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A Review of Fast Analyzing Techniques in Direct Current Converter

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Abstract
To assist computer programmers, this document outlines fast ways for analyzing DC–DC converters. The methodologies presented in the literature allow for a steady-state and transient properties for converters under consideration to be determined. When creating these methodologies, the simplifications used are discussed and their impact on computation accuracy is indicated. For DC–DC converters, rapid analysis approaches that take into account thermal processes in semiconductor devices are of particular interest. Examples of DC–DC boost type converter computations based on the chosen approaches are presented here. Certain computation methods and their running times are discussed in this article. SPICE and PLECS were used to perform the computations.

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Introduction

The constant input voltage is either decreased or increased depending on the topology of DC–DC converters, a large class of impulsive power electronic converters (Górecki & Górecki, 2021). There are LC components that store energy and filter the waveforms of the input voltage and output current in these converters, as well as semiconductor devices that act as fast switches. According to a deeper inspection of the circuits under consideration, it becomes obvious that the right operation is only achievable when the time constants associated with DC–DC converter RLC components (Ballo et al., 2021) are much less than the period of the signal regulating the transistors. Switching semiconductor devices and charging and discharging of LC components (Ballo et al., 2019) as well as all converter components (Rivera et al., 2021) thermal phenomena exist in the class of converters under investigation. (Ballo et al., 2019) Those components described above have nonidealities that lead to power losses, which in turn cause these occurrences. As the internal temperature of the electronic components increases due to thermal processes like self-heating in converters, currents and voltage values in these devices fluctuate as well (Rivera et al., 2021). Power electronic converter design relies heavily on computer simulations (Ballo et al., 2020; Matanov and Zahov, 2020; Aji et al., 2020). Circuit-level analysis of electronic circuits commonly makes use of computer approaches that solve systems of state equations that characterize the simulated system (Górecki & Górecki, 2021; Ballo et al., 2020; Parchomiuk et al., 2019). SPICE and SABER (Ballo et al., 2020**;** Parchomiuk et al., 2019; Liu et al., 2019) are two of the most often used tools of this type. In these models, semiconductor devices are depicted in physical form. Performing power converter studies on these programs is time consuming since their algorithms do not allow for efficient solution of systems of stiff differential-algebraic equations (Li, 2019). Numerically, it is difficult to solve these kinds of equations. Transistor control signals, LC component transient states, and thermal time constants describing the thermal properties of the components in the investigated system (Liu et al., 2018) all differ significantly, and this is what causes impulse systems like power electronic converters (Liu, 2021). Transient response times for semiconductor components are as low as 0 ns. No time constant in the equations means that only two states of transistor functioning are conceivable using this strategy. " Figure 1 illustrates the classification of simulation methodologies for power electronic converters by using a basic two-state transistor model to develop and solve the equations.

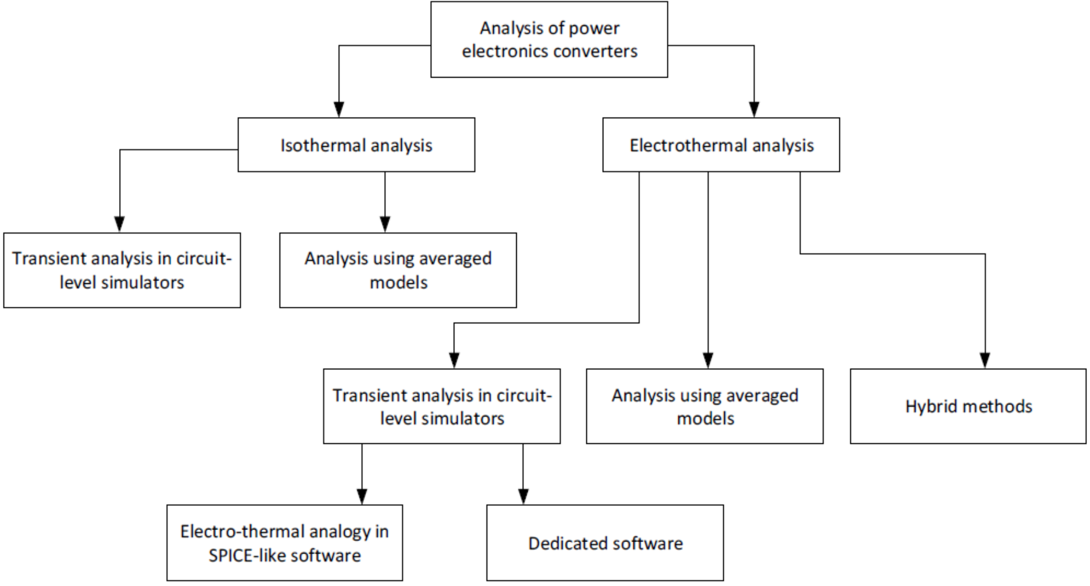

Figure 1. Methods for simulating power electronic converters have been categorized (Górecki & Górecki, 2021).

