Influence of battery aging on energy management strategy

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Abstract. In the context of Hybrid Electric Propulsion Systems, one of the main aspects to investigate is the most suitable energy management strategy, which would allow the objectives of fuel consumption minimization and electric backup availability to be attained. The present study aims to compare two different energy management strategies for a Hybrid Electric Propulsion System (HEPS) for a Air-Taxi vehicle: though both are based on the same set fuzzy rules, the first one has been implemented neglecting battery aging effects, while the second adjusts the optimal battery discharge according to its age. The impact of such adaptation on fuel consumption and battery State of Charge will be evaluated along a typical mission profile.

Keywords: Hybrid electric vehicles, Energy management, Battery aging

1 Introduction

Though today batteries performance in terms of specific power and energy density represents the major obstacle for the diffusion of electric propulsion for commercial aircrafts, their capability of enabling electrification of small aviation and Urban Air Mobility vehicles has been proven in literature [1].

The present study focuses on the performance of a parallel HEPS running the same mission with two different energy management strategies. In fact, once the propulsive system has been properly sized, one of the main issues to be deal with is the implementation of a suitable strategy which is necessary to achieve the primary objective of fuel economy, together with allowing the battery to sustain the mission in electric mode in case of engine failure occurrence [2].

Numerous literature sources address the investigation of energy management strategies with both heuristic and optimization approaches [3]. This paper applies a previously developed fuzzy logic strategy with membership functions optimized through a genetic algorithm. Moreover, the optimal battery discharge curve has been previously obtained through an off-line optimization algorithm (DPM) and will serve as reference for the implementation if the fuzzy rules. For details of the development of the energetic strategy, see [2]-[4].

The aim of the present study is that of evaluating how a health conscious strategy (that takes into account battery aging by varying its optimal discharge curve) will influence the global behavior of the hybrid system along a typical mission, in particular in terms of fuel consumption and battery SoC.

1.1 The UAM vehicle

A coaxial rotor air-taxi with a parallel HEPS is considered. The HEPS consists of a two-spool turboshaft and two identical electric motors driven by a Li-ion battery of 130 Ah nominal capacity and maximum life of 436 cycles.

1.2 Battery aging

Battery specification and model parameters are not constant, since they change during battery life due to several phenomena such as capacity fade, thermal influence, etc. Time, temperature, depth of discharge and discharge rate are among the most influential factors affecting capacity loss [**Errore. L'origine riferimento non è stata trovata.**].

The main specifications of the battery can be expressed as a function of the battery "cycle number", which is defined as the number of complete discharge-recharge cycles. A battery is conventionally said to have reached its end of life when the capacity reaches 80% of the nominal value. This usually happens, for a Li-ion battery, after 300–500 discharge-recharge cycles.

The reduction of nominal capacity together with an increase of the Peukert coefficient causes energy retention, while the power retention is associated mainly to the increase of the internal resistance. The open circuit voltage is also affected by the battery cycle number.

For each parameter P of the battery (namely nominal capacity C, Peukert coefficient n and internal resistance R), a correction factor related to battery age can be defined as follows:

$$CF = \frac{P(N)}{P^0} \tag{1}$$

where the superscript 0 denotes the initial condition.

The dependence of the correction factors on battery cycle number is expressed as a double exponential:

$$CF = a \cdot exp(b \cdot N) + c \cdot exp(d \cdot N) \tag{2}$$

where the coefficients have been found interpolating experimental data from [**Errore. L'origine riferimento non è stata trovata.**]. Their trends with respect to battery age are depicted in Fig. 1.

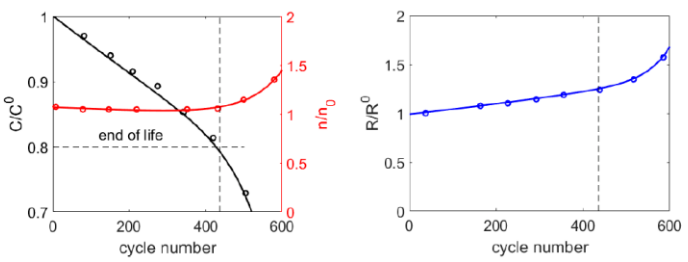

Fig. 1. Capacity, Peukert coefficient and internal resistance variation with battery age.

