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An Adaptive Framework for Efficient Simulation of Nonlinear Power Electronic Circuits

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Abstract: While modelling power electronic circuits (PECs) for detailed and accurate simulations, effects such as parasitics, reverse-recovery, saturation nonlinearities etc. need to be considered. This helps in gaining a better insight into the actual circuit operation on the breadboard. The goal is to obtain simulation results which are as close as possible to the hardware measurements. However, the simulations of these detailed models are extremely slow due to the large spread of the eigenvalues. This class of systems are stiff in nature and cannot be solved very efficiently using conventional simulation approaches. To tackle this problem, we propose an adaptive simulation scheme where the model order varies as the simulation proceeds. By approximating the dynamics of the non-dominant eigenvalues with constant terms, simplified models of PECs are derived. These approximate models of varying resolutions or orders, corresponding to different levels of accuracy are extracted from a given model during the online simulation phase with no extra computing burden. The simulator is designed to automatically jump across resolutions such that a combination of the approximated and the original models is simulated. This approach is shown to be a powerful tool for fast simulations of PECs. The simulations using this approach accurately replicates the original system dynamics and at the same time, are significantly faster with minimum approximation error.

Keywords: Computer-aided simulation; model order reduction; power electronics.

1. INTRODUCTION

Models describing power electronic circuits (PECs) are stiff in nature due to the presence of both fast and slowly evolving variables. The time-constants of these models span multiple orders in terms of magnitude. This makes the simulation extremely slow. Simulations of these circuits are conventionally carried out with variable-step size methods. Even with these variable step-size solvers, simulations are slow and often time consuming. The problem gets compounded when accurate simulations are required and when nonlinearities of the circuit elements have to be taken into consideration. The goal is to make use of simulation tools (Evans et al., 2016) for accurate estimation of parasitic effects, electromagnetic interference, thermal interactions etc. which may come into the picture during the fabrication of the device prototype. Also, in the design optimization process, numerous iterations are to be performed to meet certain set criteria. Unnecessary cost overshoots can be prevented and the prototype can be manufactured right in the first attempt.

Numerous methods have been proposed to simplify the problems in high-fidelity PEC simulation. Some of them include circuit averaging, multirate methods (Kato et al., 2009, 2007) and decoupled simulation (Deml and Turkes, 1999), to name a few. Model order reduction (MOR) methods (Benner, 2021). where the aim is to approximate a given system with its reduced-order model (ROM), have also been used to address the issues in computationally expensive simulations. Some examples include (Osipov and Sun, 2018; Evans et al., 2016; Li et al., 2017).

Here we present a novel adaptive multi-resolution simulation (AMRS) framework to efficiently simulate detailed high-fidelity models of PECs with nonlinear elements. Using singular perturbation principles, and taking advantage of the wide span of the time-constants, simplified models of varying resolutions or orders on-the-fly from a given circuit model. An adaptive switching across resolutions is performed by the simulation engine which ensures that a combination of these models is simulated.

Each of these models corresponds to a given accuracy level (Chapman, 2004) with the maximum resolution model being the most accurate representation of the circuit. These models are extracted from the system by using the concept of eigenvalue dominance and considering the steady-state contribution of the non-dominant eigenvalues. It has to

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