Isothermal methods and electrothermal methods are the two most basic types of power electronic converters simulation approaches. Assuming the temperature of the surrounding environment is constant, an isothermal technique assumes that all components in a simulated system are at the same temperature during the study period. SPICE-like circuit simulators are used to apply these techniques. Analyses in these programmes take a long time because of the difficulties in solving stiff differential-algebraic equations in power electronic converters. It is possible to save a lot of time by using the averaged models technique, which just takes into account the average magnitudes of voltages and currents in a steady-state circuit. By minimizing the number of variables to be examined, this approach makes it easier to compute the problem. Efficient electrothermal investigations of circuit components take into account all of these variables simultaneously. Such analyses require the simultaneous use of circuit analysis tools and circuit thermal models that are created using the electric-thermal analogy in order to solve the systems' electrical characteristics. An RC Foster or Cauer network (Foley et al., 2010; Foley et al., 2014) is used to model this type of network. Power converter transients must be studied using thermal electrical analogies in SPICE-like programming (Liu, 2021) for a lengthy period of time in order to conduct circuit analysis. The outcome has been the development of special transient analysis tools, such as PLECS and PSIM (Tu et al.,2019). To reduce the amount of time it takes to do transient studies, these programmers model the switching transistors and diodes in their circuit as ideal—with a duration of zero—and thus have a significantly shorter duration time.

As a result of this method, the computations are significantly easier. Power electronic converter electrothermal analyses can be conducted more quickly using averaged models. The internal temperature of the semiconductor device remains constant throughout the whole volume of the semiconductor structure at any given point in time in all of the ways described above. The temperature distribution within a structure is not uniform in practice (IEC, 2010; IEC, 2018), however. In order to effectively represent it, it is critical to use a combination of approaches. Electronic circuits can be examined using a special program built for this purpose. This type of operation calculates the device's first-time power output. Waveforms are used to solve the heat conduction equation in a programmed fashion. Using the waveforms as a starting point, a 2D or 3D thermal analysis is subsequently performed. Several research centers have been working for some time on the development of new computing methods that will allow electrothermal evaluations of power electronic systems to be completed quickly. In this study, we will examine and contrast the many methods for minimizing the time necessary for computer analysis of power electronic converters that have been reported so far. There is a particular focus on DC–DC converters in this work because of the important role that heat processes play in semiconductor devices. When the temperature of semiconductor devices rises, the quantity of power dissipated by the devices increases significantly. Increased temperatures can have a considerable effect on these devices and the DC–DC converters that employ them. In contrast, an increase in the device's internal temperature alters the behavior of the converters under discussion. This page categorizes the computational methodologies and models that have been used in popular simulation systems. Isothermal studies of DC–DC converters are discussed in Section 2. Section 3 of this document goes into detail about the possibility of heat buildup in semiconductor devices. Section 4 focuses on electrothermal analysis methods for power converters. The results of various computations, as well as a discussion of the outcomes, are presented in the fifth and last portion of the paper.

Isothermal Methods

When doing an isothermal analysis of an electrical circuit, the internal temperature of all analyzed elements remains constant and is equal to the ambient temperature (7, 8). Computing is done by a programmed system using differential algebraic equations that describe the situation under study. Many publications (IEC, 2018; IEC, 2010; IEC, 2020) describe the complex form of semiconductor devices as compact models are used in the analysis of these systems. (Aji et al., 2020) and (Matanov and Zahov, 2020) describe methods for isothermal transient analysis and methods for DC or AC analysis with averaged models, and their applications. Power electronic converter transient analysis methods are covered in detail in Section 2.1 and Section 2.2, which include methods based on averaged models and DC analysis, respectively.

Isothermal Transient Analyses

ISothermal transient analyses are the principal methods for evaluating the performance of impulse systems in programs like as SPICE. The ability to reliably forecast parasitic capacitances and inductances in semiconductor devices is the most significant advantage of transient analysis-based computational approaches. Because of this, it is possible to map the switching process with pinpoint accuracy, as well as the over voltages and over currents that are associated with the switching process. Aside from that, they have a number of significant drawbacks, including the following: Because of the high level of model complexity that SPICE-like programs include, they have significant processing times. The estimation of model parameters is fraught with difficulties. According to their authors, many models of power semiconductor devices for isothermal analyses published in the literature have been proven to be more accurate than those included in peripheral analysis programs. This is owing to the disadvantages that have already been mentioned. Aside from that, an isothermal model of the IGBT, a model of the SiC BJT, and an isothermal model of the SiC JFET transistor have all been proposed in the literature (Coignard et al., 2019; Yilmaz et al., 2012; Tran et al., 2017). As a result, conducting research using these models takes significantly longer than conducting research using models that are already incorporated into the SPICE software package. According to Wali et al. (2019) & Matanov and Zahov (2020) the model from (Coignard et al., 2019) can take as long as 14 days to compute the output characteristic of the DC–DC boost converter using the model, depending on the complexity of the model. It is vital to understand how switching semiconductor devices are modelled in transient analysis in order to succeed. Even in the most straightforward of situations, they are replaced out for perfect changes. Following the implementation of this model, the derivatives of the ideal switch terminal currents or voltages reach impossibly high values, which may result in convergence troubles or even the entire shutdown of the computer, depending on the situation. As a workaround for this issue, bivalent resistor models of semiconductor devices must be employed. In order to assess circuit operation and speed up simulation, time-varying circuit topologies must be considered when utilizing simple models to analyze circuit operation and speed up simulation. It is necessary to employ novel simulation approaches in order to achieve this. There has been a great deal of discussion on consistent starting circumstances, and theoretical solutions can be found in (Kratz et al., 2019; Zhu et al., 2017). Several articles (Liu et al., 2020; Liu et al., 2021) deal with transient analysis in DC–DC converters. These papers describe a technique based on pulse width modulation control as well as a memory-less convolution algorithm that makes use of coil and capacitor model simulations. The authors explained the transistor by utilizing an inertia-less switch model with finite on and off resistance values to simulate the behavior of the transistor. According to the authors, there is no need to be concerned about inertia or secondary phenomena when utilizing this model to protect the system against Dirac pulses at the time of switching. The nonlinear component inertia is not taken into account in this approach, which is another disadvantage. If you want to get information about the steady-state values in this circuit, you should compute values in the time interval between switching on the circuit and a time constant equal to at least a few of the circuit's longest time constants, using the ASP transient analysis algorithm implemented in SPICE. Individual time constants related to the values of electronic components and the characteristics of the control signal utilised in the converters under investigation can differ by orders of magnitude in the converters under investigation (Liu et al., 2018). While selecting the time step, the smallest time constant is employed; when completing the analysis and achieving a steady state, the biggest time constant is chosen. As a result, these systems are referred to as stiff systems (Li, 2019) from the perspective of computer analysis. In order to obtain a stable value for the converter operating parameters in the steady state, it is necessary to conduct an investigation of transient states over a time span corresponding to many thousands or even millions of control signal cycles (Wolski et al., 2021). The computational time influenced by complicated dependency models is greater than that influenced by simple dependency models because complicated dependency models necessitate more mathematical operations in each iteration than simple dependency models do. As a result, computational time is influenced by complicated dependency models beyond the range of the analysis, which can be defined as the length of time required to achieve steady state in a given circuit.

