Energy management of a hybrid electric vehicle in degraded operation

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This paper studies the energy management of a hybrid electric vehicle equipped with batteries, an ultracapacitor system (UCS) and a fuel cell system (FCS). The energy management strategy (EMS) is designed to enable degraded operation in case of failure of one of the energy sources. In the considered architecture, the vehicle is not operational without batteries because they impose the DC bus voltage, hence degraded operations are only considered for failures in the FCS or in the UCS. The objective is not to develop a new EMS for each degraded operation mode, but to slightly modify the global EMS developed for normal operation. The paper presents simulation and experimental validation results.

Introduction

The research presented in this article is realized in the framework of the ECCE project funded by the French Army (DGA). This project aims to develop and evaluate technologies for hybrid electric vehicles. ECCE hybrid electric vehicle (HEV) is a mobile laboratory which permits evaluating under real operation the components of HEV. Here, the interest is to develop and to evaluate an energy management system for a hybrid source composed by a bank of batteries, an ultracapacitor system and a fuel cell system. Considering reliability demands [1], military vehicles must present high redundancy in its energy sources, or at least must enable operation in case of failure of one of the energy sources. Previous research about this vehicle is published in [2]–[3].

As previous knowledge of the driving cycles is not available for the considered applications, the proposed energy management strategy only considers real-time information such as electrical power, current or voltage, the state of charge of the storage sources or the speed of the vehicle. The EMS is developed considering the advantages and drawbacks of each of the sources.

The main objective of this paper is to enhance the original EMS by considering degraded operations if any of the sources fails. The modified EMS must enable operation of the vehicle until the end of the mission, or until discharge of the batteries. Energy management in HEV is realised using several different techniques as presented in [4]–[15].

This paper is organized as follows: Section II introduces the energy management strategy in normal operation. Section III proposes modified energy management strategies in case of failure of the UCS or the FCS. Section IV presents simulation and experimental validation results. Section V presents the conclusions of the research.

Energy management strategy

In ECCE, finding the ultracapacitor system (UCS), fuel cell system (FCS) and batteries power references to supply the vehicle power consumption (motor drives and ancillaries) seems to be the natural objective of the energy management strategy (EMS) as defined by Equation 1. The left term of this relation can be negative when braking (regenerative braking) and Equation 1 changes if mechanical braking is applied. As the batteries are directly connected to the DC bus (see Figure 1), the power flow of this source cannot be directly controlled.

The EMS is thus, in this case, limited to finding the UCS and FCS power references. As the EMS is designed without knowledge of future driving conditions, it only uses real-time information to compute these power references.

$$P_{motor\ drives} + P_{ancillary} = P_{FCS} + Pbatt + PUCS \qquad (1)$$

The first step is to define a global EMS (second level control) regarding the characteristics and constraints of both the vehicle and the hybrid source. The objectives of this EMS are defined as: to supply the energy consumed by the load, to maximize the energy recovered in braking, to minimize the DC bus voltage variation, to regulate the UC and batteries SOC and to supply high dynamic power. However, as the control of the sources is independently realized, the next step is to identify local control strategies for each source (first level control).

The batteries are directly connected to the DC bus, and then their power is indirectly controlled by the FCS and UCS: to discharge (recharge) the battery, the power supplied by the FCS and UCS will be lower (higher) than the power consumption, so the battery has to supply (store) the difference.

The UCS is the most efficient source, and then is considered as the priority source to supply the power: the reference power of this source is calculated as the difference of the power consumed by the load and the power delivered by the FCS. A fuzzy logic controller is designed to define the power reference for the FCS. The fuzzy controller has two inputs and one output. The first input ΔSOC is the difference between the estimated state-of charge of the UCS and the value of its reference value. The second output ΔP is the difference between the power consumed by the load and the power delivered by the FCS. The output of the system ΔPF CS is the rate of change in the fuel cell system output power. Figure 2 illustrates the energy management strategy presented in detail in [14] and [15]. The objective of this research, is to propose energy management strategies for degraded operation modes. These EMS will be based on the original global strategy.

