Commun Nonlinear Sci Numer Simulat 15 (2010) 1308–1317

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

journal homepage: www.elsevier.com/locate/cnsns

# A fractional order model for lead-acid battery crankability estimation

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ARTICLE INFO

*Article history:*
Received 25 April 2009
Received in revised form 30 May 2009
Accepted 30 May 2009
Available online 7 June 2009

*PACS:*
02.30.Yy Control theory
82.47.Cb Lead-acid battery
89.40.Bb Land transportation

*Keywords:*
Fractional systems
System identification
Lead-acid batteries
Vehicle cranking

ABSTRACT

With EV and HEV developments, battery monitoring systems have to meet the new requirements of car industry. This paper deals with one of them, the battery ability to start a vehicle, also called battery crankability. A fractional order model obtained by system identification is used to estimate the crankability of lead-acid batteries. Fractional order modelling permits an accurate simulation of the battery electrical behaviour with a low number of parameters. It is demonstrated that battery available power is correlated to the battery crankability and its resistance. Moreover, the high-frequency gain of the fractional model can be used to evaluate the battery resistance. Then, a battery crankability estimator using the battery resistance is proposed. Finally, this technique is validated with various battery experimental data measured on test rigs and vehicles.



## 1. Introduction

More and more drastic automobile pollution norms and oil price increase lead car manufacturers to design new vehicles (stop and start, hybrid, or electric). The underlying idea is to reduce exhaust emissions in the built-up areas, either by stopping motor when the vehicle is not moving or by a substitution of fossil fuel by electric fuel.

To keep these new vehicles in good working order, car manufacturers must integrate a reliable electrical energy storage management in their vehicles. For electrical energy storage, various batteries, fuel cells and supercapacitors are actually studied. For the electrical energy management, State Of Charge (SOC), State Of Health (SOH) and also State Of Function (SOF) estimators of the storage system must be designed.

Many reliable battery state estimators were proposed all over the world. Most of them deal with SOC estimation exclusively [1,2]. The interested reader can consult [3] for a presentation of some methods and [4] for a specific application to battery monitoring in future vehicles. Nevertheless, a reliable battery monitoring system design remains a difficult task because on one hand, the estimator must have all the following advantages:

- good estimation accuracy,
- real-time working,

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doi:10.1016/j.cnsns.2009.05.067

- immediate estimation,
- robustness to operating conditions.

On the other hand, a battery is a complex electrochemical system whose behaviour is:

- non-linear in relation to a current input signal,
- sensitive to temperature and age,
- with long memory due to diffusion phenomena.

In this paper, only lead acid batteries are studied because they are the most widely used in cars. However, the SOF estimator proposed could be easily extended to other battery types. This method is based on system identification by a fractional order model of the battery behaviour. Fractional behaviour of lead-acid batteries has been demonstrated for a long time by chemists but only few existing estimation methods take into account this behaviour. Such a situation can surely be explained by the lack of tools for fractional systems analysis and modelling until fifteen years ago. These tools now exist [5–7]. In system identification field, several methods were created [8,9] and permit now to take into account systems that exhibit long memory phenomena (diffusion processes). Interest of these methods is the computation of low order (and thus low parameter number) models. This property is used in this paper for the lead-acid batteries behaviour modelling. Given the small number of parameters in the obtained model, a simple and efficient estimation method can be designed. The proposed method is particularly attractive for SOF estimation when the vehicle starts. It takes into account operating temperature changes and the long relaxation time of the battery. The high current level (about 1 kA), supplied by the battery to the starter, is especially used to provide information on the battery power availability and consequently the battery crankability.

Fractional differentiation has found numerous applications in fields like physics [20], finance [24], chemistry [23], bioengineering [21]. This paper is thus a new application in engineering [22] and is organized as follow. Section 2 shows that a vehicle cracking is an interesting operating phase to evaluate the battery resistance or its lack of power. Section 3 highlights the fractional order behaviour of a lead-acid battery and presents the fractional order model used to characterize this behaviour. System identification method implemented in the SOF estimation method is described in Section 4. The identification method is then applied to signals recorded during a vehicle cranking. The battery resistance and crankability estimation method are detailed in Section 5.

## 2. Interest in vehicle cranking signals

It is no longer possible to provide battery monitoring systems without taking into account the ageing. In practice, such systems would not be reliable during all the battery service life. In electrochemistry, the battery ageing can be defined as an irreversible degradation process of its performances due to various phenomena (sulphating, corrosion, loss of active material ...) resulting in the battery use. In the automobile industry, the battery ageing can also be defined as a gradual and irreversible incapacity to supply energy and power required for the vehicle functions.

The battery breakdowns mostly occurred during the coldest months of the year, because the battery is less powerful at low temperature. If the vehicle does not start and if it is really due to the battery, two situations can take place:

1 – the battery is discharged, then a recharge is enough,
2 – the battery is dead, a replacement is required.

Battery breakdowns are expensive not only for the customers but also for the car manufacturers during the warranty period. As a result, a reliable battery state estimator is important for both customers and car manufacturers to discriminate, for instance, the previous situations 1 and 2.

A good way to achieve this goal is to analyze in details the cranking function, because this is the most important function in the vehicle. The notion of crankability can be defined as the battery capability to start the vehicle engine.

Current and voltage signals of Fig. 1 have been recorded on a cranking vehicle. The duration of each voltage and current signals arcs is equal to half an engine revolution. It is a consequence of the four-stroke cycle (during two revolutions of the crankshaft) operating in car combustion engines.

The cranking produces a low discharge of the battery. The capacity of the battery used to produce signals in Fig. 1 is equal to 60Ah or 216,000C (1Ah = 3600C), which greatly exceeds the 300C required to start the engine (example in Fig. 1). On the other hand, the cranking needs a very high power, exceeding several kilowatts (Fig. 2). The vehicle cranking thus provides interesting information on the battery available power without modifying its state.

Also, the resistance of a new battery is approximately equal to 5 mΩ. Thus, a 9 A pulse will produce (about) a 45 mV battery voltage variation, compared to 4,5 V for a 900 A pulse. Obviously, the higher the current, the easier and more accurate the resistance measurement (better signal-to-noise ratio).

Moreover, a battery resistance estimation method based on cranking is not expensive, because there is no need to apply a special signal to the battery (generated by an additional device). Such an analysis permits to conclude that the cranking is a really interesting vehicle operating phase to estimate the battery resistance.