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Un-terminated Black-Box EMI Models of Power Converters Driven by Random Modulation Strategies

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Abstract— Due to the development of renewable energy systems, there is an increasing need for tools to predict the Conducted Emissions (CE) exiting from power inverters, so to provide guidelines for optimal filter design. The objective is not only to limit the high-frequency noise injected into the distribution network (ac side) but also to protect the electronic circuitry on the dc side of the inverter. Hence, it is necessary to derive Electromagnetic Interference (EMI) models of the power inverter at both sides of the device. To this end, the (ac-side) behavioral model presented in previous works is here extended to predict the CE exiting both sides of a power inverter interfacing a PV panel to the distribution grid. Besides, suitable conditions for applying black-box modelling in the presence of random modulation strategies are investigated. It is proven that model effectiveness mainly depends on the base switching frequency and frequency band, while the effect of randomness does not significantly degrade prediction accuracy.

Keywords—EMI, un-terminated model, black-box model, random modulation

I. INTRODUCTION

With the wide diffusion of renewable energy systems in distribution networks, such as photovoltaic (PV) and wind farm systems, the conducted emission (CE) generated by the power electronics converters, propagating to both the smart grid and the PV-panel sides, could affect the normal operation of the network [1]. In recent years, there are several reports about the malfunctions of energy meters due to interference with the noise generated by the power converters used in PV-inverter systems [2], [3]. Indeed, recent researches show coexistence issues between power converters and communications systems, e.g., those using Powerline Communication (PLC). Besides, the CE exiting the dc side of power inverters can also interfere with the electronic circuitry at the PV-panel side. Hence, there is an increasing need to develop effective models at both sides of power inverters for Electromagnetic Interference (EMI) analysis.

The switching frequency of inverters in PV systems is still limited to a few kilohertz, thus, it is necessary to predict the emissions starting from low frequency. Besides, since new

modulation techniques, such as Random-Pulse-Width Modulation (RPWM), are increasingly utilized for noise reduction, it is interesting to investigate their actual effectiveness in renewable energy systems.

In general, to predict the CE exiting power converters, two approaches could be adopted: circuit and black-box (behavioral) modelling. The former is preferred in simple systems since time-domain simulations are generally time-consuming in complex systems and may even lead to convergence issues. On the contrary, in complex systems, behavioral models are often adopted due to their simpler modelling procedures and to avoid the evaluation of complex parasitic coupling paths [4]. In the literature, there are two different implementations of behavioral modelling approaches. One approach, leading to the so-called 'terminated' model, represents the converter from one side only, and inherently includes the loads (or, more in general, the rest of the network) connected with the other side. This approach can be used when CE predictions at one side only are of interest. Conversely, the second approach, leading to the so-called 'un-terminated' model, preserves the 'two-port' nature of the converter, which is more flexible allowing noise predictions and filter design at both sides. In the past, un-terminated models were developed for several applications. H. Bishnoi, *et. al* built a common-mode (CM) and differential-mode (DM) un-terminated model of a DC-fed three-phase motor drive system, separately [5], [6]. This approach was also used to model wide-bandgap and SiC-based power converters [7], [8]. However, the procedure involves redundant sets of measurements, which may introduce numerical errors during data post-processing.

Since the black-box model is an inherently linear time-invariant (LTI) representation of the system, in principle, it cannot predict the behavior of power switching devices, as they are non-linear and time-variant [9], [10]. For instance, if the switching frequency of the PWM signal changes, it is required to rebuild the black-box model accordingly. The situation is even more complex when dealing with RPWM, whose modulation signals vary randomly and are subject to modulation settings.

The first objective of this paper is to build an un-terminated EMI model of a PV-inverter system. To this end, the previous work of black-box modelling procedures at the ac side of power inverters in [11] is extended for an un-terminated model to predict CE on both the ac and dc side, whose modeling procedures can overcome the aforesaid limitations in data post-processing. Another objective is to identify suitable conditions for applying the black-box modelling effectively with different modulation strategies. (here, standard PWM and the RPWM with random switching frequency are considered).

