2023 IEEE Energy Conversion Congress and Exposition (ECCE) | 979-8-3503-1644-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/ECCE53617.2023.10362655

Accelerating Switching Model-Based Simulation Through Parallel Computing

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Abstract*— Power electronics converters become an enabler for future power and energy system. High-fidelity power electronics simulation can be compute-intensive and time-consuming because of the higher switching frequency (i.e., switching actions per second) of converter using advanced power semiconductors and an increased number of converters applied in the system, such as renewable energy with energy storage and electrified transportation. Unlike the switching model, average modeling can efficiently alleviate the computational burden, and adequately represent converters' behavior for the controller design, but sacrifice the resolution for switching ripples/harmonics, which are also crucial for power electronics design, operation, and reliability studies. This digest proposes to accelerate the switching model-based simulation by leveraging a fast but low-fidelity average model plus parallel computing technique, entitled the average-to-switching (A2S) method. First, in comparison with today's sequentially-computing approach, the basic concept of the A2S method by introducing parallel computing is presented. Then, the detailed methodology of the proposed A2S approach is described with the derivation of the algorithm suitable for paralleling computing. Finally, a case study with a widely applied two-level voltage source converter is performed and a comparison among these methods is summarized. It is observed that this proposed method performed >5 times speedup than the benchmark while maintaining an r-square value of the results > 0.99.

***Keywords*— power electronics, parallel computing, simulation time, simulation accuracy**

I. Introduction

The trend of power electronics applications has become various due to the demand from low power electrical consumer devices, such as smart phone, laptop, to high power converters for electrified transportations, renewables, and grids. Regardless of the applications and requirements, simulation is one of the fundamental steps to reduce design cost from troubleshooting back and forth during the design process of electrical devices [1-4].

Average model is one of the popular modeling approaches for simulating the behavior of converters with simplified procedure of analysis and reduced complexity of the simulation model by the state-space average method [5-8]. The average model is majorly benefited from approximating the switching action of power semiconductors by averaging the switching period. Ref [9] gives a comprehensive strategy on deriving average model on different type of converters. On the other hand, switching modeling is capable of demonstrating more details considering switching ripples/harmonics because it does not average action in the switching period while with the penalty of increased computation burden and simulation time. Since switching modeling considers the switching function of individual power switches in the converter, providing more insights for accurate passive design, loss estimates, and thermal management., which are crucial for converter design, operation, reliability, and analysis of efficiency [10]. However, for the high-frequency design enabled by the advancement of power devices (e.g., wide bandgap semiconductors), high switching frequency increases computational time, as demonstrated in a case study using MATLAB/Simulink as the benchmark in Figure 1, The result shows the simulation time is almost proportional to the switching frequency.

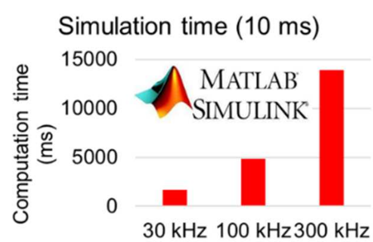

Figure 1: Trend of Switching Frequency vs. Computation Time

In summary, it can be time consuming to looking into more reaction of switching actions by switching model or less of details to achieving fast simulation results by average model. Based on the full understanding of both modeling approaches together with paralleling computing technique, this digest proposes an average-to-switching (A2S) method to acquire both fast execution time as close as average model method, and high-fidelity simulation results considering the switching behavior. Section II overviews today's switching-based simulation method with the sequential algorithm along with the basic concept of the proposed A2S method. Section III introduces the methodology of the A2S approach to perform the combination of average and switching method with parallel computing suitable algorithm. Section IV conducts a comparison case study to quantify the simulation speed and accuracy between the benchmark and the proposed A2S method. Finally, a summary and future work are given in Section V.

II. Basic Concept of the Proposed A2S Method

Figure 2 shows the waveforms of a switching-based and an average-based simulations with the given topology under the same operating condition. Two takeaways are observed: 1) switching waveform is simulated sequentially by taking the final value from the previous time step as the initial value for the next time-speed; as a result, the dependency between simulation time steps challenges the usage of high-speed parallel computing technique; 2) within one switching cycle, the average waveform value is equal to the mean value of the switching waveform, which is mathematically correct due to the definition of the average operator equation illustrated in Figure 2. Therefore, the average model (faster & regardless of switching frequency) can provide the mean value for each switching cycle, allowing the switching model to be solved independently with parallel computing. This is the basic concept of the proposed A2S method.

