EM</td>
<td>Electric machine</td>
</tr>
</tbody>
</table>
EMS    Energy Management Strategy
ETESS  Efficient Thermal / Electric Skipping Strategy
FC     Fuel consumption
HEV    Hybrid electric vehicle
HIL    Hardware in the Loop
ICE    Internal Combustion Engine
LHV    Lower Heating Value
MT     Manual Transmission
PHEV   Plug-in HEV
PIL    Processor in the Loop
PMP    Pontryagin Minimum Principle
RDC    Real Driving Cycle
RDE    Real driving Emission
SoC    State of charge

Symbols

\( m \)    mass
\( \Delta E_{batt} \) Battery energy variation
\( \dot{m}_f \) Fuel mass rate
\( s_0 \) Equivalence factor
\( k_{pen} \) Adaptive term
\( P_{batt} \) Battery Power

Greeks

\( \eta \) Efficiency

Subscripts

\( a \) Acceleration
\( \text{batt} \) Battery
\( \text{dem} \) Demanded
\( \text{diff} \) Differential
\( \text{eq} \) Equivalent
\( f \) Adaptive - ECMS
\( \text{fin} \) Final
\( \text{GB} \) Gear-box
\( i \) Initial
\( \text{inv} \) Inverter
\( m \) Mission
\( \text{max} \) Maximum
\( \text{min} \) Minimum
\( \text{tot} \) Total
\( v \) Velocity

Superscripts

\( * \) Target
\( - \) Mean Value