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A cycle-based and multirate approach for power system simulation application to the ageing estimation of a supercapacitor-based ferry

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ABSTRACT

This paper presents a general multi-rate method for the simulation of power systems with a wide range of time scales and with high mutual dependency between the fast and slow state variables. The original concept developed in this work relies on a cycle-based problem formulation, which consists in finding the repeating operation sequences of the system, at the different time scales. Next, a discrete form version of a conventional second order variable step solver is proposed and allows the extrapolation of the results beyond a large number of cycles, while maintaining and controlling a predetermined error tolerance on the state variables. This cycle-based formulation is applied to the ageing behaviour simulation of the energy storage unit of an all-electric ferry which only uses supercapacitors as energy storage. This problem needs the simulation of the electrical power operation of the boat, throughout its lifetime of 20 years. With this original cycle-based formulation, the computation effort can be reduced by several hundreds while maintaining low error tolerances.

1. Introduction

More and more power conversion and storage applications rely on complex and heterogeneous architectures. These multi-physical systems also depend on a large number of parameters that must be optimized making the simulation of such complex systems a major challenge [1–4]. Mathematical modelling of power conversion and storage systems leads to a set of differential equations which describe different phenomena from different natures. Today, many multi-physics simulation platforms are available and allow to readily combine different physical domains [5,6]. They are most of time based on acausal modelling approach, founded on the same principle as the Bond-Graph and using physical connections [7]. It facilitates the construction of large and complex systems by making physical models as flexible and reusable as possible [8]. But even if the modelling is largely simplified by these new tools, it still remains to efficiently simulate such a complex system, which solution requires the simulation of non-linear differential equations and mainly leads to the computation of stiff systems. These stiff systems are described by different ranges of time scales related to the physical domains taken into account. For instance, stiffness can appear when modelling an energy storage device by coupling the thermal and the electrical models with multiple chemical reaction processes. Once again, to solve efficiently these systems, there are different tools and approaches to improve the performance or stability of numerical solvers. Well adapted method for this kind of problem is the multirate methods [9,10]. The basic principle of this method is to split the system into sub-systems allowing to define local solvers, adapted to the constraints and dynamics of each physical layer of the model [11,12]. The coupling between the different models is generally obtained by approximating the slowly varying solution components [9,13]. However, these methods become ineffective for systems in which the fast response is sustained for a large portion of the simulation interval. A good example that illustrates this kind of problem is the simulation of a power converter, controlled with a pulse width modulation (PWM) [14,15]. It is found that even for a very simple system (i.e. stiffness and in *steady state*), its simulation is only possible by adapting the sampling time at a much lower value than the switching period. Then, even with an efficient variable step solver, it is only possible to limit the number of evaluations per period, but never to go beyond it. In fact, what is considered as a steady state in such a power converter are the *average values* for the current and voltage plus an high frequency ripple due to the PWM controller. The method proposed in [16], which is the most used today, permits to avoid this problem by working with average values. The idea is to replace the power stage by two switched models. In the framework of the piecewise linear

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systems, it is possible to deduce a single equivalent linear circuit which is then only set by the value of the duty cycle and switching frequency [15,16]. This approach can be seen as an homogenization method, where only the system state variation per period is considered.

It turns out that this problem can be easily extended to applications working with operation cycles. For instance, the design of the powertrain for public transport applications is commonly based on a representative driving cycle. For these applications, the results obtained for one cycle are extrapolated on the lifetime of the vehicle by considering a given driving schedule per day, week or year [17,18]. For the sizing of hybrid power systems with renewable energies (especially solar and wind), the simulation is generally done for one year, through the extrapolation of few days per week or per month [19,20]. This raises the question of the selection of the simulation horizons, which appear in many works arbitrarily chosen.

It therefore seems appropriate to look for a general formalism for the simulation of cycle-based multi-physics systems. This paper attempts to address this problem through an original concept of multi-layer cycle formulation. Indeed, the objective is to propose a method which consist in finding the different repeating sequences at the different time scales, from a limited number of elementary problems. These problems can be easily implemented in the classical multi-physics simulation platforms. The next step is to adapt the conventional variable step solvers to discrete problems, permitting the extrapolation of the results beyond the cycle, while maintaining and controlling a predetermined error tolerance on the state variables. Error estimate can be performed thanks to the embedded methods, which are based on the comparison of two different methods with different orders.