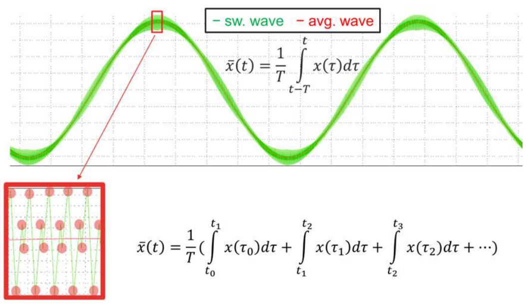

Figure 2: Sequential Mathematic Simulation Algorithm of Switching and Average Model

III. Methodology

A widely applied two-level three-phase voltage converter in Figure 3 is adopted as an example to illustrate the proposed A2S methodology below. A five-step method is proposed, as illustrated in Figure 4.

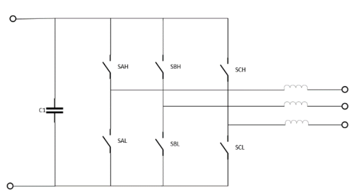

Figure 3: Circuit Topology

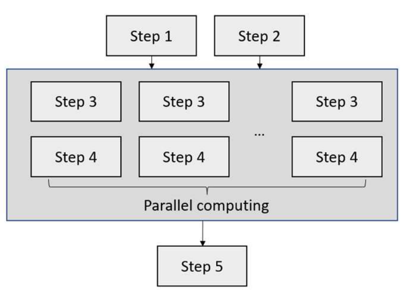

Figure 4: Flow Chart of the Proposal A2S Method

Step 1 − average model simulation: the execution of the average method [2] is necessary to provide the mean value to the following step calculation in switching cycles for switching behaviors. The average value will be one of the inputs in step 3.

Step 2 − switch-based circuit equations derivation: the circuit equations are formed by the combination of the switch functions determined by the modulation scheme. Table 1 summarized all eight combinations of switch functions in this two-level three-phase converter example. Individual combinations form a specific linear circuit. Therefore, the corresponding ordinary differential equation for each switch function combination could be derived, as summarized in Table 2, to support the following steps.

As can be observed in Figure 5, a repeating pattern is shown and defined as one "cycle". Switch-based waveforms under different "cycles" will be able to conduct in parallel to speed up the simulation time. Furthermore, by looking into each "cycle", there is a few ramps causing by the change of switching functions, meaning that different equations in Table 2 should be conducted sequentially. The enlarged switch-based waveform in Figure 5 indicates there are six steps (i.e., six equations – "a" to "f" – out of eight cases in Table 2) within one "cycle". The specific "a" ~ "f" equations within one "cycle" could be determined by the pre-defined pulse width modulation plus the controller output with carrier waveform.

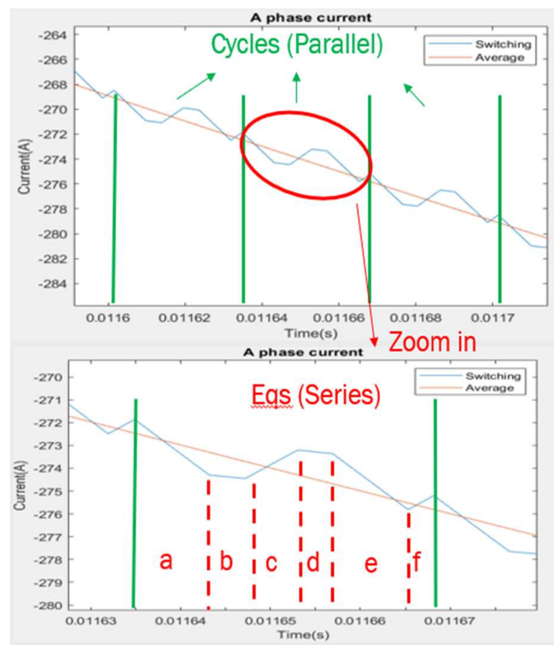

Figure 5: Parallel Sections & Sequential Equations

Table 1: Switching Behaviors

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
SAH/SAL	**ON/OFF**	**ON/OFF**	**OFF/ON**	**OFF/ON**	**ON/OFF**	**ON/OFF**	**OFF/ON**	**OFF/ON**
SBH/SBL	**ON/OFF**	**OFF/ON**	**OFF/ON**	**OFF/ON**	**ON/OFF**	**OFF/ON**	**ON/OFF**	**ON/OFF**
SCH/ SCL	**ON/OFF**	**ON/OFF**	**ON/OFF**	**OFF/ON**	**OFF/ON**	**OFF/ON**	**ON/OFF**	**OFF/ON**
SAB	**0**	**1**	**0**	**0**	**0**	**1**	**-1**	**-1**
SBC	**0**	**-1**	**-1**	**0**	**1**	**0**	**0**	**1**
SCA	**0**	**0**	**1**	**0**	**-1**	**-1**	**1**	**0**