EMS under degraded operation

The EMS introduced in Section II is designed to normal operation but does not consider degraded operation in case of failure of one of the sources. In the considered architecture, the vehicle is not operational without batteries because they impose the DC bus voltage, hence degraded operations are only considered for failures in the FCS or in the UCS.

As it can be seen in Figure 2, the global energy management strategy has two outputs: the reference power of the fuel cell system and the reference power of the ultracapacitor system. If one of these sources (FCS or UCS) fails, it is useless to compute a power reference for this source, then during degraded operation the EMS only have one output: the reference power for the source which is still operational.

Degraded operation without FCS

The first degraded operation mode is a failure in the FCS. Here, ECCE operates as it were a plug-in vehicle (i.e. the batteries provide the whole amount of energy until discharge) and as a consequence the SOC regulation in the batteries is not possible anymore. Nevertheless, the UCS SOC could be still controlled via the batteries. In this case, the control of UCS state-of-charge is possible. When the FCS fails, a fast DC bus voltage regulation could be still expected, but the state-of-charge of the batteries can not be regulated. The battery voltage will have relatively low variations, however the mean value of this voltage is expected to be decreasing.

The proposed solution is to use the batteries to supply the power that the FCS cannot supply. The batteries power is indirectly controlled by controlling the UCS supplied power. The modified EMS for the operation mode after a FCS failure is illustrated in Figure 3. The power reference for the FCS is still computed to be used as input to the UCS local EMS. The reference UCS power is calculated as the difference of the power consumed by the load and the FCS reference power which is supplied by the batteries. This is done to reduce the UCS power reference and avoid its fast discharge.

Degraded operation without UCS

The second case considered is a failure in the UCS. In the original strategy, the UCS is the source which provides the high dynamic characteristic of the hybrid source, and then the fast regulation of the battery voltage. In this case, the control of batteries state-of-charge (SOC) is possible, however the UCS SOC control is not performed anymore. When the UCS fails, the batteries supply the fast dynamic power not supplied by the UCS and then its voltage have higher variations than in the normal operation mode. However, the mean value of this voltage is expected to be constant because the fuel cell system is still providing the mean requested power on the DC bus.

The proposed solution for this failure is to maintain the same global EMS. However, as the UC SOC control is not required, the ΔSOC input at the fuzzy logic controller is imposed to be zero. This is equivalent to say that the reference UCS SOC is achieved, and then the only objective for the FCS is to supply the energy consumed by the load. The modified EMS for the operation mode after a UCS failure is illustrated in Figure 4.

Simulation results

The proposed EMS is evaluated by computer simulations using power profiles measured during real operation of the vehicle. The power profiles represent with good accuracy the operation of the vehicle. The energetic macroscopic representation formalism is used to perform the simulations as presented in [17].

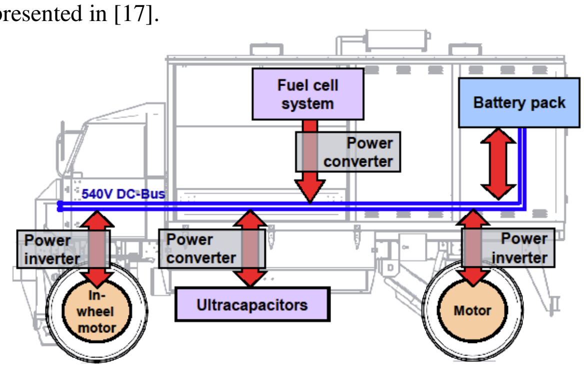

Figure 1 *ECCE hybrid electric vehicle architecture.*

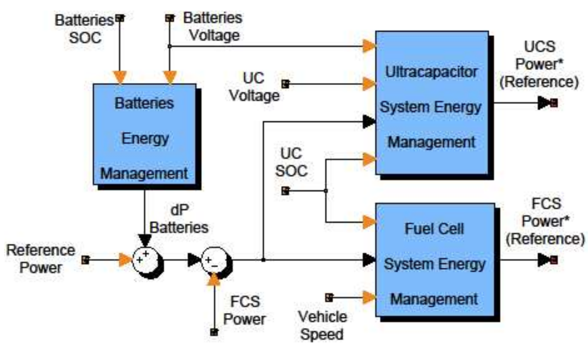

Figure 2 *Global energy management strategy.*

Failure in the FCS

Simulation results are presented in Figure 5. In this configuration the UCS supplies the dynamic response and the output voltage variation (ΔVmax = 60V) is lower than in the degraded configuration without UCS (ΔVmax = 75V). The batteries control the UC SOC, however, the batteries SOC cannot be controlled, and then a progressive decrease in the batteries voltage can be noticed.