Fast approaches for DC–DC converter analysis are documented in the literature because they are intended to reduce the amount of calculation time that is necessary for the converter. This is made possible by using simplified representations of circuit components, particularly semiconductor devices, in order to simulate a circuit. Schematics for switching circuits, such as DC–DC converters, can be simplified by incorporating ideal switches to simulate semiconductor devices (such as those described in the publications (Ballo et al., 2020; Aji et al., 2020; Texas Instruments Desigh Guide, 2021; Akhila et al., 2018; Dan, 2017; Kim et al., 2019) or bivalent resistors, which have been found in a variety of investigations (used, e.g., in the papers (Liu et al., 2021; Hua et al., 2015; Zahid et al., 2014). While basic switching device models and SPICE's ASP approach are employed, the calculation time required to define the coordinates of a single point on the steady-state characteristics is significant. They have demonstrated that the conventional ASP technique employed in SPICE with physical models of semiconductor devices is time-consuming in the case of nonisolated DC–DC converters as well as isolated DC–DC converters. If you are looking at anything that is continually changing, such as a circuit that is being excited by a quickly fluctuating signal, you may see that the algorithm of SPICE is being interrupted on a regular basis by this problem. That is, using SPICE, an interval analysis should be performed that should be repeated numerous times using the save bias and loadbias commands, and the values that affect the accuracy of computations should be determined experimentally, as well as the maximum number of iterations that are permitted. The selection of the values for these alternatives is a tough and time-consuming operation that requires a large amount of effort to ensure that computations are convergent over the projected analytical time span of the problem. In order to analyze these circuits under transient conditions, a thorough model of their DC–DC converter components must be created, and this model must be compatible with the simulation tools being used, such as the SPICE program. Detailed models of semiconductor devices and passive components are included in this program, and they may be found in the articles (Han et al., 2020) and elsewhere. (Arazi et al., 2018; Jasinski et al., 2021) When performing a SPICE transient analysis, a variable calculation step is employed, the value of which is determined by how quickly the voltage and current levels fluctuate in the nodes and branches, as well as the overall scope of the investigation. A tiny time step makes it easier to achieve a stable result in general, and executing calculations with a small time step makes this easier. In transient analysis, increasing the step ceiling option from 1 to a value greater than 1 allows the user to choose a maximum value for the computing steps to be used in the analysis. The value of the step ceiling parameter should be kept between a few dozen and several hundreds of kilohertz if you are going to be looking at switched circuits that are being controlled by high-frequency signals. Whenever possible, it is better to utilize a step ceiling value of 29.17 ns rather than 30 ns when computing the convergence of calculations when this parameter is not an integer multiple of the natural power of 10. In order to keep computation time and output file size to a bare minimum without sacrificing speed, it is recommended that this option be set to the highest possible value. One of the objectives of studying DC–DC converters is to have a better understanding of the attributes of the devices when they are functioning at steady state. The publications in this category (Teodorescu et al.,2007; Elma et al., 2020; Leone et al., 2021; nrel.gov, 2021; Rosso et al., 2020) study ways for speeding calculations until steady state is obtained in DC–DC converters, based on the results of transient investigations conducted over a single period. These methods, which make use of piece-wise linear models of switches, necessitate the development of computer software that is not currently available on the market. SPICE for power electronic circuit analysis requires the use of sophisticated, nonlinear models of semiconductor devices, which can be difficult to converge, as well as lengthy analysis time (San-Sebastián et al., 2012).