II. MODEL EVALUATION AND VALIDATION

The system under analysis includes a three-phase inverter connecting a string of PV panels to the power grid through an LCL filter (see Fig. 1). The circuit model of the PV-inverter system in [11], containing not only functional parts but also main parasitic components to represent high-frequency behavior, is implemented in PSPICE and used as reference circuit. Since modulation can be easier implemented in Simulink, PSPICE-Simulink co-simulation is used to carry out the required time-domain simulations used as reference. A detailed description of co-simulation procedures can be found in [12].

The proposed un-terminated model contains five ports (Fig. 1) to represent the EMI behavior of the system at both the dc (phase P and N) and ac side (phase U, V, and W). The active part of the black-box model includes five current sources between each phase and ground. The passive part is modelled by a 5×5 admittance matrix. The evaluation procedure to derive model parameters is discussed hereinafter.

A. Evaluation of the passive part of the model

The parameters of the passive part of the model can be extracted as the first step starting from Vector Network Analyzer (VNA) measurement, as shown in Fig. 2. If a two-port VNA is used to measure a N -port system ($N > 2$), $N(N-1)/2$ measurements are required to evaluate the full matrix of scattering parameters (e.g., a five-port network requires 10 measurements) [13]. Besides, to connect the VNA to the inverter terminals, suitable *ad hoc* adapters should be used. For simulations, the measurement procedure is mimicked in PSPICE using the S-parameter measurement block in [11] from 2 kHz to 200 kHz. Afterwards, the 5×5 admittance matrix (\mathbf{Y}_{DUT}) is derived from the S-parameters [14].

It is assumed that the passive part of the model is mainly determined by the passive elements at both ac and dc terminals (i.e., the DC link capacitors and the LCL filters), regardless the on/off status of the transistors. Thus, the S-parameters are obtained when all transistors are switched off. However, this assumption needs to be verified in the frequency range of interest. For instance, conditions to apply black-box modelling techniques for a boost converter were discussed in [15].

B. Evaluation of the active part of the model

The second step is to evaluate the active part, i.e., the five current sources in Fig. 1. To improve measurement accuracy and reduce the influence of the 50 Hz component, two Line Impedance Stabilization Networks (LISN) are employed at both the dc and ac sides (see Fig. 3) [11]. The CE at both sides are recorded by two oscilloscopes with 50 Ω input impedance. Afterward, the active part can be obtained from measurement data by:

$$\begin{bmatrix} \mathbf{V}_{123} \\ \mathbf{I}_{123} \\ \mathbf{V}_{45} \\ \mathbf{I}_{45} \end{bmatrix} = \begin{bmatrix} \mathbf{ABCD}_{\text{ac}} & \mathbf{0}_{6 \times 4} \\ \mathbf{0}_{4 \times 6} & \mathbf{ABCD}_{\text{dc}} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{123\text{m}} \\ \mathbf{I}_{123\text{m}} \\ \mathbf{V}_{45\text{m}} \\ \mathbf{I}_{45\text{m}} \end{bmatrix} \quad (1)$$

$$\mathbf{I}_{\text{s}12345} = \mathbf{I}_{12345} + \mathbf{Y}_{\text{DUT}} \mathbf{V}_{12345} \quad (2)$$

where, $\mathbf{I}_{\text{s}12345}$ is a 5×1 vector containing the derived current sources. \mathbf{I}_{12345} and \mathbf{V}_{12345} are the voltages and currents at the terminals of the system, and \mathbf{Y}_{DUT} is the admittance representative for the passive part of the model. A similar notation is adopted for the measured voltages and corresponding currents (V_{xm} , I_{xm} , $x=1, 2, 3, 4, 5$) (see Fig. 3), where the subscripts 'm' denotes the measurement data, and $[\mathbf{V}_{123\text{m}} \ \mathbf{I}_{123\text{m}} \ \mathbf{V}_{45\text{m}} \ \mathbf{I}_{45\text{m}}]^T$ is a 10×1 vector containing the aforesaid measured values. The $\mathbf{ABCD}_{\text{ac}}$ and $\mathbf{ABCD}_{\text{dc}}$ represent the 6×6 and 4×4 ABCD matrices of LISNs at ac and dc side, which can be obtained by ad hoc VNA measurement.

