Black-box Modeling of Converters in Renewable Energy Systems for EMC Assessment: Overview and Discussion of Available Models*

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Abstract: The development of renewable energy systems interfaced with the grid by power electronic converters leads to increasing issues of electromagnetic coexistence between power and communication lines, as well as severe power quality issues, such as total harmonic distortion at the consumer side. Therefore, high-frequency modeling of renewable energy systems is of great importance to guide the design and development of distribution networks involving renewable sources. Owing to system complexity, black-box modeling approaches offer more advantages than traditional circuit modeling, as far as electromagnetic compatibility (EMC) analysis and filter design are the targets. In this study, different black-box modeling techniques for power converters are introduced and systematically analyzed. First, the general theory of black-box modeling is explained. Subsequently, three different modeling approaches are compared in terms of accuracy and the required experimental setup. Finally, the possible limitations of black-box modeling of power converters are investigated and discussed.

Keywords: Renewable energy system, black-box modeling, electromagnetic compatibility (EMC), conducted emission (CE)

1 Introduction

Recent advances in renewable energy systems have allowed the widespread diffusion of power converters, which currently find increasing applications in various sectors such as electricity distribution networks and microgrids (with distributed power generators) [1]. However, the massive use of power converters entails and is still involving considerable problems in terms of electromagnetic compatibility (EMC) [2]. For instance, the conducted emissions (CEs) from renewable energy systems can propagate to the medium-voltage grid, causing malfunctions in connected devices [3]. Moreover, several reported EMC issues were related to coexistence issues with data communication systems, such as those using power line communications (PLC)[4] and significant reading errors in smart meters [5].

For all of these applications, electromagnetic interference (EMI) issues should be minimized to ensure system reliability. A possible solution to reduce the CEs generated by power converters is the adoption of alternative modulation schemes based on 'spread spectrum' techniques, which allow attenuating the emission peaks potentially responsible for EMI (uniformly distributing the emissions in the frequency range of interest) [6]. Another possible solution is to add appropriate passive and/or active filters to the output of the converter to reduce its emissions [7]. In both cases, the availability of a power converter model that is sufficiently accurate and valid in the frequency range of interest is key for adopting suitable countermeasures.

In line with this objective, this paper intends to provide the reader with an overview of the EMI modeling of power converters, especially those approaches based on black-box modeling, which can be used to derive guidelines for the EMC-oriented design of renewable energy systems (Fig. 1).

The remainder of this paper is organized as follows: Section 2 discusses the general classification of modeling techniques, focusing on a comparison of circuit and behavior models; in Section 3, the general

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features of black-box models, applications of terminated and unterminated types, and an overview of state-of-the-art contributions are presented; in Section 4, three different methods for identifying the model parameters are compared in terms of accuracy and the experimental setup and possible limitations of black-box modeling are presented in Section 5.

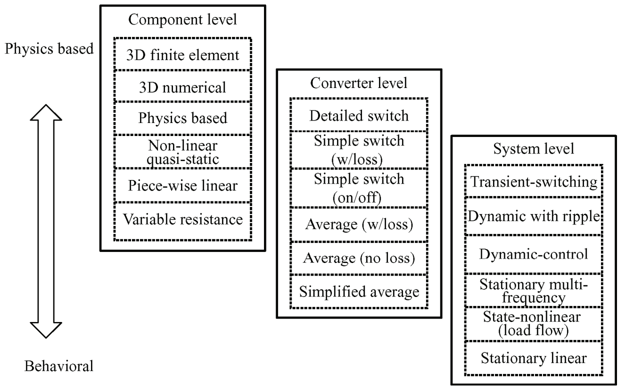


Fig. 1 Classification of available approaches for the modeling of power converters [8]

2 Overview of available modeling techniques

There are a vast variety of contributions in the technical literature targeted at the modeling of power electronics converters. An attempt at classification can be found in a study by Arnedo [8]. Several contributions have been devoted to studying specific phenomena concerning semiconductor devices (for component-level analysis) and the design of distribution networks involving power converters (for system-level analysis). As far as EMC analyses are the target, the available models of power electronic converters can be classified into two main categories: circuit and behavioral models [9].

Circuit models include accurate models of the different components representative of the functional behavior of drive and control systems [10]. For EMC analysis, these functional models must be augmented by including additional circuit elements to represent the parasitic coupling phenomena occurring at high frequencies inside the converter [11-12].

Despite circuit modeling offering undoubted advantages such as the possibility of simulating different operating conditions of the converter both in time and frequency [13-15], this approach becomes unfeasible for system-level analyses involving complex power converters. This is owing to the inherent difficulties in accurately estimating the values of the circuit parameters representative of parasitic phenomena, whose contribution is dominant at high frequencies [16-17]. In addition, the implementation and simulation of circuit models may lead to convergence issues, especially when multi-converters are involved in the system.

For these reasons, behavioral (or black-box) modeling strategies are usually preferable. Behavioral models make use of an equivalent representation of the converter in terms of a noise source, whose parameters are obtained by processing the experimental data of a suitable set of measurements carried out at the external ports of the converter [18-21]. Accordingly, the active part of the converter is represented by voltage or current sources, whereas the passive part is represented by a matrix of impedances or admittances [22]. Model parameters do not retain any physical meaning, but are aimed at reproducing the frequency response of the converter (at the external ports) despite the specific set of loading conditions exploited for the measurements [23]. Further details on the behavioral modeling techniques, along with a comparison of the three different approaches available in the literature, are presented in the following sections.

3 State-of-art of behavioral modeling

3.1 General characteristics

Behavioral (or black-box) modeling provides an equivalent representation of the converter in terms of the Thevenin/Norton circuit, which reproduces the frequency response of the converter at external ports. Consequently, the applicability of this modeling strategy is theoretically limited to the representation of linear and time-invariant (LTI) systems [24]. Since power converters are non-linear and time-varying systems, exploiting black-box modeling strategies requires preliminary investigations aimed at assuring that the device can be actually treated approximately (or under specific conditions) as an LTI system.