An alternative strategy presented in (nrel.gov, 2021) computes the accelerated steady-state analysis method in DC–DC converters using SPICE and Mathematica software, with SPICE being used more frequently. This strategy is more efficient than the previous one. These computations are repeated multiple times in this manner, with SPICE performing transient analysis for one control period and Mathematica extrapolating the solution to the steady state based on data from the previous computations. The main advantage of the proposed method for nonlinear semiconductor devices is that it provides a fast steady-state solution for nonlinear models, whereas the main disadvantage is that it has a large calculation error and that some nodes of the analyzed circuit do not have access to the computation results in some cases. The steady state characteristics of single-inductor DC–DC converters are investigated using an iterative transient analysis approach, which is described in (Muhlethaler et al., 2013). It is based on the beginning condition of the averaged model in order to establish the features of the converters. For the purpose of obtaining the voltage drop values at the diode and transistor terminals, the averaged model makes use of transient analysis. This technique takes into account the nonlinearity of semiconductor devices, which results in a much faster computation time than when using an ASP algorithm, but it also results in a significantly longer computation time when utilizing the method described in the publications (Hua et al., 2015; Jalili & Bernet, 2009; Bloemink & Green, 2011).

Analysis Using Averaged Models

When building DC–DC converters, employing averaged models of the diode–transistor switch can greatly minimize the amount of time necessary to determine DC characteristics. To identify the properties of the class of systems under investigation in the steady state, averaged models and a DC analysis, as well as a DC analysis, can be utilized together. Using small-signal frequency analysis, it is possible to determine the amplitude and phase characteristics of the system under investigation. It is possible to determine the time courses of average values and currents in a system through the use of transient analysis (Górecki & Górecki, 2021; Ballo et al., 2020; Jasinski et al., 2021). In the early investigations (Liserre et al., 2005; Teichmann et al., 2005), these models were developed from state equations, which were then translated into a form that described average voltage and current values in a circuit. According to the cited papers, in the models, the losslessness of all of the converter's components is assumed by all of the components. When losses occur in low-voltage converters, the performance of the device might be significantly affected (Piasecki, 2014). Piasecki (2014) Several models of the DC–DC converter are described in papers (Piasecki et al., 2013; Styński, 2011), including an averaged model of the converter and a model that takes into account both LC element losses and losses related with the conduction of semiconductor devices (Piasecki et al., 2013; Styński, 2011). The losses in LC elements, as well as those associated with the conduction of semiconductor devices, are discussed further below. An investigation into the usage of averaged DC–DC converter models in the design of a control system for this type of converter is presented in paper (Kołomyjski, 2009). It is presented in Paper (Kazmierkowski et al., 2002) that, using the averaged model of the 50 kVA DC–DC converter, the results of the research carried out using this model are presented, and the accuracy of the calculation results produced is empirically confirmed. (Jasinski et al.,2012; Jasinski, 2005) and others employ the classical method for creating average models of DC–DC converter converters to analyze the attributes of converters specifically built for microgrid applications in steady state, as demonstrated by the studies in (Jasinski et al.,2012; Jasinski, 2005). In these types of analysis, the isothermal piece-wise linear properties of a semiconductor device are taken into consideration. It was necessary to use the findings of these analyses in order to demonstrate the influence of transistor and diode on-state resistance on the attributes of the networks under consideration. With the help of the PLECS software, it was also possible to conduct successful power loss investigations. For the purpose of developing an averaged model in the manner described above, it is required to formulate converter state equations, which might take on a highly sophisticated form when losses in semiconductors and LC elements are taken into consideration. In Kołomyjski (2009), Malinowski (2001), PWM (pulse width modulation) switches (also known as diode-transistor switches in other pages) are used to explain how to address this problem using diode-transistor switches. A diode and a transistor are substituted with their corresponding averaged models from the literature in circuit-level simulations of switching devices, which is essentially what this technique does. The currents I1 and I2 and the voltages V1 and V2 in the circuit represent the average values of the circuit's diode and transistor currents and voltages, respectively. In this paradigm, on the other hand, the frequency f and the duty cycle d are what determine the control signal. It was necessary to use these properties in order to define the output voltages and currents of the controlled sources ET, ER, and GD, which were used in this experiment. It is possible to replicate the voltage drop that occurs as a result of altering the converter output voltage and the duty cycle of the control signal by utilizing an ET controlled voltage source. To represent the voltage drop across semiconductor devices that have been turned on, the controlled voltage sources ET and GD are also employed. The way in which the characteristics of the semiconductor devices contained in the switch under consideration are defined dictates the form in which the equations defining the voltage or current output of these devices should be written down. To give an illustration, if we assume that these devices have piece-wise linear characteristics, we obtain dependencies of the kind (Wali et al., 2019). In article (Baba et al., 2021), PWM switch models are used to research converters with galvanic isolation, while in published (Bachman et al., 2021), PWM switch models are utilized to study resonant converters with galvanic isolation. When compared to methods that rely on transient analysis, the averaged model of the PWM switch results in a significant reduction in the amount of time required for computation. The features of the isothermal averaged models described in this part are addressed in greater detail in the following section.