More details about battery model and aging can be found in [**Errore. L'origine riferimento non è stata trovata.**].

2 Methods

The system is supposed to run a typical mission with a duration of 2080s which goes in input to the model (Simulink model validated with Gas Turbine Simulation Program) in the form of PLA command, altitude and airspeed. The simulation is repeated for different ages of the battery, ranging from new (1 cycle) to 401 cycles. The energy management strategy is set by a supervisory controller on the basis of fuzzy rules which consider power request, battery SoH and deviation of actual SoC from a reference SoC (ideal battery discharge obtained with the application of a DPM which guarantees minimum fuel usage and electric backup availability during the entire mission). At this point, a dual strategy has been tested: in one case, the RSoC is considered that of a new battery; in the second case, the RSoC is interpolated with battery age to take into account the effects of battery performance decay. In fact, the RSoC curve was been previously obtained by running the mission in electric mode with both new and aged battery and resulted in a minimum allowed SoC of 60% for the new battery and 70% for incipient end of life battery to complete the mission safely (see [**Errore. L'origine riferimento non è stata trovata.**]). The typical RsoC curves are depicted in Fig. 2.

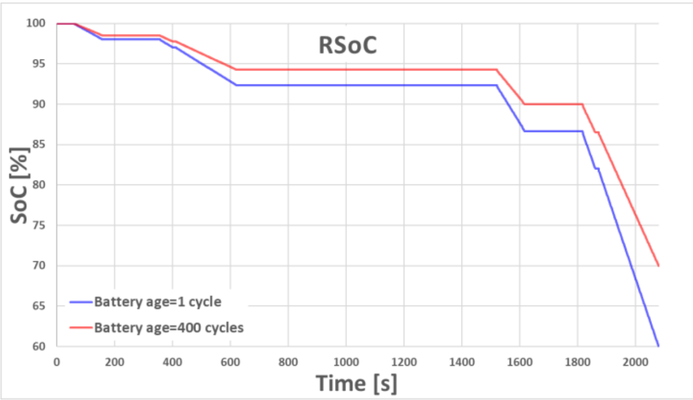

Fig. 2. Reference State of Charge of new and aged battery.

Of course, the output of both strategies is the same when the battery is at the beginning of its life, while the difference in electric machine usage becomes more evident with battery aging: in fact, if battery age is not neglected, the supervisory controller will determine a lower torque load for the electric part with increasing number of cycles, at the expense of a higher recourse to thermal engine. The implications of these strategies in terms of fuel consumption and battery charge depletion will be evaluated in the following section.

3 Results and Discussion

The torque ratio of electric to total request (named k), resulting as output from the supervisory controller with both RSoC curves (either interpolated with battery age or typical of new battery), is depicted in Fig. 3 on varying battery age every 100 cycles.

Obviously, the electric torque request is always lower when battery age is taken into account. Moreover, k gradually decreases with battery age for both strategies, since fuzzy logic rules built in the supervisory controller take as input battery SoH, too. The latter is strongly affected by internal resistance increase, declining from more than 90% at the beginning to 75% at the end of life. Note that, in the last 100 cycles of battery life, recourse to electric power source is zero and all the power request is loaded onto the turboshaft engine.