This cycle-based formulation is applied to the ageing behaviour simulation of the energy storage unit of an all-electric ferry which only uses supercapacitors as energy storage [21,22]. The simulation should be performed for 20 years of operation with a known power profile. To compute the lifetime of this storage unit, electrical and thermal models are coupled with an ageing model. This multi-physics system is represented by a set of ordinary differential equations and algebraic differential equations containing different time constants associated to each model. It is implemented in Matlab/Simscape, which is an acausal modelling tool, permitting to solve such a multi-domain problem. The proposed multi-rate and cycle-based methodology is then applied to this system and permits to reduce the computation time by hundreds while controlling the error estimate of the state vector.

The paper is organized as follows. In Section 2, the general problem formulation is presented. It is based on a reformulation of a continuous but cyclic problem, into a recursive discrete system. The formulation is then extended to the multi-layer concept, permitting to describe a cycle as a function of other subcycles, at different time scales. A second order modified one-step embedded method is then proposed to solve this new discrete problem with variable time step. Section 3 is focused on the application of the method to the supercapacitor-based ferry previously described, with a two-layers cycle description. Numerical results for several imposed tolerances are presented and then compared and discussed. Section 4 is the conclusion.

2. Problem formulation

2.1. Cycle-based formulation and homogenization

The multilayered formulation proposed in this paper is based on an initial homogenization step which is presented in this section. This method assumes that the problem to be addressed can be decomposed into a finite number of elementary cycles, named *cycle-based formulation*. So, we consider a series of k subproblems, each one defined by a nonautonomous ordinary differential equation (ODE) such as:

$$\dot{x} = f_i(x,t),\ i \in [1;k] \tag{1}$$

Each elementary problem $f_i(x,\ t)$ is simulated on a time lap T_i, corresponding to an elementary cycle simulation. The simulation of each cycle permits to pass from an initial state x_n to the next state x_{n+1}, such as (see Fig. 1):

$$x_{n+1} = x_n + \int_{t_n}^{t_n+T_i} f_i(x,t)\,\mathrm{d}t \tag{2}$$

The proposed method consider that the evolution of the state vector $x(t)$ can be substituted by its average rate of change at the scale of an elementary cycle of length T_i. This averaging method is well known in power converter modelling [14,16,23,24] where the electrical state variables are replaced by their mean value, at the scale of the switching frequency.

Here, this approach is generalized to any kind of cycle. The average state vector derivative at the scale of T_i is given by the next equation:

$$F_i(x_n,t_n) = \frac{1}{T_i}\int_{t_n}^{t_n+T_i} f_i(x,t)\,\mathrm{d}t \tag{3}$$

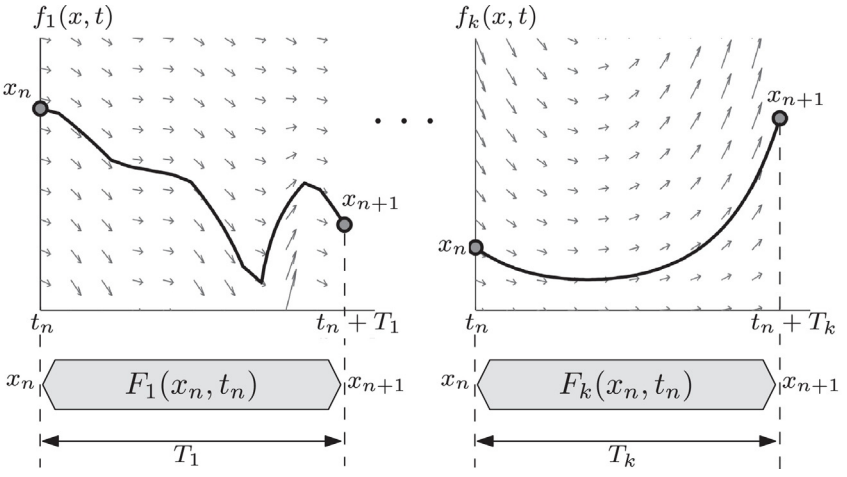

Fig. 1. Illustration of the decomposition of a continuous problem into k-nonautonomous ordinary differential equations.