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Efficient simulation of Hybrid Renewable Energy Systems

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ABSTRACT

This article explores the usage of novel tools for realistic modeling and efficient simulation of Hybrid Renewable Energy Systems (HRES). Using the object oriented Modelica language, a new library providing component models such as photovoltaic (PV) cells, proton exchange membrane (PEM) fuel cells, electrolyzers, hydrogen storage tanks, batteries and electronic converters is developed and used to build different HRES models. Since the components are represented under realistic assumptions, the resulting models exhibit frequent discontinuities, strong non-linearities and combinations of slow and fast dynamics (i.e. stiffness). As these features impose severe limitations to classic numerical simulation solvers, we analyze the use of a new family of numerical algorithms called Quantized State Systems (QSS) that overcome most of those difficulties. The results obtained show that these algorithms applied to realistic HRES are more than one order of magnitude faster than the most efficient classic solvers, allowing to simulate these systems in reasonable times.

Introduction

Standard HRES consist of arrays of photovoltaic panels and/or wind generators powering AC, DC or mixed loads [1]. Since energy supplied by renewable sources depend mainly on environmental conditions, it is necessary to use energy storage systems to reduce the consequent power variations. For this reason, batteries are usually a necessary component of HRES [2], that can be complemented by fuel cell (FC)–electrolyzer [3].

The design of some of the control units, particularly those that act on the switching power supplies that connect the different elements, strongly affect the efficient operation of these systems. Due to the complexity of the resulting mathematical models, it is necessary to use numerical simulations for dimensioning the different components, and for designing and tuning the controllers.

The presence of switching elements in the DC–DC converters operating at high frequencies impose several difficulties to classic numerical integration methods. The reason is that, in order to obtain decent results, the algorithms must perform several calculations to compute the time of each discontinuity [4], restarting the simulation after the occurrence of each event. Moreover, realistic representation of the

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switching elements (diodes and transistors) may results in stiff models (i.e., with simultaneous slow and fast dynamics) requiring the use of implicit numerical solvers that perform expensive iterations and matrix inversions. Consequently, the simulation of a few minutes of a realistic HRES can take several hours of CPU time even in modern powerful computers.

To overcome this problem, switching converters are usually represented by time–averaged models [5–7]. This simplification, which is adequate to solve many problems, is limited to particular operating conditions and hide some real phenomenons such as transient discontinuous conduction in the converters, the harmonic content they introduce, the presence of failures in some switching components, etc. Thus, in cases where these phenomenons are relevant, the replacement of power electronic converters by their time–averaged models is not possible and the simulation with conventional numerical solvers experiences the aforementioned problems. In order to make simulations suitable, only a few seconds of the system evolution is actually simulated [8].

However, there is a new family of numerical integration algorithms called Quantized State System (QSS) [4]. These methods replace the time discretization of classic solvers by the quantization of the state variables. A remarkable feature of QSS methods is that they are very efficient in the simulation of ordinary differential equations (ODEs) with frequent discontinuities. There are also Linearly Implicit QSS (LIQSS) methods that are very efficient to simulate some stiff systems [9]. Thus, it can be expected that LIQSS algorithms can efficiently simulate HRES without making use of time–averaged models. In fact, it has been already shown that LIQSS algorithms are very efficient to simulate different topologies of DC–DC converters [10], which constitute a critical component of HRES as well as smart–grid models [11].

A limitation of the QSS methods was that its implementation required the use of specific software tools that were unfriendly to describe complex models such as HRES. However, an autonomous QSS solver [12] was recently developed that can simulate models previously translated from Modelica representations making use of a novel compiler [13]. Modelica [14], is a standard object oriented modeling language where models can be easily defined and composed to form complex systems making use of different available graphical user interfaces and existing multi-domain component libraries. That way, a DC–DC converter, for instance, can be easily modeled by connecting the corresponding electrical components from the existing Modelica electrical library and then it can be used as part of the HRES model. Making use of the mentioned Modelica compiler, the resulting model can be then automatically simulated by the QSS solver.

In this work we first developed a Modelica library of realistic HRES components, including models of PEM fuel cells, electrolyzers, hydrogen storage tanks, batteries, converter controllers and switched models of most typical DC–DC converters. Then, we used the library to build different configurations of HRES and simulated the models using classic solvers and LIQSS methods. The analysis of the simulation results shows that LIQSS can simulate these complex systems in reasonable CPU times (near to real–time, in fact), speeding up more than 10 times the results of classic ODE solvers.

The paper is organized as follows: Section Modeling and simulation tools introduces the modeling and simulation tools used along the rest of the work, then Section HRES Modelica library describes the HRES, their components and the corresponding Modelica library. Section Simulation results shows and discusses the simulation results, and finally, Section Conclusions concludes the article.

Modeling and simulation tools

In this section we introduce the tools used along the article. We first describe the Modelica language used to define the libraries and models. Then, we recall the main features of classic ODE solvers and their difficulties to simulate HRES models and we introduce the QSS family of numerical algorithms. Finally, we present a tool chain that allows to simulate Modelica models using the QSS methods.

Modelica

Modelica [14] is an open object–oriented declarative modeling language that allows the combination of models coming from different technical domains in a unified way. In Modelica, elementary mathematical relationships between variables are described by non–causal equations to form basic subsystems, that are then connected together to compose more complex systems. Then, for simulation purposes, the resulting models are processed by Modelica compilers in order to produce the simulation code.

For instance, an electrical connector can be defined by the following Modelica class:

```
connector pin
  Real v;          //potential
  flow Real i;     //current
end pin;
```

Here, pin is a class of type connector characterized by two real variables representing the potential and current. This new class can be used to define a generic one–port element composed by two pins as follows:

```
model oneport
  pin p;          //positive pin
  pin n;          //negative pin
  Real v;         //element voltage
  Real i;   //element current
equation
  i=p.i;
  p.i+n.i=0;
  v=p.v-n.v;
end oneport;
```

This generic one–port model can be used to derive specific elements like resistors, inductors, etc:

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