Thermal Phenomena in Power Converters

The ambient temperature is considered to be the same for all of the electronic components inside the converters in the procedures described in the preceding section. This is a correct assumption. Self-heating and mutual thermal couplings cause the temperature of all converter components to rise at the same rate as the amount of power squandered by converter components. (Hillers et al., 2013) As the distance between them grows, the mutual thermal connections between them become more powerful. Their action raises the temperature of the components (Rahman et al., 2018; Krismer, 2010) as a side effect. Inside and outside of the components, there are also thermal couplings that occur. There are thermal couplings, for example, between semiconductor structures put in the common case (JJung et al., 2012; Chen et al.,2009) and thermal couplings between inductive components' core and windings (Piasecki et al.,2019; Piasecki et al., 2016). It is essential to precisely estimate the life expectancy of electronic components by accurately determining their temperature. For every eight degrees Celsius increase in internal temperature, a semiconductor device's internal temperature drops by a factor of two (Kazmierkowski et al., 2002). As a result, while developing power converters, electrothermal simulations are essential and should not be ignored. These simulations yield the voltage and current amounts and waveforms in the examined converter, as well as the temperature of its components. The cooling system for the converter under discussion can be selected based on the results of these simulations. Power losses in semiconductor devices are critical to accurately calculating the device's internal temperature. Calculating the steady-state power loss is straightforward. The problem of calculating losses in semiconductor devices while accounting for oscillations has been documented in investigations (Jasinski et al.,2012; Jasinski, 2005) over voltages and over currents. It is necessary to employ specific electrothermal models to account for the interactions between electrical and thermal phenomena that occur in electronic components during the study in order to conduct electrothermal research on the selected electronic circuit. As an illustration of how these models are constructed, consider the model (Jasinski et al.,2012). An internal temperature increase caused by thermal processes can be discovered in the class of models under examination. (see Figure 1). In addition to microscopic models, these models can take the form of compact models, among other things. Using microscopic thermal models (Kazmierkowski et al., 2002), the time–spatial distribution of the temperature of electronic components can be estimated. (Hillers et al., 2013) The waveform of a single internal temperature can be utilized to characterize the thermal state of a semiconductor device using a compact thermal model. A method for conducting electrothermal assessments of DC–DC converters that uses both detailed and compact thermal models, respectively, will be discussed in the next section

Electrothermal Analyses

Due to the relevance of thermal properties in the design of power electronic converters, electric and magnetic field simulations are of particular interest (Krismer, 2010). However, due to the difficulty in resolving a set of stiff differential algebraic equations as detailed in the introduction, engineers must accept a large increase in computation time when utilizing SPICE-like systems to do traditional transient assessments that account for thermal events. The scientific community has come up with a number of ideas for cutting down on this timeframe. The following sections go into deeper depth on a few of these strategies. Circuit simulators specialized to transient analysis are discussed first in Section 4.1, followed by electrothermal studies utilizing averaged models in Section 4.2, and finally hybrid analysis approaches, which call for the use of at least two simulation programs in Section 4.3. Analyses of electrothermal data using averaged models are discussed in detail in Section 4.2.

Methods Based on Transient Analysis

One of the most important steps in doing an electrothermal transient analysis is creating isothermal models of system components and connecting them to compact thermal models such as RC Cauer or Foster networks in the circuit analysis program (Kołomyjski, 2009). Electrothermal concentration of a semiconductor element is shown in Figure 1 using the generalized model (Liu et al., 2021; Hua et al., 2015; Zahid et al., 2014). The electrothermal model under consideration consists of three parts. the model's voltages v and currents I are described using an electrical model given by the function f(v,i), while the power dissipated by the model can be calculated using a power model given by the function g(v,i), and the final component is a thermal model described by the function h(t), which takes into account temperature changes. Electrothermal models of semiconductor devices have been extensively studied in their physical form. Similar models for the SPICE programming language have been discussed in a number of papers. Models for SiC MOSFET power modules, thermal models of electronic components and models for power MOSFETs and BJTs are all presented in (Jasinski et al.,2012; Jasinski, 2005) in accordance with (Rahman et al., 2018). According to an application perspective, the hybrid electrothermal models provided in (Jasinski et al.,2012) and their modifications are critical. These models use a combination of isothermal semiconductor device models integrated into SPICE and controlled voltage or current sources that simulate the temperature-dependent voltages or currents generated by these devices.

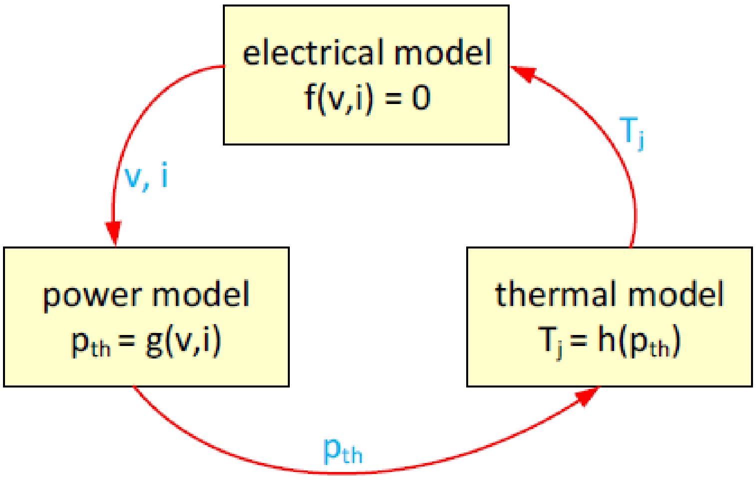

Figure 1. General form of the compact electrothermal model of a semiconductor device (Górecki & Górecki, 2021)