Table 2: Equations for Corresponding Cases

Case 1 **Case 4**	$\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\end{bmatrix}=\begin{bmatrix}\frac{-Ra}{La} & 0\\ 0 & \frac{-Rb}{Lb}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}+\begin{bmatrix}0\\ 0\end{bmatrix}V_{dc}$	**Case 6**	$\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\end{bmatrix}=\begin{bmatrix}\frac{-Ra}{La} & 0\\ 0 & \frac{-Rb}{Lb}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}+\begin{bmatrix}\frac{2}{3La}\\ \frac{-1}{3Lb}\end{bmatrix}V_{dc}$
Case 2	$\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\end{bmatrix}=\begin{bmatrix}\frac{-Ra}{La} & 0\\ 0 & \frac{-Rb}{Lb}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}+\begin{bmatrix}\frac{1}{3La}\\ \frac{-2}{3Lb}\end{bmatrix}V_{dc}$	**Case 7**	$\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\end{bmatrix}=\begin{bmatrix}\frac{-Ra}{La} & 0\\ 0 & \frac{-Rb}{Lb}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}+\begin{bmatrix}\frac{-2}{3La}\\ \frac{1}{3Lb}\end{bmatrix}V_{dc}$
Case 3	$\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\end{bmatrix}=\begin{bmatrix}\frac{-Ra}{La} & 0\\ 0 & \frac{-Rb}{Lb}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}+\begin{bmatrix}\frac{-1}{3La}\\ \frac{-1}{3Lb}\end{bmatrix}V_{dc}$	**Case 8**	$\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\end{bmatrix}=\begin{bmatrix}\frac{-Ra}{La} & 0\\ 0 & \frac{-Rb}{Lb}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}+\begin{bmatrix}\frac{-1}{3La}\\ \frac{2}{3Lb}\end{bmatrix}V_{dc}$
Case 5	$\begin{bmatrix}\frac{di_a}{dt}\\ \frac{di_b}{dt}\end{bmatrix}=\begin{bmatrix}\frac{-Ra}{La} & 0\\ 0 & \frac{-Rb}{Lb}\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix}+\begin{bmatrix}\frac{1}{3La}\\ \frac{1}{3Lb}\end{bmatrix}V_{dc}$		

Step 3 − input initial value: input the initial value to the sequential "a" ~ "f" equations gained in step 2. After determining the "a" ~ "f" equations in step 2, it is to complete the sequential calculation for each "cycle" by substituting an initial value for the equation "a". Then, the output value from the equation "a" will be the input for the equation "b", and so on. In fact, the initial value for the equation "a" could be any value close to the average value because a calibration step will be conducted afterward. In this example illustrated in Figure 6, the initial value for the equation "a" is selected as the mean value of the average method waveform, x^_avg, within the period starting from the equation "a" to the end of the equation "f" which is showing as the initial A2S waveform in Figure 6..

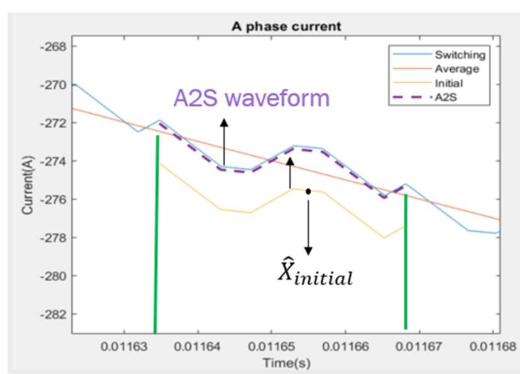

Figure 6: A2S waveform Calibration

Step 4 – waveform calibration: calibration is needed to correct the waveform generated in step 3 by the mean value calculated in step 1. The mean value of the initial A2S waveform can be calculated after step 3 so in the calibration step, a loop algorithm is introduced. If the error between the mean value of the average method waveform and the mean value of the initial A2S waveform is larger than the **threshold** value, as (2), add or reduce a bias on the mean value of the average method waveform and goes to step 3 again until the error between the mean value of the average method waveform and the mean value of the initial A2S waveform is within the threshold value.

In this case, the **threshold** is self-defined, and the value selection needs to be investigated further for optimization due to the impact on the number of iterations in the loop causing the trade-off between accuracy and execution time.

$$Error = \hat{X}_{avg} - \hat{X}_{initial} \quad (2)$$

Step 5 – data fusion: in this last step, the calculated waveform under individual switching cycles generated by parallel computation under step 3 and step 4 will be integrated as the final A2S result.