In this regard, it is worth mentioning that several models available in the literature were validated under operating conditions very close to those used for model extraction, thus making it difficult to clearly define their actual limitations. For example, from studies by Mazzola et al. [25-26] it was inferred that the common-mode (CM) impedance of the converter could be effectively evaluated with the converter switched off. However, it was not possible to draw the same conclusion for the differential mode (DM) impedance because it exhibited a different frequency response when the drive was ON or OFF. If the linearity assumption was not satisfied, the extracted parameters depended on the specific operating conditions adopted for the experimental characterization. Hence, they were no longer valid if operating conditions changed.

3.2 Unterminated and terminated models

Black-box models can be further classified into two subcategories, as illustrated in Fig. 2. Unterminated models (refer to the top panel of Fig. 2) provide a representation of the converter in terms of an *N*-ports network and are independent of the loads connected on both sides. Conversely, terminated models (refer to the bottom panel of Fig. 2) provide a representation from one side only and are derived with a specific load connected to the opposite side of the converter. The procedure for deriving the terminated model is simple. However, the representation obtained by an unterminated model is definitely more flexible because it does not depend on the loads connected to both sides [27].

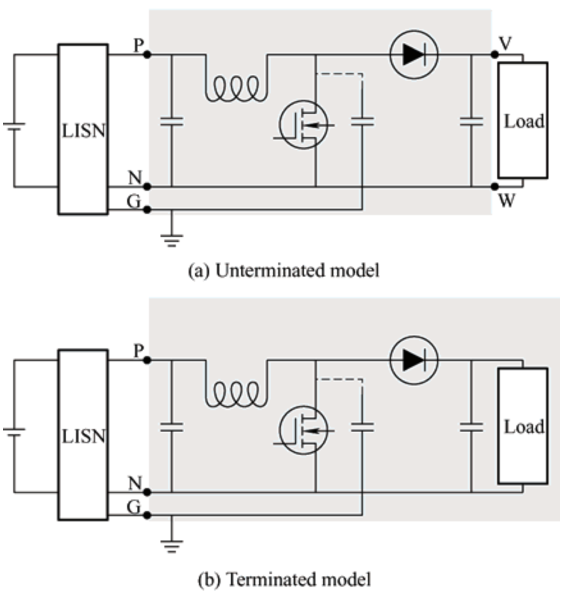


Fig. 2 Unterminated and terminated behavioral models

The choice between these two models depends on the two modeling strategies and objectives of the analysis. In other words, resorting to unterminated models is necessary when the goal is to predict conducted emissions (e.g., to design suitable EMI filters) at both sides of the power converter and/or when there is a need to connect several power converters in series [28-29]. On the contrary, if the analysis focuses on the emissions at one side only, and/or on converters connected in parallel, resorting to terminated models is preferable because the procedure for model derivation requires fewer measurements [18].

3.3 Review of different modeling approaches

Liu et al. [30-31] proposed a three-terminal model to represent a single converter leg, as shown in Fig. 3, and defined the proposed model as a modular terminal behavioral (MTB) model. Once the model of one leg was known, the overall model of the converter was obtained by replicating the model for all the converter legs.

In addition to the difficult procedure to extract model parameters, the proposed approach suffered from the following limitations: ① the passive part was modeled using only two impedances, while the minimum number of impedances necessary to describe a three-terminal network (phase, neutral, and earth) was three [27]; ② mutual couplings between legs were neglected. The model was proven to provide an accurate prediction of the emissions exiting single-leg converters [30]. The prediction accuracy decreased significantly in the presence of more complex devices [31].

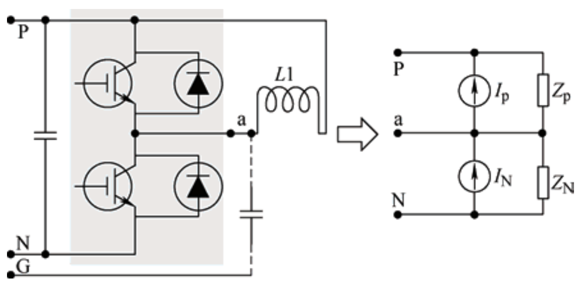


Fig. 3 Modular terminal behavioural (MTB) model representative for a single converter leg [6]

To overcome these limitations, a generalized terminal model (GTM) was proposed by Baisden et al. [23]. The difference with respect to the previous approach was two-fold. First, the GTM made use of an equivalent network, as shown in Fig. 4, involving three (instead of two) impedances. Second, an equivalent network was used to model the entire converter instead of a single leg.

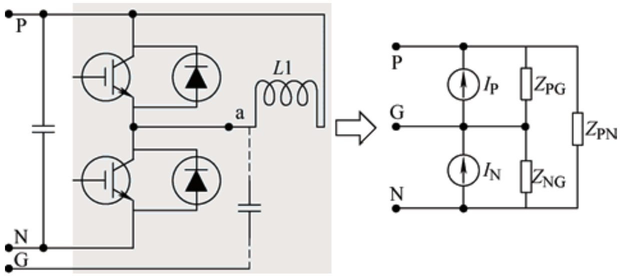


Fig. 4 Generalized terminal model (GTM) representative of the whole converter at external ports [6]

Without loss of generality, the equivalent network in Fig. 4 can be replaced with one of those shown in Fig. 5, where Z_{DUT} and Y_{DUT} are 2-by-2 sized impedance and admittance matrices used to model the passive part of the converter. Although the use of different equivalent networks does not significantly affect the model accuracy, some representations may be preferable depending on the final objective.

For example, adopting the equivalent Norton circuit (refer to Fig. 5d) and the Thevenin circuit (refer to Fig. 5e) offers advantages when the target is investigating converter integration into complex networks, where other components are also represented by 2-N port models [32]. For instance, Spadacini et al. used the black-box model topology in Figs. 5d and 5e to predict the conducted emissions in the presence of twisted-pair cables or high-voltage direct current (HVDC) cables modelled by 2-N port networks [22, 29].