C. Model validation

To evaluate the accuracy of the derived black-box model, a different operating condition should be considered. To this end, two EMI filters are inserted at both the ac and dc sides of the inverter (see Fig. 4). The corresponding CE at the LISNs receiver ports V'_{xm} , $x=1, 2, 3, 4, 5$) can be predicted by reversing the procedure in (1) and (2), where the ABCD parameters of the two EMI filters should be considered along with the LISNs. For reference, the complete circuit model of this setup is implemented in PSPICE.

First of all, the accuracy of the un-terminated model is evaluated with the inverter driven by standard PWM. In this case, the PWM control is implemented in Simulink with 5 kHz switching frequency. The amplitude modulation ratio (m_a) is 0.86 and the frequency modulation ratio (m_f) is 100. The CE predictions at the LISN receiver ports by the black-box model and by the reference PSPICE circuits are compared in Fig. 5. For brevity, only the results of one phase at the ac (V'_{1m}) and dc side (V'_{4m}) are shown in Fig. 5(a) and Fig. 5(b), respectively.

The results in Fig. 5 puts in evidence the capability of the derived un-terminated black-box model in predicting the CE when the inverter is driven by a standard PWM. The discrepancies observed above 100 kHz are mainly ascribed to numerical processing of data, due to the extremely low CE levels at high frequency. CM and DM voltages can be obtained by decomposing the phase voltages and were found in good agreement [see modal predictions at dc side in Fig. 5 (c-d)]. It is also obvious to see that the derived model with a 5 kHz switching frequency cannot be used to predict the situation with a different switching frequency (such as 7 kHz as shown in the red dash spectrum in Fig. 5).

III. PREDICTIONS FOR THE CASE WITH RPWM

The objective of this section is to investigate under which conditions black-box modelling can be effectively applied to model power converters driven by random PWM strategies.

Random PWM strategies intend to spread the CE at the switching peaks so as to achieve lower CE levels compared with standard PWM strategies. In general, there are several ways to apply randomness, such as modifying the period, the duty cycle, the pulse delay, etc [16]. In this work, the randomness is applied to the period of the triangular waveform, i.e., the switching frequency is changed for each period.