In summary, as illustrated in **Error! Reference source not found.**, steps 1 and 2 are conducted separately as the input for the following steps. Steps 3 and 4 to solve the time-consuming ordinary differential equations in **Error! Reference source not found.** are performed in parallel, and final results are given after step 5 with the data fusion.

IV. CASE STUDY

According to the methodology above, this paper provides a case study to demonstrate the performance of the A2S method. The parameters for this case study is listed in Table 3 for the topology shown in Figure 3 for the 0.04 second simulation.

Table 3: Application Parameters

Normal power rating	DC voltage	Fundamental frequency	Switching frequency	Load pf
150kW	600V	60Hz	30kHz	0.99

V. RESULTS COMPARISON

As shown in **Error! Reference source not found.**, A2S method has a considerable performance on reducing execution time due to the characteristic of introducing average method and conducting switching action in parallel. Looking into the A2S method execution time, the average model has to be conducted as the step 1 so the A2S model execution time should include the average model execution time and the overhead coming from addressing the switching behaviors and A2S result of each cycle. One thing that should be noted is that due to the parallel implementation no matter how large the number of cycles is simulated (i.e., regardless of the switching frequency), execution time is counted for only one cycle. **Error! Reference source not found.** demonstrates a simulation waveform comparison in one fundamental cycle between the average model, switching model, and A2S model. As can be observed in **Error! Reference source not found.**, the results based on the A2S method agree with the switching model benchmark waveform by MATLAB/Simulink − R-square values are all above 0.993. In the meantime, A2S model execution time reduces by 4X.

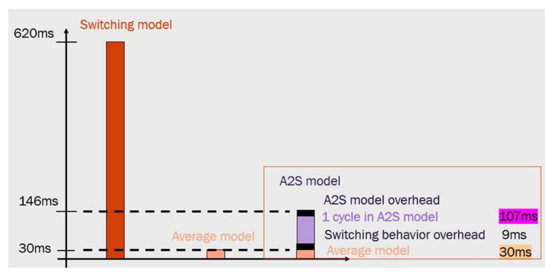

Figure 7: Execution Time Comparison Among Modeling Methods

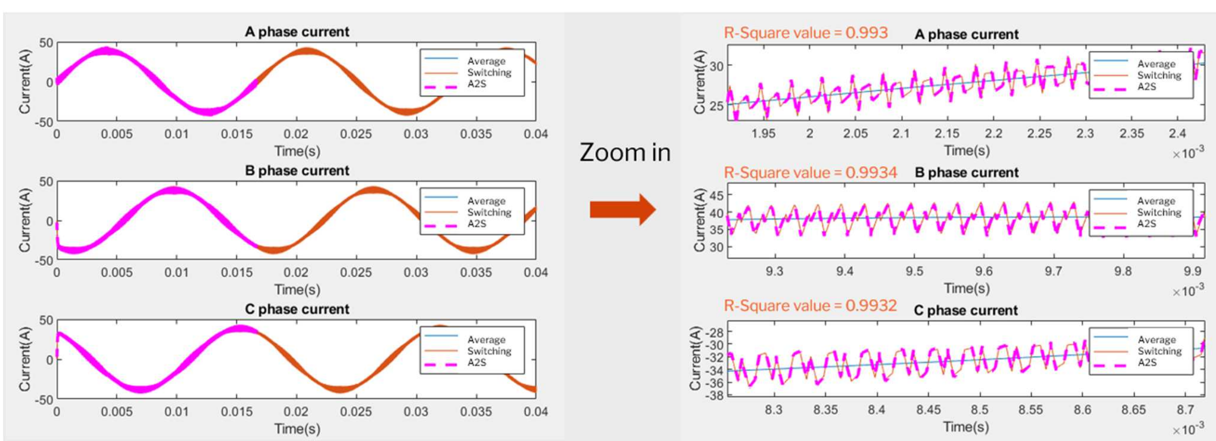

Figure 8: Waveform Comparison Among Modeling Methods

VI. Summary

This section proposes a method to accelerate the switching model-based simulation by leverage high-speed but low-fidelity average model plus parallel computing technique. Based on a case study, it shows > 4X simulation speedup as compared to a MATLAB/Simulink benchmark while the corresponding R-square value of the compared waveforms exceeds 0.993.

Acknowledgment *(Heading 5)*

This work was supported by the Simulation Based Reliability and Safety (SimBRS) Program for modeling and simulation of military ground vehicle systems, under technical services contract W56HZV-17-C-0095 with the US Army DEVCOM Ground Vehicle Systems Center (GVSC). Distribution A. Approved for public release; distribution unlimited. (OPSEC 5622)

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