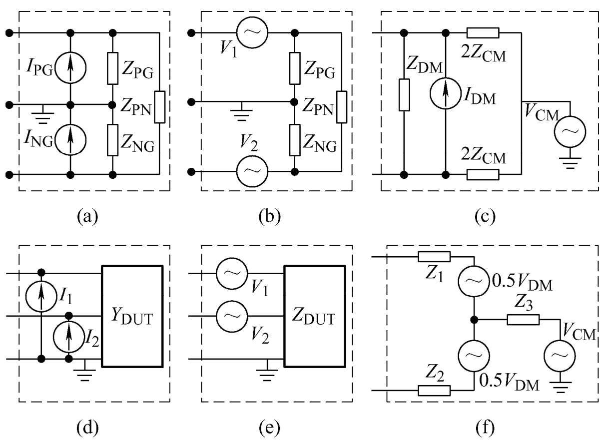


Fig. 5 Examples of three-terminal network topologies for black-box modeling of power converters (terminated models)

The topologies in Figs. 5c and 5f are commonly used to study DM and CM emissions and mode conversion [33]. In addition to the aforementioned topologies used for modal analysis, it is possible to derive black-box models that represent the generation of CM or DM noises separately [34].

Although Fig. 5 shows possible network topologies for terminated models only, suitable extensions of these topologies can also be used for unterminated models. These models can be regarded as extensions of terminated models, where the ports at both sides of the converter are accessible. For example, consider a three-phase inverter. It is possible to model it from either the direct current (DC) or alternating current (AC) side using a two-port or three-port terminated model, respectively. Alternatively, it is possible to model it using a five-port unterminated model with both the three ports on the AC side and the two ports on the DC side accessible [28-29]. The minimum number of sources and impedances required depends on the number of ports. For a network with N ports, at least N sources and $N(N+1)/2$ impedances are required because of reciprocity. Hence, if the system has three or more ports, an admittance or impedance representation is preferable.

Regarding the LTI assumption, this condition is usually satisfied in the frequency range of interest as a result of the ‘mask impedance’ effect introduced by the presence of large-valued reactive/linear components between the power switches and the output terminals [18, 35].

In the absence of such a masking effect, a linear representation is not possible and other modeling frameworks are necessary. For instance, the theory of periodical linear time-varying (PLTV) systems, which considers the mutual coupling between each frequency through a frequency coupling matrix (FCM) [36-37], can be used to model periodically switched linear systems by the augmented Thevenin [38] and enhanced Norton circuit models [21].

Recently, there has been an emerging trend in the use of machine learning algorithms to model power converters. However, some of these methods neglect the parasitic components of power converters or filter waveforms using low-pass filters for generating training data, which is inherently unsuitable for EMC analysis [39].

4 Identification of model parameters

The key factor in ensuring the effectiveness of a black-box model is the experimental procedure adopted for the model parameter estimation. In this section, we present and compare three possible strategies.

4.1 Method 1

The identification of black-box model parameters (either for the MTB or GTM approaches) requires a number of independent tests carried out by connecting suitable networks (with known impedance) on the external ports of the converter, as shown in Fig. 6. Enforcing the corresponding port constraints yields a set of equations involving the black-box model parameters as unknowns. The number of different configurations to be tested depends on the number of unknown parameters. For instance, regardless of the specific topology, the terminated black-box models (N-port network, N=2) in Fig. 5 involve five unknowns (two sources and three impedances). Hence, because it is possible to measure two currents/voltages at a time in each configuration, it follows that a minimum of three test configurations must be set up to write a sufficient number of equations. This is illustrated in Fig. 7 [27]. However, this approach actually lead to an overdetermined system when N was an even number, whose solution was addressed by different authors who developed ad hoc algorithms [23]. The minimum number of model components and measurement setups required to model an N-port network are listed in Tab. 1.

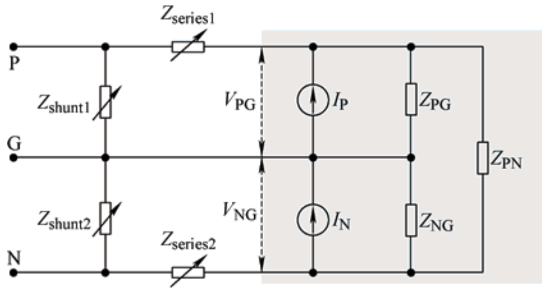


Fig. 6 Illustration of the parameter extraction process for the GTM

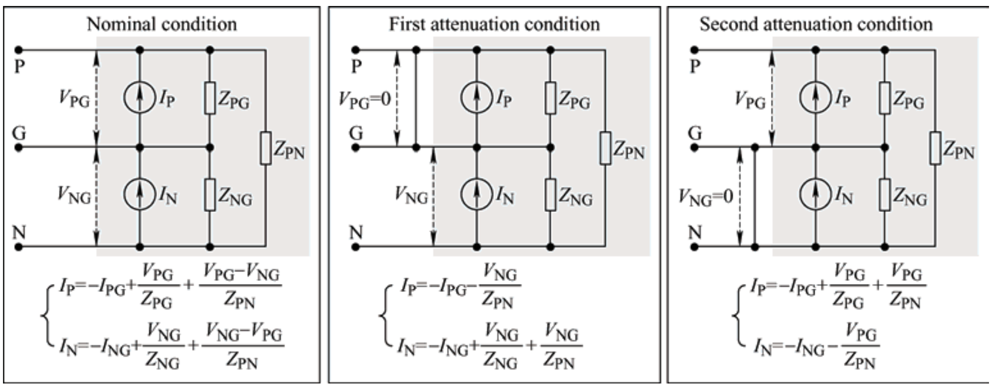


Fig. 7 Experimental configurations used to extract black-box model parameters [27]

Tab. 1 Modeling N-port network by the methods in Figs. 6 and 7

Parameter	Value	
Number of ports	N (odd number)	N (even number)
Number of model sources	N	
Number of impedances	$N(N+1)/2$	
Required number of equations	$N(N+3)/2$	
Minimum number of setups	$(N+3)/2$	$(N+4)/2$
Actual number of equations	$N(N+3)/2$	$N(N+4)/2$
Number of redundant equations	0	$N/2$
Over-determined issues	No	Yes

However, both methods in Figs. 6 and 7 are subject to limitations. For example, the method in Fig. 7 requires shortening each phase to the ground, which may not be practical for some converters. In addition, this method inherently assumes that the switching behavior remains the same under different conditions, which is not always the case. Shortening the phase to ground can change the converter switching behavior, leading to a violation of the LTI assumption. Another drawback is related to the overdetermined system of equations (N/2 equations are redundant for an even number of ports) to be solved. For instance, in a study by Frantz et al. [27], it was shown that the two equations in the nominal condition allowed for an acceptable prediction, but this conclusion was the result of a 'trial and error' approach to finding the best choice of equations.

