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On the order reduction of the radiative heat transfer model for the simulation of plasma arcs in switchgear devices

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ABSTRACT

An approach to derive low-complexity models describing thermal radiation, employed to simulate the behavior of electric arcs in switchgear systems, is presented. The idea is to approximate the (high dimensional) full-order equations, describing the propagation of the radiated heat intensity in space, with a model of much lower dimension, whose parameters are identified by means of nonlinear system identification techniques. The proposed order reduction approach is able to systematically compute the partitioning of the electromagnetic spectrum in frequency bands, and the related absorption coefficients, that yield the best matching with respect to the finely resolved absorption spectrum of the considered gaseous medium. In addition to the order reduction approach and the related computational aspects, an analysis by means of Laplace transform is presented, providing a justification to the use of very low orders in the reduction procedure as compared with the full-order model. Finally, comparisons between the full-order model and the reduced-order one are presented.

1. Introduction

The switching performance of circuit breakers depends strongly on the behavior of the electric arc that originates when the contacts are opened in the presence of relatively large electric current values [36,8]. In turn, the arc dynamics are influenced by multiple interacting physical phenomena which, together with the short timescale of the arcing event and the large values of temperature and pressure, increase the complexity and difficulty of understanding, carrying out experiments, and deriving numerical models of the switching behavior. Computational fluid dynamic (CFD) approaches are being used in both public and private research efforts to simulate the time evolution of the plasma that carries the current during the interruption process, see e.g. [13,6,2,18]. The CFD simulations are often coupled with solvers for the electro-magnetic (EM) phenomena, resulting in sophisticated multi-physics simulation tools (see [6,18]) that allow one to gather an insight of what is actually happening during the current interruption process – aspects that are very difficult to quantify with direct measurements, for the above-mentioned reasons. Such simulation tools provide a significant added value to explain the results of experimental tests and to support the development of switchgear devices, however they also bring forth an important issue in addition to the inherent difficulty of plasma modeling: the need to find a good balance between the accuracy of the employed physical models and their computational complexity. The modeling of radiative heat transfer during the arcing process is an illuminating example of such an issue.

Radiation is one of the most important cooling mechanisms during switching, as it redistributes the heat

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produced by the current flowing through the plasma and transfers part of this power to the boundaries. Hence, accurate models of radiation are of fundamental importance to simulate the arc behavior, which is, due to the physics of radiation at the temperatures present in the plasma, a challenging task. Typically, the core of the arc is heated up to 25,000 K, meaning that the EM radiation emitted by ions, atoms, and molecules of several different species (e.g. nitrogen, oxygen, copper) have to be taken into account. The relevant window of the EM spectrum ranges from 3×10^{13}–6×10^{15} Hz, corresponding to wavelengths between 10^{-5} m and 5×10^{-8} m, i.e. from infrared to ultraviolet. The main difficulty in simulating the EM radiation emitted by an arc derives from the complexity of the emission spectrum, where the relevant property, the absorption coefficient, changes by many orders of magnitude at spectral lines of which several 10,000 exist in the range under consideration. The propagation of radiative heat in space for each frequency is modeled, under assumptions that are reasonable for the arcing phenomena encountered in switchgear devices, by a first-order differential equation taking into account the absorption and the emission of radiation along the direction of propagation. The energy removed from the arc is with this defined by the temperature, pressure, and composition distribution within. Due to the complexity of the emission spectrum, a simple discretization according to frequencies leads to hundred thousands of very thin frequency bands; within each one of such bands the absorption coefficient can be assumed to be constant for fixed temperature, pressure and composition of the gaseous medium. This, however, leads to the same number of three dimensional field equations which need to be solved. Given the large number of finite volumes that have to be considered in CFD simulations of realistic geometries (see e.g. [28]), the use of such a large-scale radiation model is not feasible. Hence, there is the need to derive models for the radiative heat transfer with much lower complexity, possibly without compromising too much the accuracy as compared with the large-scale model.

This issue has been tackled by several contributions in the literature [19,30,15,26]. Most of the existing approaches consist in discretizing the fraction of the EM spectrum of interest into few bands, and assuming for each one some averaged absorption properties. The mentioned approaches have the advantage of being quite simple to implement, however in principle one should optimally choose ad hoc different bands and averaged absorption coefficients as a function of pressure, temperature and chemical composition of the considered medium, since the radiation parameters are affected by all these aspects. If the bands and/or the averaged absorption coefficients are not chosen in an appropriate way, the model accuracy is worse and more bands are needed to improve it, resulting in a relatively large number of bands (6–10) in order to achieve accurate results with respect to the original, large-scale model. Hence, this procedure can be time consuming, not trivial to carry out in a systematic way, and ultimately suboptimal in terms of complexity/accuracy compromise.

In this paper, we present a new approach to derive small-scale, band-averaged models of the radiative heat transfer. We first describe the problem of radiation modeling from a novel perspective, where the aim is to approximate the input–output behavior of a large scale, linear-parameter-varying (LPV) dynamical system with that of a low-order one. The large scale system has one input (black-body intensity), one output (radiated intensity), three scheduling parameters (temperature, pressure and composition), and a large number of internal states (one for each considered frequency of the EM spectrum), while the low-order LPV system has the same input, output and scheduling parameters, but just a handful of internal states. From this point of view, the problem can be classified as a model-order reduction one [23]. Then, using classical tools for the analysis of signals and dynamical systems, we provide evidence that indeed models with quite low order (typically 2–3 bands) can be already good enough to capture the main behavior of the full-order model. Finally, we tackle the order reduction problem by using nonlinear system identification techniques (see e.g. [24]), where we collect input–output data from the large-scale system and use it to identify the parameters of the reduced-order model. The approach results in a nonlinear optimization problem (nonlinear program – NLP) with a smooth non-convex cost function and convex constraints, which are needed to preserve the physical consistency of the reduced-order model. We show through examples that the obtained reduced-order models enjoy a high accuracy with respect to the full-order one, while greatly reducing the computational times. As compared with the existing approaches, the method proposed here has the significant advantage of being systematic, i.e. there is no need to tailor or tune it for each different composition of the absorbing/emitting medium. The main user-defined parameter is the desired number of frequency bands in the reduced-order model, which can be then increased gradually until the desired tradeoff in terms of model quality vs. complexity is reached.

The paper is organized as follows. Section 1.1 collocates the present work in the wider context of arc simulation activities carried out at ABB Corporate Research to support the development of switchgear. Section 1.2 provides a formal description of the problem we tackle. In Section 2, such a problem is analyzed from a system's perspective and connections are made to the order reduction of a large-scale LPV dynamical system. The proposed computational approach is described in Section 3, finally results are presented in Section 4 and conclusions and future developments are discussed in Section 5.

1.1. The Arc Simulation Tool

The Arc Simulation Tool is a simulation suite developed at ABB Corporate Research with the aim to model the behavior of electric arcs in switchgear [28,9]. In the tool, the electric arc is treated using the magneto hydrodynamic (MHD) approach [34,31], where the dynamics of electrically conductive fluids are represented combining the Reynolds-averaged Navier–Stokes (for the fluid part) and Maxwell (for the EM part) equations. In addition, equations for the radiative heat transfer are computed, since one of the dominant energy redistribution processes inside