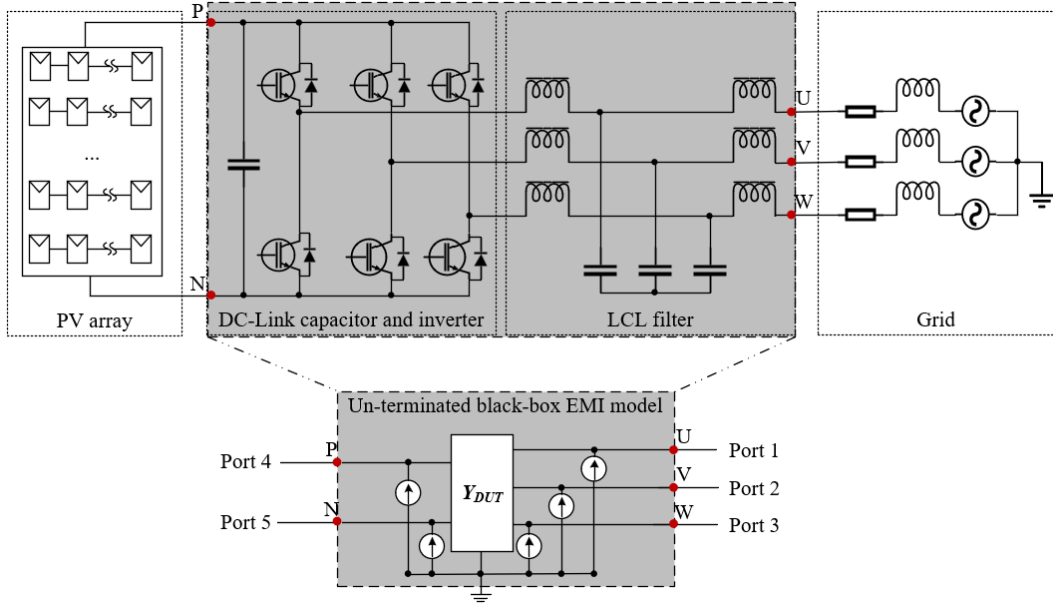


Fig. 1. Principal schematic of the PV-inverter system and the corresponding un-terminated black-box model.

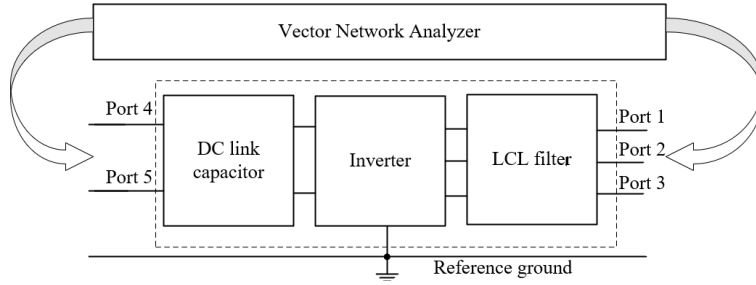


Fig. 2. Measurement setup to evaluate the passive part of the black-box model.

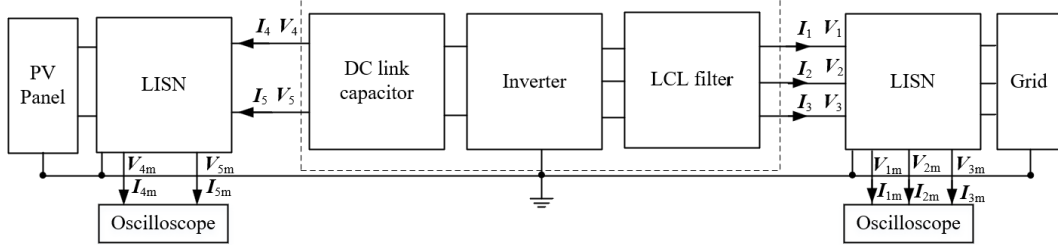


Fig. 3. Measurement setup to evaluate the active part of the black-box model.

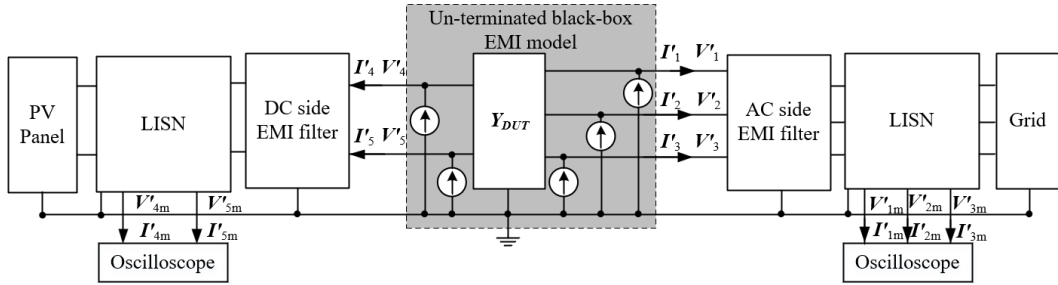


Fig. 4. Setup used for model validation

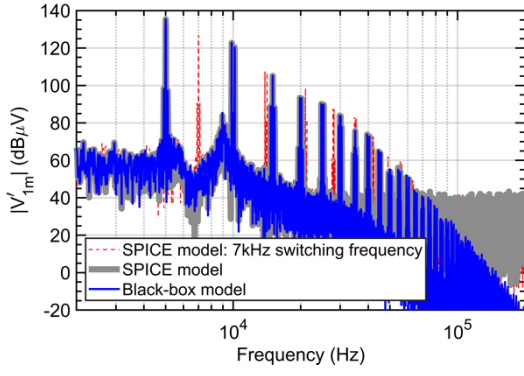
In PSPICE-Simulink co-simulation, this modulation is implemented by assigning the switching frequency f_{random} of the triangular waveform by:

$$f_{\text{random}} = f_s + \Delta f \xi_k \quad (3)$$

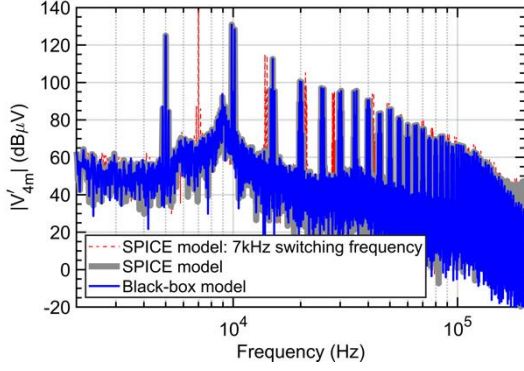
where f_s is the base switching frequency, Δf is the allowed frequency band of deviation from the base switching

frequency, and ξ_k is the pseudo-random numbers ranging from -1 to 1.

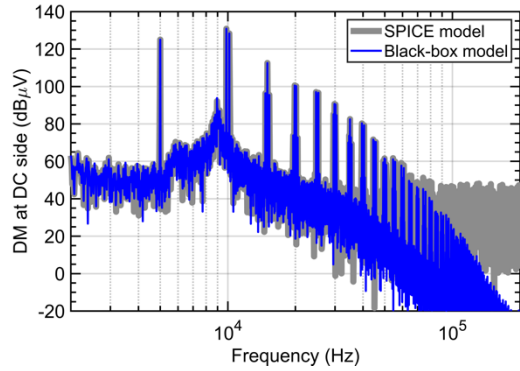
It is necessary to evaluate the influence of the aforesaid three parameters in (3) on the accuracy of the predictions. To this end, for the PSPICE reference circuits, three sets of simulations with respect to each parameter are carried out, and their corresponding RPWM settings are summarized in Tab.I.



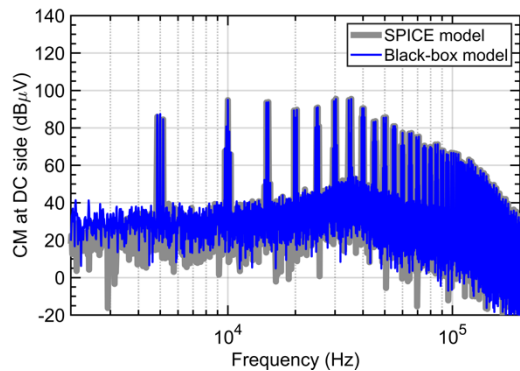
(a)



(b)



(c)



(d)

Fig. 5. PWM: prediction of phase voltages at (a) ac side (port 1) and (b) dc side (port 4). DC side modal voltage (c) DM and (d) CM. Red spectra are obtained by changing the switching frequency.

TABLE I. SIMULATION SETTINGS IN SECTION III

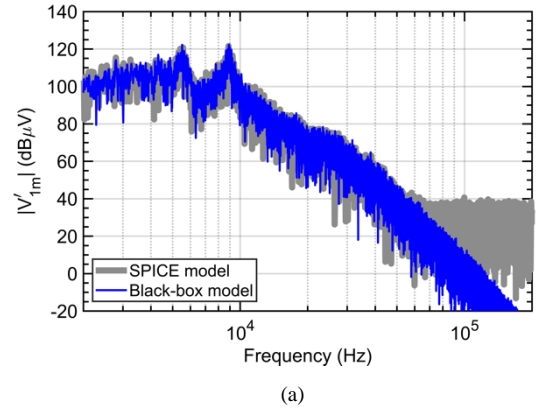
	RPWM parameters		
	f_s (kHz)	Δf (Hz)	ξ_k
Black-box models	5	500	series 1
Influence of ξ_k	5	500	series 2
Influence of Δf	5	125, 250, 1k, 2k	series 2
Influence of f_s	1.25, 2.5, 10, 20, 40	500	series 2