To overcome the limitations of shorting a phase to ground, various conditions can be created by using shunt or series impedances, as shown in Fig. 6. However, the choice of external impedance can significantly affect the accuracy of the model. First, the external impedances should be sufficiently different to create a consistent set of independent equations [40]. Second, knowledge of model impedance is required [18].

If the model impedance cannot be determined in advance, it is possible to intentionally overdetermine the systems by exploiting a variety of measurement setups and apply optimization methods, such as the non-linear least squares algorithm, to obtain the model parameters [20]. However, this method requires significant measurement effort. For example, in a study by Donnelly et al. [41], 72 different measurements obtained by adjusting the load impedances at the ad hoc line impedance stabilization network (LISN) were used for the optimization algorithm to cover a wide impedance range.

Although this method could reduce the influence of the measurement error of a single setup and was independent of the knowledge of the model impedance, it suffered from certain limitations. Since the measurement setups were performed sequentially rather than simultaneously, the behavior of the switches in different setups was not in phase. Therefore, it was reasonable to optimize only the amplitude difference using a non-linear least-squares algorithm. However, the lack of phase information prevents the use of this method in multi-converter systems. Therefore, only the approximate worst-case analyses can be performed, as described in a study by Donnelly et al. [20, 41].

The advantages, limitations, and measurement requirements of the aforementioned approaches are compared in Tab. 2.

Tab. 2 Approaches in method 1: Advantages, limitations, and measurement requirements

Methods	Techniques	Measurement requirements	Advantages	Limitations
(1) Setup in Fig. 7 [23, 27]	Short each phase to ground separately	1. Minimum number of measurements in Tab. 1 2. Measure both currents and voltages	1. No need to select different external impedances 2. Simpler compared to (2)	1. Not feasible to short phase to ground for some converters 2. Need to select equations in over-determined system
(2) Setups in Fig. 6 [18, 40]	Apply different external impedances		1. No need to short phase to ground 2. More accurate than (1)	1. Need to know model impedances in advance 2. Need to select equations in over-determined system
(3) Non-linear-least-squares algorithm [20, 41]	Over-determine the system intentionally	1. Several load impedances to cover a wide range 2. Measure voltages	1. No need to know model impedance in advance 2. Reduction of influence of a single measurement error	1. More setups compared to (1) and (2) 2. No phase information of model sources

4.2 Method 2

Alternatively, the active (noise sources) and passive parts (impedance/admittance matrices) of the model can be evaluated using separate sets of measurements. This approach is potentially more promising than the previous one because ① it requires setting up only two measurement test benches regardless of the number of unknowns, and ② it avoids the solution of an over-determined system of equations. Such a feature significantly contributes to improving the model accuracy because the post-processing of measurement data may often introduce non-negligible numerical errors. A generalization of the modeling of an N-port power converter with passive and active blocks can be found in a study by Mrad et al. [32].

There were four main approaches for characterizing the passive part of the model. The most commonly used method was to directly measure the S-parameter matrix of the converter with a vector network analyzer (VNA) and to convert the S-parameter representation into impedance/admittance notation [22, 29]. It was possible to measure the S-parameters through an LISN and then de-embed the effects of the LISN and interconnecting cables [42].

An impedance analyzer (IA) can also be used to measure the impedance matrix [32-33], but it requires additional equipment (such as a current sensor, standard 50 Ω loads, voltage, and current probes), which makes this method cumbersome as compared that of the VNA measurement. Therefore, an IA is usually used to measure individual impedances at the terminals, for example, the impedance between the phase and ground, phase, and neutral [43].

The VNA-based approach is the most promising in terms of minimizing post-processing effort. However, a possible disadvantage stems from the need to switch the converter off during measurement. This drawback is discussed in Section 5.1.

The impedance concept is defined in a sinusoidal steady state; however, it is not well-defined for switching devices. Some analytical methods have been proposed to understand the effects of the switching behavior on modal impedance. For instance, the analytical method proposed in a study by Ales et al. [44] expressed the DM and CM impedances considering all the operating states of the converter. This method used a switching function and Fourier series decomposition, which were useful for understanding the non-linear mechanism of the switching behavior. However, accurate knowledge of the value of each component in the converter, including the parasitic component, was required.

Kerrouche et al. [45] presented an analytical method using the switching function but was more suitable for black-box modeling. This required only an offline measurement of the terminal impedances in the ON and OFF states of the power switch. This method was suitable for simple buck or boost converters; however, when the number of switches increases, the number of combinations of switch states to be measured becomes unfeasible.

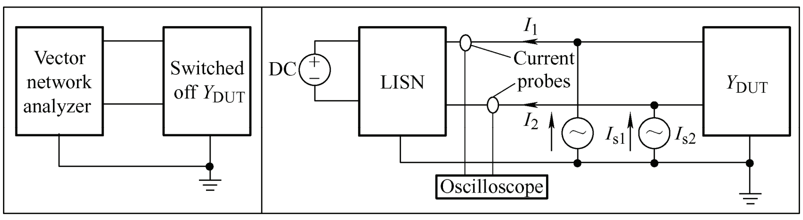
Zhang et al. [46] proposed another method for separately determining the CM and DM impedance called the insertion loss (IL) method. For each measurement, an additional filter element was connected in series or parallel between the load and converter. The amplitude of the modal impedance was calculated from the measured IL magnitude and the impedance of the inserted element. The phase information of the modal impedance was obtained using the Hilbert Transform [46] or a vector diagram to determine the impedance range [47]. The IL method has been extended to determine not only the modal impedance but also the CM/DM noise sources in a study by Meng et al. [34]. However, the IL method required knowledge of the modal impedance in advance to select the proper insertion method and inserted elements.

