IET Circuits, Devices & Systems

Research Article

Journals
The Institution of Engineering and Technology

Adaptive multi-resolution framework for fast simulation of power electronic circuits

ISSN 1751-858X
Received on 16th July 2019
Revised 17th October 2019
Accepted on 4th February 2020
E-First on 30th April 2020
doi: 10.1049/iet-cds.2019.0320
www.ietdl.org

Hadhiq Khan[1] ✉, Mohammad Abid Bazaz[1], Shahkar Ahmad Nahvi[2]

[1]*Department of Electrical Engineering, National Institute of Technology Srinagar, Jammu and Kashmir, India*

[2]*Department of Electrical Engineering, Islamic University of Science & Technology, Awantipora, Jammu and Kashmir, India*

✉ *E-mail: hadhiq@nitsri.ac.in*

Abstract: An adaptive multi-resolution simulation (AMRS) framework for fast and accurate simulation of high-fidelity models of power electronic circuits (PECs) is presented in this study. The wide span of eigenvalues makes PEC simulation prohibitively slow. This problem can be tackled using the proposed approach. Singular perturbation approximation is used to extract simplified models by ignoring the transient contribution of the non-dominant eigenvalues. Simplified models of different orders or resolutions, each corresponding to a particular level of accuracy are derived on the fly at no additional computational cost. The simulation engine is set such that it adaptively switches across resolutions based on a predefined tolerance during the simulation. This approach is advantageous in the sense that instead of simulating the original model over the entire time-range, a combination of the original and simplified models is simulated. The combined use of the original and the simplified models is thus shown to be a powerful tool for efficient and accurate simulation of PECs. The examples illustrated, show that the AMRS approach makes the simulation considerably faster and ensures the complete response of the system is obtained with negligible error. The method is illustrated on a Class-E amplifier and a DC–DC buck–boost converter.

1 Introduction

Power electronic circuits (PECs) are known to have time constants spanning multiple orders of magnitude. The switching transitions in these circuits are of the order of micro or nanoseconds whereas load transients or closed-loop start-up transients may last for seconds or minutes [1]. To capture the fastest transients and to ensure convergence, an extremely small time-step has to be taken. Also, to factor-in the large time constants, the simulation must continue for a few hundred or more conversion cycles till steady-state is achieved. Simulation of power-electronic-based systems is thus a time-consuming process.

In situations where computation of the peak voltage and current stresses, determination of switching losses or precise detection of switching events etc. is of critical importance, detailed high-fidelity models have to be used [2]. This further escalates the simulation problem. In addition, accurate simulation is desired so that repetitive design alterations and breadboarding of PECs are minimised. The idea is to use software for evaluation of the performance of the systems for precise prediction of electromagnetic interference, evaluation of complex parasitic, thermal and mechanical effects which may arise while fabricating the hardware prototype. During the design optimisation process, many iterations have to be carried out to satisfy the target performance criteria. This helps in preventing unwanted cost overruns and helps to get the prototype ready in the first attempt.

For simulating systems where the rates of change of variables are almost the same at all times, fixed step-size methods such as Euler, Runge–Kutta etc. work well [3]. For stiff systems where the rates are not constant and the slow and fast variables occur at different times, variable-step-size methods are used. A small time-step is chosen to capture the fast transients, which is gradually increased to capture the slow transients and obtain the long-term steady-state response of the system. In another category of systems, slow and fast variables are often present at the same time. Such systems are referred to as multirate systems [4]. At least one fast variable is always present. This makes the simulation inefficient for the slow variables that could have been efficiently solved with an increased step-size. The advantages of the variable-step-size methods are thus nullified in these systems. PECs generally belong to this category [5].

Several attempts have been made to solve and simplify the PEC simulation problem. In the circuit averaging method [6], the circuit is split into fast and slow subcircuits and the dynamics of the fast subcircuit is averaged out. This method, however, ignores the ripple and switching dynamics. Decoupled simulation approach [7] uses a transmission line model to link the two subcircuits. The disadvantage is that the switching cycles of the fast subcircuit cannot be omitted. In the envelope-following methods, even though the circuit is not split, only the shortest periods of the circuit can be tracked [1]. Multirate simulation methods [5, 8] have also been used to accelerate the simulation of PECs where the partitioned subcircuits are solved with different time-steps.

Alternatively, model order reduction (MOR) methods can be used to simplify the PEC simulation problem. MOR aims at finding a reduced-order model (ROM) which approximates the dynamics of the original system. Some examples are in [9–14].

Some applications of MOR to PECs are mentioned here: in [15], a discrete-time state-space model based on the sampled-data modelling approach has been proposed. Starting with a generalised discontinuous current and voltage mode, the continuous mode, discontinuous current mode and the discontinuous voltage mode are derived as special cases. Then, ROMs are derived using principal component analysis (PCA) from the balanced realisation of the system. It is shown that the order reduction in all modes is possible after analysing the controllability and the observability gramians of the balanced system. PCA has also been used in [16] to approximate the frequency response of a fourth-order DC–DC converter by a second-order system. Balanced truncation (BT) has been used in [17] to derive ROM for a half-bridge series resonant inverter. Order reduction techniques have been applied to high-fidelity magnetic equivalent circuits incorporating saturation, relative motion and multiple winding systems yielding efficient simulations [18]. Non-linear model reduction for fast simulation of power systems has been outlined in [19, 20]. A procedure for fast simulation of thermal and parasitic models of power-electronic-based systems using MOR has been presented in [21–23]. In [24], reduced models of converters are derived by discarding the fast states at first with an approximation of their interaction with slow