Failure in the UCS

Simulation results for failure of the UCS are presented in Figure 6. In this degraded operation the batteries supply the dynamic response and the the output voltage is not stable as in the configuration including the UCS. The batteries SOC is nevertheless controlled by the FCS.

Experimental results

The energy management system (software & hardware) is implemented using a dSPACE AutoBox programmable controller. Driving validation is performed on a drive circuit located in PANHARD (industrial partner of the project) at Saint-Germain Laval, France. The evaluation of the EMS is performed under real conditions (these driving cycles are also used in simulation) and no previous knowledge of the driving cycle is considered.

Failure in the FCS

To emulate the FCS failure, the output of this element is imposed to be zero. The strategy is modified as shown in Figure 3. Experimental results are presented in Figure 7.
In this configuration the UCS supplies the dynamic response and reduces the output voltage variation (ΔVmax = 65V). This variation is lower than the obtained in operation without UCS (ΔVmax = 80V). The batteries control the UC SOC, however a progressive decrease in the DC bus voltage is noticed. These results corroborate those obtained in simulation and show that the proposed strategy can be used in failure of the FCS.

Failure in the UCS

Experimental results for failure of the UCS are presented in Figure 8. To emulate the UCS fail, the output of this element is imposed to be zero. Additionally, the EMS is modified as illustrated in Figure 4.
In this degraded operation the batteries supply the dynamic response and the the output voltage is not stable as in the configuration including the UCS. The batteries SOC is controlled by the FCS. The reinforcing results obtained in experimental and in simulation show that the proposed strategy can be used in failure of the UCS.

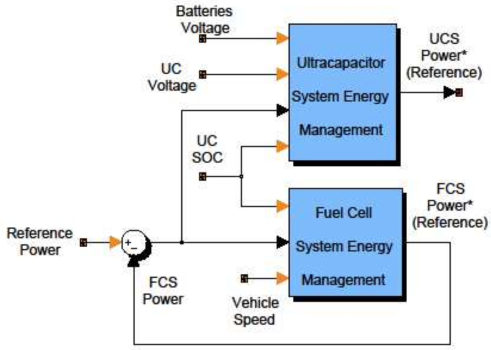

Figure 3 *Degraded operation strategy - without FCS*

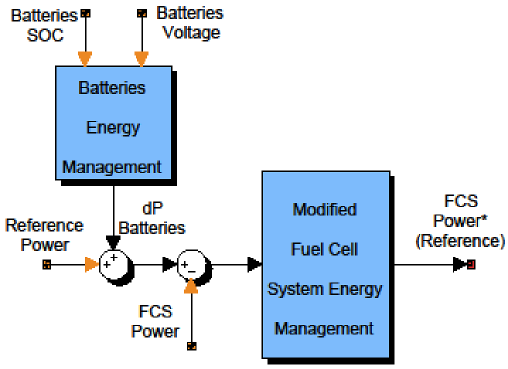

Figure 4 *Degraded operation strategy - without UCS*

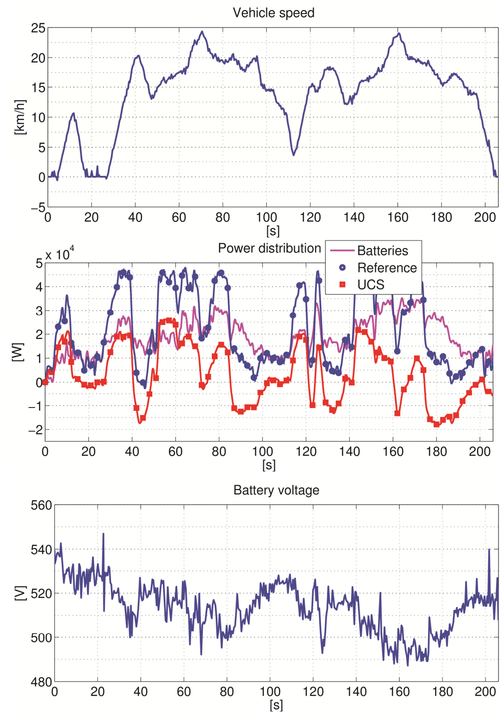

Figure 5 Degraded operation EMS without FCS - Simulation results: vehicle speed (up), power distribution (middle) and battery voltage (down)