The active part was evaluated by measuring the terminal currents or voltages of the converter in the time domain at a steady state. To this end, wideband current probes and an oscilloscope with a high dynamic range were required [22, 33].

However, when the current contained a high amplitude of the base frequency (50 Hz or 60 Hz) component and its harmonics, such as on the AC side of an inverter, it was difficult to achieve accurate current measurements at the switching frequency and higher harmonics. Alternatively, it was possible to measure the voltages through the LISN using an oscilloscope, which can decouple the measured RF voltages from the base frequency component [48].

In both cases, it was necessary to simultaneously measure the voltage/current waveforms for each port to preserve phase information. An attempt to measure the currents directly in the frequency domain was described in a study by Guibert et al. [29]. This method required the use of a spectrum analyzer and preliminary assumptions (usually not satisfied in the entire frequency interval) regarding the phase shift between different sources.

As an example of the implementation of Method 2, Fig. 8 illustrates the black-box modeling procedure from a study by Spadacini et al. [22], including the evaluation of the passive and active parts. The different measurement setups for passive and active part evaluations are compared in Tab. 3.



(a) Passive (b) Active

Fig. 8 Experimental setups used to extract the parameters of the black-box model [22]

Tab. 3 Approaches in method 2: Advantages, limitations, and measurement requirements

Methods	Techniques	Measurement requirements	Advantages	Limitations
Passive part	(1) VNA-based [22, 29, 42]	1. Converter switched off 2. VNA directly connected to converter or through a LISN 3. Measure S-parameter matrix	1. Simple setup 2. One-shot measurement	Mask impedance is required
	(2) IA-based imped. matrix [32-33]	1. Measure impedance matrix 2. Require additional devices	Alternative way to substitute VNA	1. Require the T/R working mode of IA 2. Complex compared to (1)
	(3) IA-based single imped. [43]	Measure several single model impedances	Simple setup	Not feasible for three-port or more ports systems
	(4) Analytical method [45]	Measure offline impedance under different states of converter	Suitable for simple buck/boost converter	Not feasible for systems with more switches
	(5) IL method [34, 46-47]	1. Insert a filter between converter and load 2. Evaluate DM and CM separately	1. Suitable for filter design 2. Modal sources can be evaluated	Require knowledge of modal impedance in advance
Active part	(6) Time-domain current measurement [22, 33]	Measure phase currents simultaneously with wideband current probes and oscilloscope	Non-invasive method	Less accuracy if the current contains the base frequency (50 Hz or 60 Hz) component
	(7) Time-domain voltage measurement [42, 48]	Measure CE voltages simultaneously for each phase with LISN and oscilloscope	LISN can decouple base frequency from CE	Each phase requires a measurement port on LISN(s)

4.3 Method 3

In this method, PLTV theory was applied to approximate the behavior of periodically switched linear (PSL) components that cannot be regarded as LTI. The concept of using FCM to represent the behavior of PSL components accounted for mutual coupling between frequencies [36-37]. Trinchero et al.[49] simplified the mathematical complexity of FCMs and proposed an augmented time-invariant representation to describe the steady-state behavior of a PSL circuit. In these studies, the augmented admittance matrices of LTI elements (resistor, capacitor, and inductor) and PSL elements (switch and diode) considering frequency coupling were first derived based on Fourier expansions of dual frequencies (excitation frequency and switching frequency). The augmented admittance matrices were then used to run the classical modified nodal analysis (MNA).

Based on the concept of the augmented admittance matrix of electrical components, Trinchero et al. [21] extended the application to modeling arbitrary PSL circuits from external measurements only. The authors provided insight into the augmented admittance matrix of an arbitrary PSL circuit. The augmented matrix could be decomposed into fully coupled admittance, DC terms, high-frequency source terms and dominant LTI behavior. Thus, it has been shown that instead of using the full augmented admittance matrix, it was sufficient to use only the diagonal terms (dominant LTI behavior) and central column terms (high-frequency source terms) to model power converters with satisfactory accuracy [21].

This approach has also been applied by several authors to address different concepts. For example, in a study by Sona [38], the augmented Thevenin model was proposed to analyze the condition when any port/branch of a PSL circuit was changed, which had the advantage that the entire large augmented admittance matrix did not need to be recomputed. In a study by Donnelly et al. [20], the PLTV model was applied to an inverter with different decoupling DC capacitors. This demonstrated the possibility of using LTI equivalent circuits to model inverters with large decoupling capacitors.

In general, the PLTV method was beneficial not only for revealing the inherent switching mechanisms of the switching devices, but also for providing acceptable prediction accuracy without requiring mask impedances, as in other methods. However, the method required a measurement for every single excitation frequency, which was time-consuming and cumbersome. In particular, if more accurate predictions are required at high frequencies, the number of measurements should be significantly increased. For instance, in a study by Trinchero et al. [50], the predicted frequency could only reach 30 kHz if 15 measurements were performed. If the model needed to cover a range of 150 kHz to 30 MHz, a large number of measurements were required. In addition, this method was applied only to model one-port systems. From an experimental point of view, this method was difficult to apply to model complex systems such as three-phase inverters in renewable energy systems.

5 Limitations of black-box modeling

This section discusses some general limitations of black-box modeling and caveats of the experimental procedures. To demonstrate these limitations, the circuit model of a simple boost converter was implemented in Simulink along with a battery and LISN, as shown in Fig. 9, where parasitic components are highlighted in bold [51-52]. The switching frequency of the converter was set to 1 kHz. For the circuit model of the battery, a 10 μH inductor (L_x) was used to decouple the DC source and the rest of the circuit at high frequencies [53].