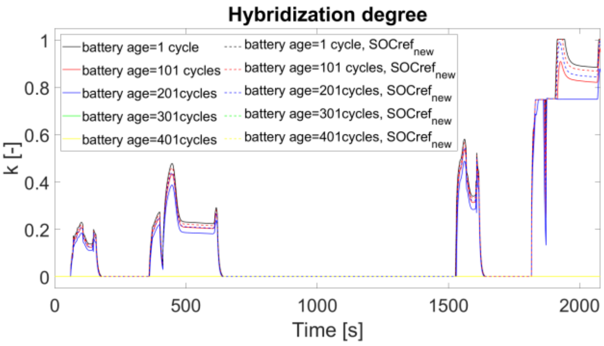

Fig. 3. Hybridization degree along the mission.

The amount of fuel required to run the mission is shown in Fig. 4.

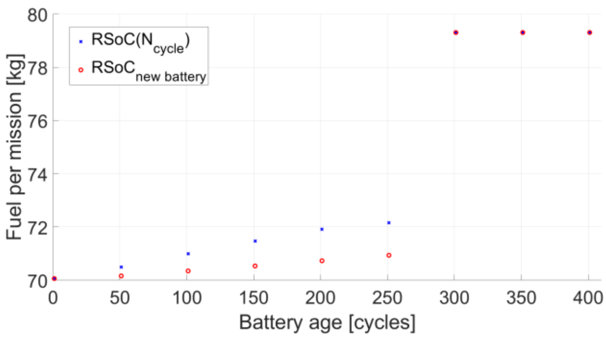

Fig. 4. Total fuel consumption.

As it can be seen, the worsening of battery SoH has a huge negative influence on fuel consumption. The slight difference in k due to dependence of RSoC from cycle number results in a weak increase of fuel consumption for the age-dependent strategy. Such increase is quite negligible during battery early life, becoming more evident with cycle number increase, as long as the turboshaft power request becomes higher (the maximum difference between the two strategies is noticeable at 250 cycles, when the age-dependent strategy consumption is higher by an amount of 1.7% with respect to age-independent strategy at the same cycle number). However, fuel consumption at battery end of life can be considered as a benchmark, representing the amount of fuel that would be required by a only-thermal propulsive system, so that an estimate of fuel savings due to the hybridization of the system can be made: a percentage as high as 11.7% could be saved thanks to system electrification (in the best case, that is with new battery).

Finally, the battery SoC at the end of mission is given in Fig. 5.

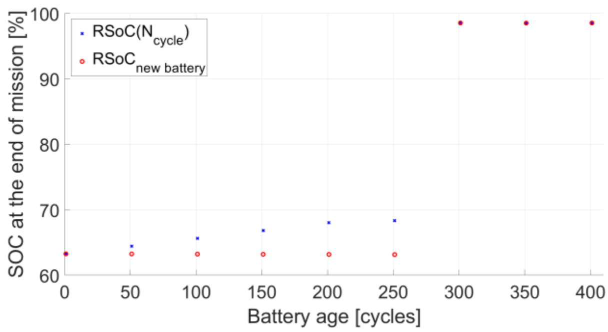

Fig. 5. Battery State of Charge at the end of mission.

The battery is exploited almost until SoC threshold value (60%) when battery aging is neglected, except for the last 100 cycles when the too low SoH determines k to go to 0, so that SoC remains unaltered at its initial value. However, discharging the battery up to 60% independently of its age is against safety because the battery will not be able to perform an electric back-up operation in case of engine failure.

4 Conclusion

In the present study, authors intended to evaluate the impact of battery aging on fuel consumption and battery discharge of a parallel HEPS whose energy management strategy for a given mission is determined by a unique set of fuzzy rules implemented into the supervisory controller.

In particular, it has been evaluated how raising SoC threshold to compensate for battery aging effects, and thus ensure electric operation in case of engine failure even with aged battery, affects overall fuel consumption and battery discharge.

As expected, since age-dependent strategy reduces recourse to electric motor torque with increasing cycle number, this results in slightly higher consumption when such strategy is adopted. Though, it must be said that this increase is quite negligible, especially considering that minimum SoC level necessary to have electric backup available could be violated by the other management.

Both strategies revert to only-thermal mode when the battery becomes too aged, because of prevailing SoH decay.

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