They feature higher convergence of computations and quicker computation times when compared to electrothermal models that include only controlled sources and passive components. Electrothermal models defined in this manner have low accuracy in calculating the interior temperature of semiconductor devices when paired with a linear thermal model. When a semiconductor component's thermal resistance is not constant, as is predicted by linear thermal models based on the Foster and Cauer networks (Hillers et al., 2013), this phenomenon occurs. Like the models in (Górecki & Górecki, 2021; Ballo et al., 2020; Jasinski et al., 2021) and (Rahman et al., 2018), the thermal resistance is influenced by the amount of power emitted by the device, and the junction temperature of a semiconductor device and ambient temperature are also important factors in determining thermal resistance. Working with the Cauer or Foster structure of a thermal model can be simplified by decreasing the model's longest thermal RC time constant (Liu et al., 2018), which can drastically cut down on computation time required to reach steady state. Using this method, we can precisely determine the steady-state mean values for junction temperatures of semiconductor devices, but it mandates the usage of a constant load value throughout our calculations because the longest thermal time constant is reduced. A system's steady-state characteristics can only be studied using this method. When determining the steady-state internal temperature of semiconductor devices, a more sophisticated but also more successful approach to reducing computation time is to use dedicated computing techniques. Rapid acquisition of voltage, current and temperature waveforms in DC–DC converter components in the steady state is possible using a memoryless convolutional algorithm proposed by (Liu et al., 2018). While in Rahman et al. (2018), power converter transient states are studied using the envelope-following method, which is implemented in a specific simulation program. DC–DC converter steady-state voltage and current waveforms might be determined using a new algorithm, according to a study in (Jasinski et al.,2012; Jasinski, 2005). While Liu et al. (2018) and (Hua et al., 2015) are accurate, they are not practical because of the complexity (Liu et al., 2018) or inability (Hua et al., 2015) of implementing them into the commonly used circuit-level modeling programs. Such a problem does not occur in the case of (Arazi et al., 2018). A more accurate simulation is achieved by modeling the transistor as a lossy switch using a simplified gate circuit model. PSCAD electrothermal analysis can be completed in a similar amount of time to that necessary to investigate a system in which transistors are replaced by perfect switches using this method. The precision of the technique being demonstrated suffers when a linear thermal model is used. Some of the most prominent tools for doing electrothermal evaluations on peripheral power converters include PLECS and PSIM. Simulating the electrical properties of transistors and diodes is done using the piece-wise linear function. In addition, more advanced models of transistor and diode loss are used to represent their thermal properties. When interpolating between user-specified coordinates, they are determined from datasheet DC characteristics as well as an investigation into the relationship between energy losses in transistor switching and other parameters (Jasinski et al.,2012; Jasinski, 2005)." Using this kind of calculation provides for a relatively short computation period duration. Simulated converters are difficult to construct because of the simplified description of semiconductor device switching operations (Hua et al., 2015). This results in over voltages and over currents that increase energy losses during switching. Consequently, it follows that the value of the power dissipated in semiconductor devices, determined from the programmed values, is always underestimated. The precision of the calculations in these systems is harmed by the use of linear thermal models like the Cauer or Foster networks, which are applied in these situations. Thermal resistance in the device is dependent on junction temperature, and this approach (Tu et al.,2019) takes that into account, which was not previously taken into account, in order to make improvements.

Methods Using Averaged Models

The computation of data can be done in the shortest amount of time using averaged models, such as isothermal models and electrothermal studies. If the isothermal diode-transistor switch model is combined with the linear compact thermal model, a converter model that accurately simulates the electrothermal properties of a diode-transistor switch at low switching frequencies can be obtained. MOSFET and IGBT models of this type have already been produced. The output voltages and currents of the controlled sources included in the averaged models are, of course, affected by the diode and transistor temperatures estimated using the thermal model. At high switching frequencies, it is necessary to account for the energy losses associated with transistor switch operation when modeling transistor thermal properties. (Górecki & Górecki, 2021; Ballo et al., 2020; Jasinski et al., 2021) shows a switch model with a SiC MOSFET in this way formulated (Dan, 2017). The model also allows for the prediction of changes in the resistance of the transistor's switched-on channel as a result of its aging, as well as taking into account the effect of this phenomenon on the device's internal temperature. For the purposes of this study, "averaged electrothermal models" were used to describe the interior temperatures of the converter's diode and transistor. When it comes to designing DC–DC converters, the quality of inductors is critical. Temperatures rise due to self-heating phenomena and thermal interactions between these components, as well as losses that occur in both the core and the winding of these components (Piasecki et al., 2013; Styński, 2011). Using an average model, the temperature of the core and winding of the inductor working in a DC–DC converter can be computed, as well as the internal temperature of the transistor and diode, according to (Górecki & Górecki, 2021; Ballo et al., 2020; Jasinski et al., 2021). Assistive block, CCM/DCM and thermal model are all included in the model's four sections. Isothermal averaged thermal model of PWM switch is a primary circuit that corresponds to this basic circuit. The thermal model estimates the internal temperatures of transistor TT and diode, respectively, of the PWM switch. This block lets you choose whether to use a CCM or a DCM analyzer and how much of an equivalent duty cycle (measured in voltage at voltage source Eu) should be utilized for the control signal. Many things affect this voltage, including the inductance L of the inductor in the converter under examination. This inductance influences the voltage. Depending on which mode you select, the sources that make up the main circuit can be expressed in a variety of ways (Jasinski et al.,2012; Jasinski, 2005).