5.1 LTI assumption

Since power converters are inherently non-linear and time-varying devices, the possibility of applying black-box modeling techniques to represent their frequency behavior is subject to conditions.

The first condition is related to linearity. Indeed, if the converter cannot be treated, at least approximately, as a linear system, the use of different operating conditions to identify model parameters could lead to different black-box models. Hence, the effectiveness of the model is limited to setups involving operating/loading conditions that are very similar to those used for the experimental characterization.

In particular, because several procedures (refer to Section 4.2) foresee measurements with the converter switched OFF to identify the passive part of the model, further investigations are needed to clearly identify the conditions that ensure the effectiveness of this approach. In fact, although running the measurement with the converter switched OFF is not correct from a theoretical viewpoint, several contributions in the literature proved the possibility of achieving effective predictions of converter emissions by following this approach. This was the case for the method in a study by Spadacini et al. [22], which has been successfully applied to predict the emissions generated by DC/DC converters on spacecraft DC power buses. This apparent contradiction with the general theory can be explained by observing, similar to the vast majority of off-the-shelf converters, the converter in a study by Spadacini et al. [22] was equipped with an input EMI filter, whose presence masked the non-linear behavior of the switching modules. In Ref. [24], it was shown that in boost and buck converters, a similar mask effect was achievable owing to the presence of functional inductors and input capacitors. In a study by Wang et al. [35], the masking effect of the EMI filter in a motor drive system was identified and the DM impedance observed from the filter was considered to be time-invariant. Hence, it can be observed that the presence of high-value linear components (either inductors or capacitors) at the input of the converter may play a role of “mask impedance,” thus making the LTI assumption satisfied despite the non-linear behavior of the switching modules [24]. However, such a conclusion cannot be generalized unless confirmed by preliminary experimental verifications because it was necessary that the effect due to such a linear impedance was dominant at the external ports of the converter.

As stated in Section 3.1, unlike the CM impedance (whose frequency response was dominated by parasitic effects), the DM impedance could exhibit a different frequency response, depending on the ON or OFF status of the converter. In this case, the LTI constraint was not satisfied and more sophisticated modeling techniques were required, as stated in Section 4.3.

An effective test to verify whether the LTI assumption was satisfied was the measurement of the DM impedance with the converter switched ON and OFF, and to compare the obtained frequency responses. If they exhibited significant differences (particularly at low frequencies), this indicated a violation of the LTI assumption [24]. For this purpose, suitable experimental procedures/setups were required for measuring the in-circuit impedance with the converter switched ON. The reader can refer to some studies on inductive coupling [54], capacitive coupling [55] and VI methods [56].

To investigate the effects of the LTI assumption, the black-box model of the boost converter shown in Fig. 9 was evaluated using the procedure in a study by Spadacini et al. [22]. To this end, the S-parameter at the converter ports was predicted by Simulink under two conditions: ① the metal-oxide-semiconductor field-effect transistor (MOSFET) in the OFF state with a zero-voltage gate signal and ② the MOSFET in the ON state with a high-voltage gate signal (refer to Fig. 10). Details of the implementation of the S-parameter measurement by directional couplers were found in a study by Benson [57].

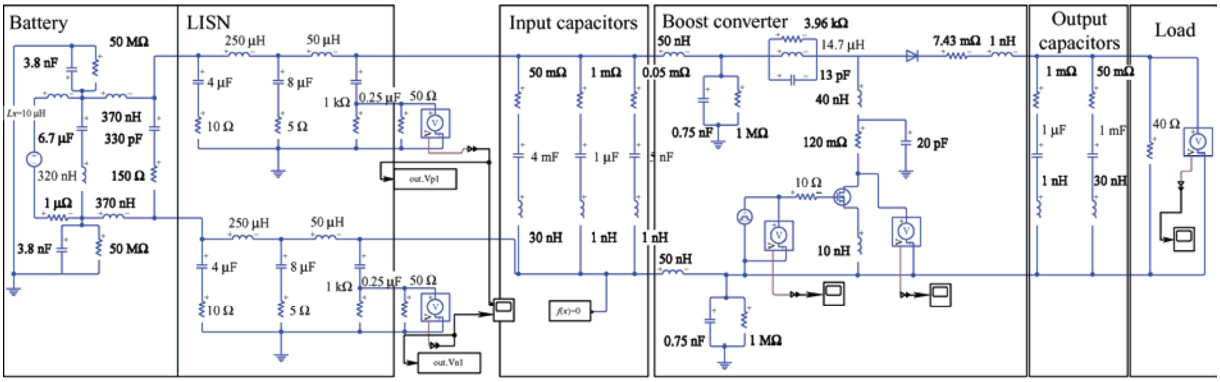


Fig. 9 Simulink schematics for CE prediction: Boost converter with the Standard LISN [(50 μH+5 Ω) || 50 Ω] specified in CISPR16-1-2