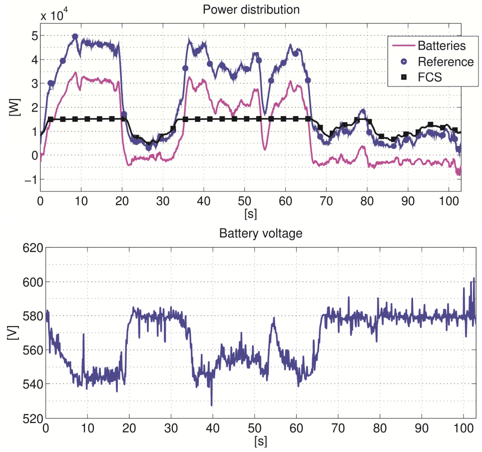

Figure 6 Degraded operation EMS whithout UCS - Simulation results: power distribution (up) and battery voltage (down)

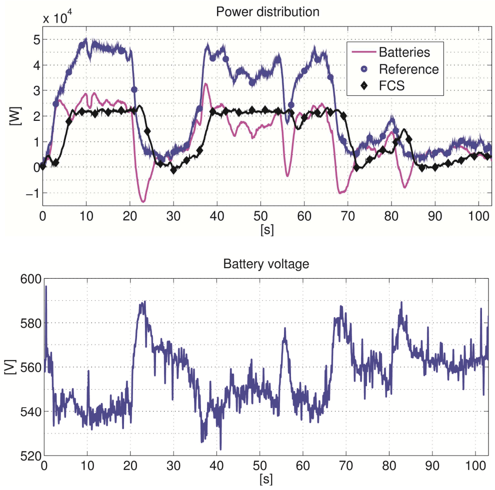

Figure 7 Degraded operation EMS whithout FCS - Experimental results: power distribution (up) and battery voltage (down)

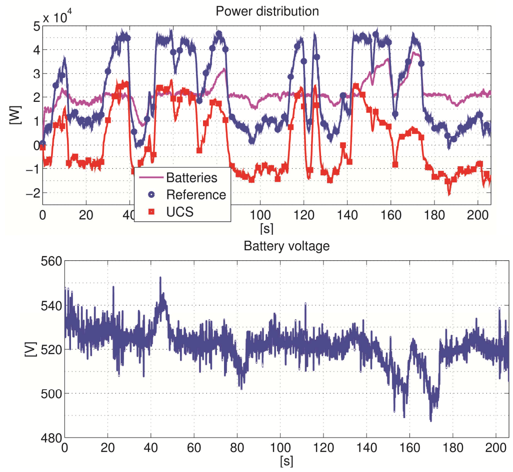

Figure 8 Degraded operation EMS without UCS - Experimental results: power distribution (up) and battery voltage (down)

Conclusion

This paper studied the energy management strategy of a HEV operating after failure of one of its energy sources. A global EMS used in normal operation is modified to consider either failure on the UCS or in the FCS.

Simulation and experimental results shows that the new strategies enable operation of the vehicle after the failure occurs. After an UCS failure, the battery voltage will have high variations but the state-of charge will be regulated by the FCS. After an FCS failure, the battery voltage will be regulated by the UCS, with lower variations but a decreasing mean value, because the SOC could not be regulated anymore.

The two degraded operation EMS are easily implemented from the normal operation EMS. Validation results show that these degraded EMS are well suited for real operation of the hybrid vehicle. Further research should be performed on the fast identification of degraded operation conditions.

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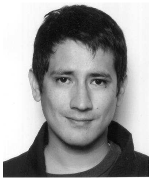

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