This dependency is depicted by the voltage sources in this aided block. The junction temperature of the enabled semiconductor devices is used to model the voltage drop on those devices' transistors. It is possible to calculate the junction temperature of a transistor or a diode in a steady-state operation using a thermal model that accounts for self-heating events. Jasinski et al. (2012) and Jasinski (2005), provides a comprehensive explanation of the model under consideration, as well as the analytical dependencies that characterize its many components. If the proposed design is to be used in a converter, it must be replaced with the transistor and diode illustrated in the image below: The drain and source terminals of the device should be replaced by the MOSFET's terminals 1 and 2. Using the duty cycle signal to connect the control signal to the correct terminal 5 is recommended. Finally, the diode's terminals should be replaced with terminals 3 and 4. DC–DC converters with electrothermal averaged nonlinearity have been proposed in (Piasecki et al., 2013; Styński, 2011). If these models are to be developed correctly, it is vital to take into account both operating characteristics and the amount of power lost in semiconductor devices when developing them. As a result, these models are not very flexible; each converter system must have its own model of this type. For DC–DC converters, thermal inertia of semiconductor devices and mutual thermal coupling between these devices are taken into account in the work (Górecki & Górecki, 2021; Ballo et al., 2020; Jasinski et al., 2021). The paper cited above uses RC networks for the thermal model and an averaged PWM switch model for the electrical model. It is possible to predict the steady-state features of the DC–DC converter and the waveforms of the internal temperatures of MOSFET and diode using this model, according to the findings of this study. Semiconductor devices, as well as their thermal interactions with one other, have been discovered to influence the converter output voltage and the internal temperature of these devices in a significant way. For the computations in the studies above, power losses related with switching were omitted because it was assumed that semiconductor devices only lose power when they are turned on. Only if the switching time of these devices is much less than the control signal's duration can this strategy be justified (Jasinski et al.,2012; Jasinski, 2005). The study Yang et al. (2017), goes into great length about the limitations of the averaged PWM switch paradigm in conjunction with the IGBT. The experiments were performed on a test bench using a boost converter, varying the duty cycle of the control signal, and varying the load current. CCM mode has been shown to provide a good level of accuracy in converter computations when using the averaged model discussed above. Internal temperature values are higher at high frequencies and lower at low currents when operating in DCM mode, compared to running in DCM. As depicted, there are many ways to "formalize" something. The power MOSFET is included in the electrothermal model of the PWM switch, which is depicted as a network. For DC–DC converters, thermal inertia of semiconductor devices and mutual thermal coupling between these devices are taken into account in the work (Piasecki et al., 2013; Styński, 2011). The paper cited above uses RC networks for the thermal model and an averaged PWM switch model for the electrical model.

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Hybrid Methods

When designing small electrothermal models, the assumption is that the heat created by the semiconductor device is drained in a targeted manner, and that a single value characterizes the internal temperature of the device (Górecki & Górecki, 2021). In contrast, the temperature distribution of real-world semiconductor devices is not uniform, and heat is only emitted in a fraction of the volume of the device, for example, in the channel of a MOSFET. Thermodynamics equations can be used to calculate the temperature distribution in the transistor's entire volume using the specific simulation tools. As a result, the creation of such models requires a significant amount of time and comprehensive material, thermal and geometric data. Programs created for such simulations are not intended to perform peripheral assessments, which are necessary in the design of power electronic circuits, but rather are intended to calculate the temperature distribution within a single device. It is for this reason that circuit simulations for electrical circuit design have been combined with 3D thermal modeling of the devices contained inside those circuits in the literature (Liu et al., 2021; Hua et al., 2015; Zahid et al., 2014). Thermal data from specific devices must be collected and transferred into a 3D thermal model in order to make this combination workable. The temperature distributions over time and space are then estimated, frequently utilizing the finite element approach (FEM). Transient thermal impedance can then be used to estimate the parameters of the Cauer or Foster network thermal model in the network simulator based on the transient thermal impedance gathered from the temperature waveforms. (Wali et al., 2019) The high order of the focused thermal model developed as a result of this transformation is a major challenge. According to Yang et al. (2017), the model order reduction method might be utilized to reduce the computation time for power transistors by a significant amount. There have been numerous more applications of this technique, including the investigation of specific integrated circuits (Liu et al., 2021; Hua et al., 2015; Zahid et al., 2014), multi-structure power transistors (Bachman et al., 2021), and energy modules (JJung et al., 2012). In Muhlethaler et al. (2013), the author provides a new approach to solving this problem. MATLAB, SPICE, and MATLAB all use a small electric transistor model for determining voltage and current waveforms. Based on these data, MATLAB is used to determine the transistor's losses during conduction and switching. To develop a tiny thermal model in Simulink, we used the data from the ANSYS Icepak software to convey the information about lost power. This model is used to determine the waveforms of the transistor's internal temperature Tj and the case temperature TC. Simulating a transistor and its heat sink using materials with temperature properties is possible with this approach, which can produce simulation results in a very short period. For the study of circuits with IGBT modules, (JJung et al., 2012) provided a similar approach, which was further enhanced. No papers mentioned discussed the influence of the transistor's internal temperature on the device's power losses. Because of this, it's possible that the calculations you're doing are going to be wrong. Thermal models mentioned in this part were computed using the finite element technique (FEM) throughout this section. While the finite difference method (FDM) was employed in (IEC, 2005), the finite volume approach (FVM) was used in (Muhlethaler et al., 2013). hybrid techniques offer an advantage in determining the reliability of power electronic converters. Using a hybrid electrothermal analysis approach, the authors of the paper (Muhlethaler et al., 2013) propose simulating the thermal reliability of electric car inverters. In the publication, the process is explained in great depth. There is a distinct lack of information concerning the position of the transistor's heat source in the linked article. No information could be found on how reputable or generally accessible this source was. There is a cuboid-shaped volume (for example, silicon) that is part of the heat-flow channel in all circumstances where the heat source is located. They, however, do not have access to a thermal model of a transistor, which would allow them to determine the temperature distribution of the transistor's internal temperature while it is functioning in a switched mode converter while it is in operation. To answer this problem numerically in an acceptable period of time is currently impossible. In the papers Kołomyjski (2009), Malinowski (2001), power losses and internal temperatures of transistors used in switched mode power converters are thoroughly examined. The Fourier equations that describe heat movement are used in this procedure, and the MATLAB software was used to perform the calculations. It has been shown that this method's calculation time is much less than the detailed thermal model and FEM's calculation time.