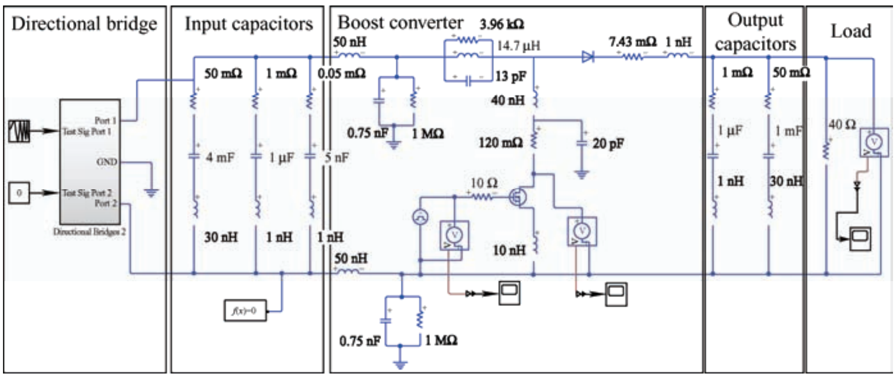
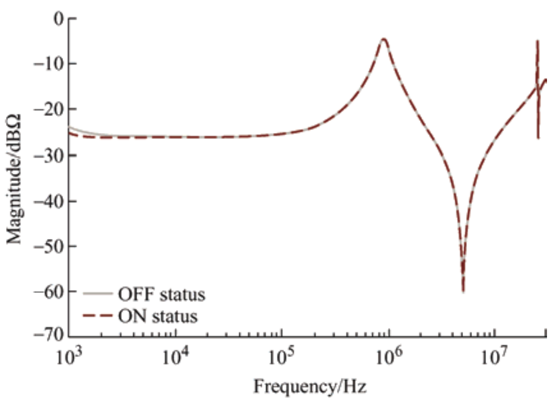
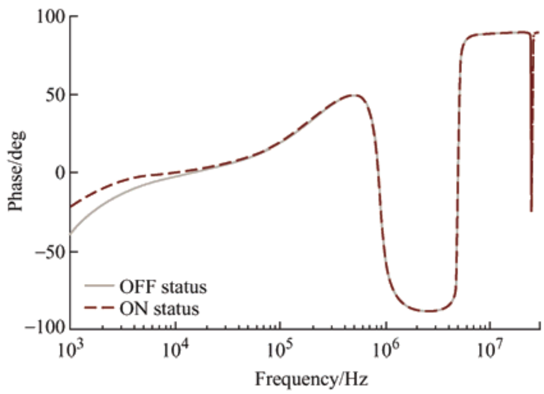


Fig. 10 Simulink schematics for S-parameter prediction at the ports of the boost converter using a directional bridge

To investigate the possible violations of the LTI assumption, the amplitudes and phases of the DM impedance in the OFF and ON states of the MOSFET are compared in Fig. 11. The comparison shows that for the specific boost converter in this example and the observed differences are small and limited to frequencies below 10 kHz.



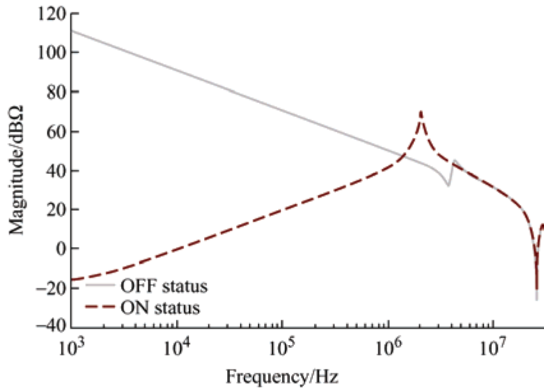
(a) Magnitude



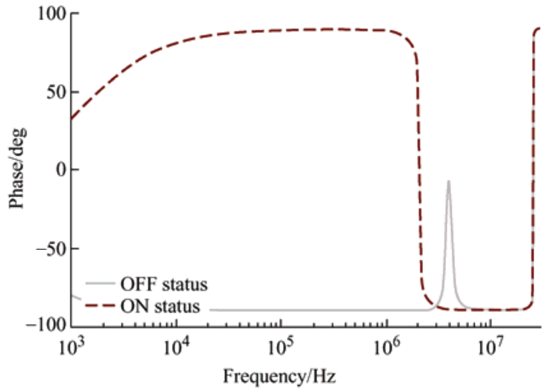
(b) Phase

Fig. 11 The DM impedance of the boost converter (input capacitors present) with the MOSFET in the ON and OFF status

To prove the effect of the mask impedance, a second example was carried out with the boost converter input capacitors removed. A comparison of the DM impedance with that of the MOSFET in the ON and OFF states revealed significant differences below 4 MHz (refer to Fig. 12).



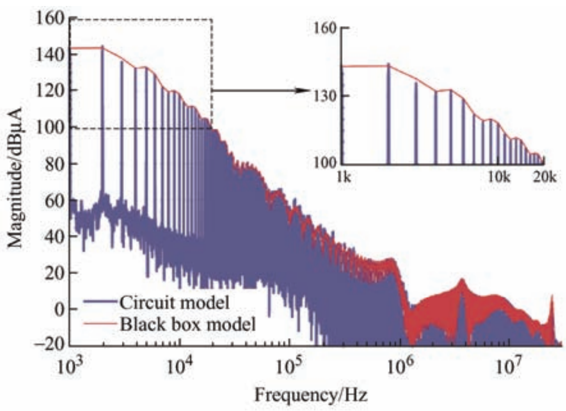
(a) Magnitude



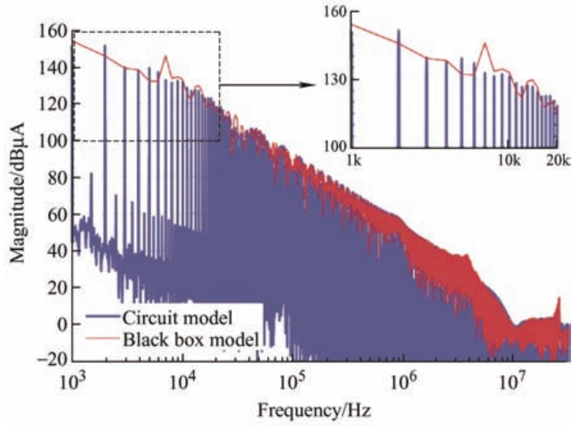
(b) Phase

Fig. 12 The DM impedance of the boost converter (input capacitor absent) with the MOSFET in the ON and OFF status

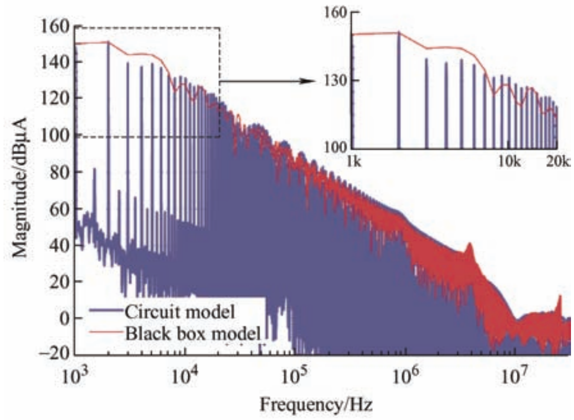
The predictions of the black-box model were compared with those of the circuit model in Fig. 13, which show an acceptable agreement, even at low frequencies, when the input capacitors were present (refer to Fig. 13a). However, when the input capacitors were absent, the comparison (refer to Figs. 13b and 13c) exhibited larger deviations at low frequencies regardless of how the passive part of the boost converter was evaluated (with the MOSFET in the OFF or ON state).