A. Influence of the pseudo-random number

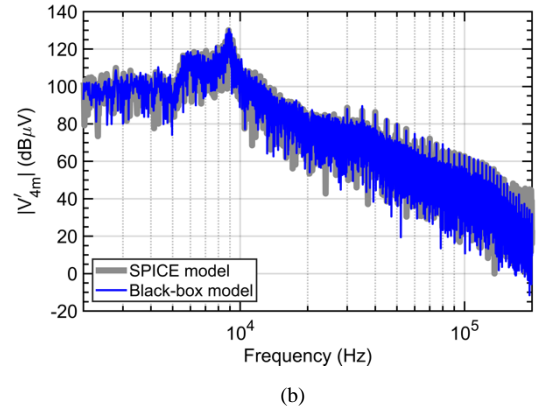
Since the pseudo-random number series captured when extracting the model is generally different from the series used for validation, it is necessary to preliminarily analyze the influence of this phenomenon. To this end, the pseudo-random number series used to evaluate the black-box model is different from the one used for PSPICE reference circuits as reported in Tab. I. Apart from that, the settings for the base switching frequency f_s (5 kHz) and the frequency band Δf (500 Hz) are the same.

Predictions obtained by black-box models are compared with PSPICE simulations in Fig. 6. With respect to the comparison in Fig. 5, it is confirmed that RPWM can help to reduce the noise at the switching frequency and its harmonics.

Although for RPWM the prediction accuracy is degraded. The deviations due to the different sets of pseudo-random numbers are still acceptable. In other words, as long as the base switching frequency f_s and the frequency band Δf are known, black-box modelling can assure satisfactory prediction of CE levels for converters driven by RPWM.



(a)



(b)

Fig. 6. Influence of the pseudo-random number: phase voltages at (a) ac side (port 1) and (b) dc side (port 4) with different series of pseudo-random numbers.

B. Influence of the frequency band

The influence of the frequency band is here investigated. To this end, the aforesaid conditions are assumed, and PSPICE simulations are carried out for four different values of Δf (see Tab. I for details). The envelope of the predicted spectrum and the spectra obtained by PSPICE are compared in Fig. 7. The results show that even if the frequency band Δf increases fourfold or shrinks by a quarter, the overall prediction accuracy is satisfactory except for the deviations at low frequency (mainly below 10 kHz).

C. Influence of the base switching frequency

In the third case, the influence of the base switching frequency is evaluated. PSPICE simulations are performed for five different values of f_s (see Tab. I), and the spectrum envelopes of the predictions and PSPICE simulations are compared in Fig. 8. In this case, the spectrum is highly affected by the base switching frequency.

Comparing all the simulation settings, it can be drawn the conclusion that the base switching frequency f_s can highly affect the spectrum which makes the predictions not accurate. This is in line with the conclusion for standard PWM. If the base switching frequency changes, a new black-box model should be derived. However, although the switching frequency f_{random} of the RPWM changes for each period, on condition that the base switching frequency f_s keeps constant, black-box modelling is still applicable, even for different frequency bands (Δf).