Conclusions

An analysis of power converters is discussed in this work using several methods. Virtual machines, among other approaches, are studied as a way to speed up the time it takes to reach steady-state computation results while analyzing this sort of converters using computers. Analyzing transiently as well as using averaged models in a DC analysis are both viable options. Models of semiconductor devices ranging from perfect switches to physical electrothermal models, as well as models in various forms, were mentioned. Consideration is given to the usage of simulation programs. Computer analysis of electronic circuits has two competing expectations that must be weighed against each other. In order to keep calculation time to a minimum, it is imperative that the precision of the computations is top-notch. As a result, the circuit design process requires varying levels of precision in computations at different points in time. Therefore, it is acceptable to use models and computation methods that range in accuracy and time requirements. A simple model of an electrical component can be used to validate the basic design of the system's operation using fast procedures with modest accuracy. There are various factors that affect the accuracy of the computations, including the power, load, and cooling conditions for each system under consideration. Because of this, various levels of precision and complexity are needed in the analysis. The shortest computing durations were found to be for averaged isothermal models and isothermal models implemented in SPICE-like settings, with average computation times less than 100 ms. The electrothermal transient analysis result is displayed in the associated software program after a few dozen seconds of computing time. Using an isothermal technique, the amount of time it takes to perform computations depends heavily on the model being used. A SPICE-like tool can finish simulations involving such models in less than 10 minutes, according to the authors. A semiconductor device's temperature can only be determined by solving the thermodynamic equations. Only with the use of 3D modeling software are such simulations possible. Electrothermal transient analysis can also be used to obtain the residual decomposition that displays the temperatures of semiconductor structures on the common substrate. This can be done in both SPICE-like and dedicated software environments. An important drawback of models that use averages is that they cannot be used to extract the temperature waveform. In rare circumstances, the temperature amplitude might rise to 20 degrees Celsius (Wali et al., 2019) when forced cooling is utilized in conjunction with a low working frequency. Hybrid techniques, on the other hand, have the major disadvantage of necessitating the use of multiple simulation programs, resulting in significant increases in costs. Both in terms of estimating model parameters and in terms of the engineer's abilities to use them, these methods are the most demanding currently being considered. These models may be used to accurately calculate voltage drops on switched-on semiconductor devices, which is illustrated in Section 5 of the paper. The nonideality of semiconductor devices must be taken into account when working with low input voltages. The junction temperature of semiconductor devices can be determined by conducting an electrothermal inspection. Averaging models can be used to identify steady-state voltage levels in a very short period of time assuming control signal frequencies are not too high (below several hundred kHz). The power losses Electronics 2021, 10, 2920 19 of 23 that occur during the switching of semiconductor devices can be taken into account using the electrothermal transient analysis. Each of the converters covered so far has a specific set of applications for the quick analysis methodologies discussed thus far. These equations are based on a boost converter, but they may be applied to other single-inductor DC–DC converters, such as the buck or buck-boosting converters, without modification. Isolated and nonisolated DC–DC converter topologies can benefit from the transient analysis methods proposed in this study. Naturally, this study only discusses the most critical aspects of a rapid analysis of power converters. The methods used to perform such an analysis are constantly being updated in order to improve their accuracy and speed up computations. Only DC–DC converters with inductors were the subject of these considerations. Charge pumps, for example, demand the employment of specialist methods for fast computer analyses, which are not examined in this study, which is a drawback of the current investigation.

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