(a) With input capacitors and MOSFET OFF



(b) Without input capacitors and MOSFET OFF



(c) Without input capacitors and MOSFET ON

Fig. 13 Predictions of the noise current by the black-box and the circuit model

5.2 Conducted emissions at low frequency

Since the black-box model is mainly based on measurement data, the impedance of the external circuits (the load impedance/filter/LISN) should be known to be effectively de-embedded from the measurement data. However, the impedances of the power supply, for instance, the DC sources for DC/DC converters and the power grid impedance for DC/AC inverters, are generally unknown. To overcome this limitation, the procedure presented in Ref. [48] used an LISN to provide a stable external impedance that was not affected by possible variations in the grid impedance. The analysis showed that stable impedance conditions could be achieved in the frequency bandwidth of the emissions [58]. However, for frequencies below the minimum frequency for CE measurements (i.e., 9 kHz or 150 kHz, depending on the standard), significant variations were observed. For instance, the LISN specified in the standard CISPR16 ensured stable impedance conditions in the frequency interval from 9 kHz to 30 MHz (bands A and B). Hence, if the switching frequency of the converter under analysis was below 9 kHz, the extraction of the frequency response of the noise sources could lack accuracy below that frequency. Owing to the fluctuations in the grid impedance [59], the unstable impedance provided by the (50 μH+5 Ω) || 50 Ω LISN in the CE measurement of a grid-tied inverter system was presented in Ref. [58]. To investigate how this effect may degrade the effectiveness of the black-box model, the same LISN was used here to measure the CE from the boost converter, as shown in Fig. 9.

The setup for evaluating LISN impedance in Simulink is shown in Fig. 14. The DM LISN impedance seen by the boost converter is plotted in Fig. 15 for different values of the decoupling inductor L_x. It can be observed that the LISN cannot provide a stable impedance below 9 kHz, thus affecting the measurement repeatability at low frequencies. The impact on the model accuracy also depends on the relative values between the converter and LISN impedances. This issue was severe if the emissions were measured on the AC side of inverters equipped with LCL filters, with an impedance comparable to the LISN impedance [58].

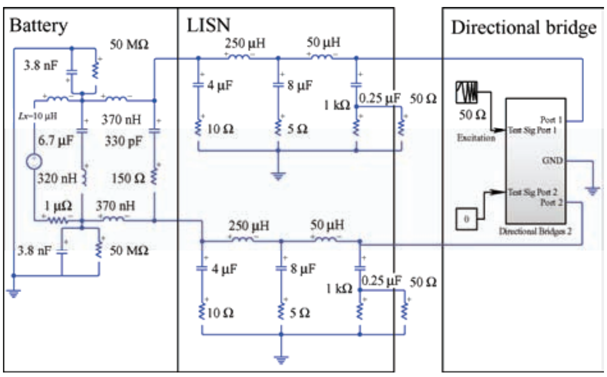
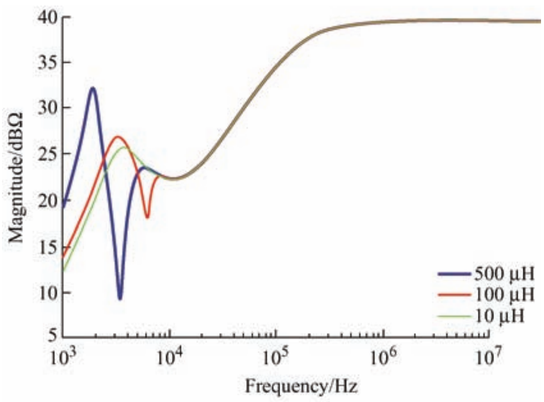
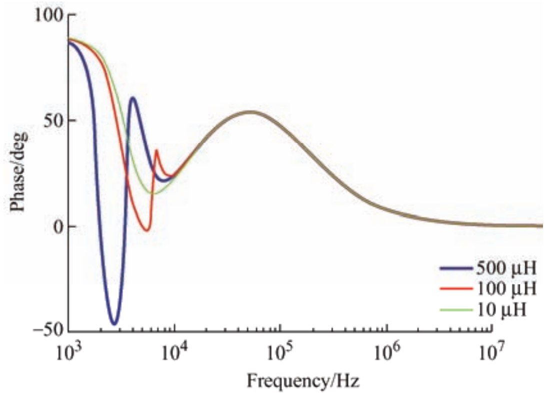


Fig. 14 Simulink schematics for LISN impedance evaluation



(a) Magnitude



(b) Phase

Fig. 15 The LISN DM impedance for different values of the decoupling inductor L_x

6 Conclusions

The manuscript presents a review of available modeling techniques for power converters targeted at EMI prediction, with a particular focus on behavioral modeling strategies, which are more suitable for EMC analyses of complex systems involving power converters, such as in renewable energy systems.

Among the possible approaches, three representative methods for identifying model parameters were presented and compared. It has been emphasized that particular attention should be paid to the possible limitations arising from the violation of the LTI assumption. To preliminarily verify this assumption, in the absence of additional information on the converter inner architecture, a solution based on the experimental measurement of the converter DM impedance with the converter under two different operating conditions was proposed. Moreover, other possible limitations have been demonstrated, such as those due to the limited bandwidth of standard LISNs, which were required in the process of model parameter evaluation to ensure stable and controlled impedance conditions for the required measurements.

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