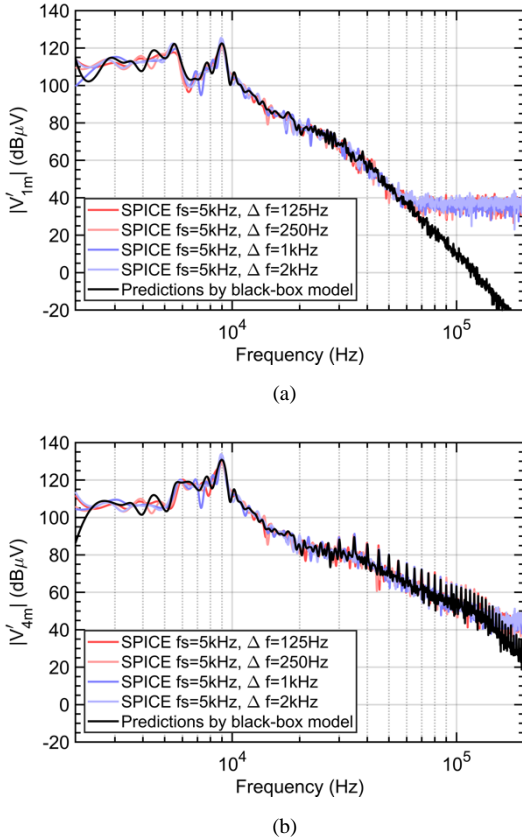


Fig. 7. Influence of the frequency band: phase voltages at (a) ac side (port 1) and (b) dc side (port 4) with different frequency band Δf (125Hz, 250Hz, 1kHz, and 2kHz).

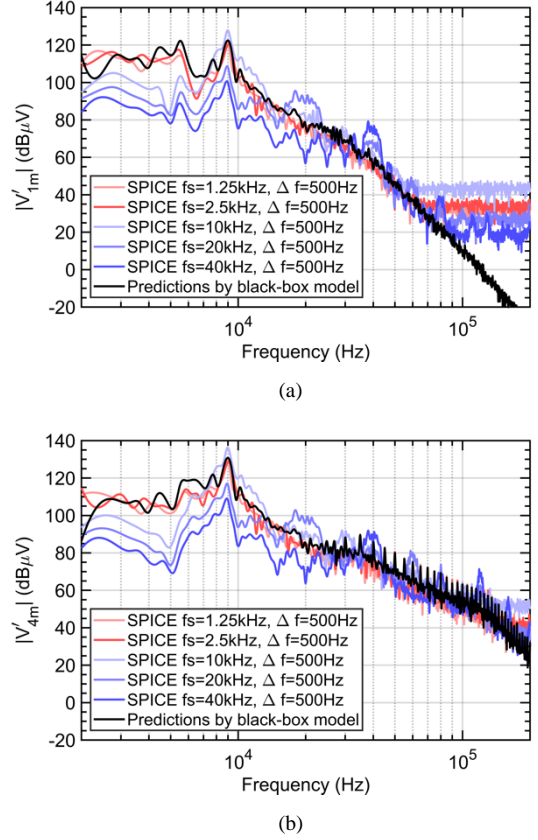


Fig. 8. Influence of the base frequency: phase voltages at (a) ac side (port 1) and (b) dc side (port 4) with different base switching frequency f_s (1.25 kHz, 2.5 kHz, 10 kHz, 20 kHz and 40 kHz).

IV. CONCLUSIONS

Black-box models are usually preferred to circuit models for modelling complex systems, such as renewable energy systems, and they can be used to provide guidelines for filter design and EMC analysis in the smart grid framework. In this work, the un-terminated black-box model of a PV-inverter system is introduced, which can be used to facilitate the design of the filters at both the ac and dc sides of the inverter.

Further, the prediction accuracy of the derived model is evaluated with different modulation strategies. For a standard PWM, CE predictions are accurate at both the ac and dc sides. However, if the switching frequency changes, the black-box model needs to be re-derived for the corresponding condition.

For RPWM, the prediction accuracy of the black-box models depends on the random levels of the switching frequency, whose influence is investigated with respect to the pseudo-random number, the frequency band, and the base switching frequency. The obtained results allowed to draw the following conclusions. (1) The pseudo-random number has the least effects. As long as the base switching frequency and the frequency range are known, predictions are satisfactory. (2) The variations of the frequency band can degrade the accuracy of the models at low frequency, but the overall predictions are still acceptable. (3) As expected, the base switching frequency has a significant effect. Similar to a standard PWM, the black-box model is no longer valid and needs to be re-evaluated if the base switching frequency changes.

For future study, it is desirable to investigate measurement validations with real full-scale setups and corresponding experimental challenges.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 812753.

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