Techniques and Challenges in Conducted EMI Analysis of Renewable Energy Systems

Xinglong Wu
DEIB
Politecnico di Milano
Milan, Italy
xinglong.wu@polimi.it

Xiaokang Liu
DEIB
Politecnico di Milano
Milan, Italy
xiaokang.liu@polimi.it

Lu Wan
Department of Energy
Aalborg University
Aalborg, Denmark
luwa@energy.aau.dk

Flavia Grassi
DEIB
Politecnico di Milano
Milan, Italy
flavia.grassi@polimi.it

Giordano Spadacini
DEIB
Politecnico di Milano
Milan, Italy
giordano.spadacini@polimi.it

Sergio A. Pignari
DEIB
Politecnico di Milano
Milan, Italy
sergio.pignari@polimi.it

Abstract—**Renewable energy sources have been widely integrated into modern power systems, leading to the massive use of power converters, which represent the main sources of conducted electromagnetic (EM) noise. Furthermore, power grids employ interactive devices including smart meters that resort to powerline communication (PLC) technology and are usually more susceptible to EM noise than traditional electrical machinery. This paper provides a state-of-the-art overview of conducted EM interference (EMI) analysis in power systems, focusing on EMI prediction models, PLC coexistence issues, and measurement challenges. Insights into the use of various methods in different application scenarios are provided, and relevant future studies are foreseen.**

Index Terms—**Conducted emissions (CEs), electromagnetic interference (EMI), power electronics, powerline communication (PLC), power system**

I. INTRODUCTION

With the emerging integration of renewable energy sources, nonlinear devices, including power electronic devices, are widely applied in modern power systems. Meanwhile, new information-technology-enabled equipment such as smart meters, phasor measurement units (PMUs), and electric-vehicle chargers are intensively installed in the grid. The evolution of the grid has introduced new challenges. One aspect is related to electromagnetic interference (EMI), and specifically, conducted emissions (CEs) in such systems. To guarantee electromagnetic compatibility (EMC) within the system, the conducted EMI should be properly predicted or measured, imposing new challenges for EMC engineers and researchers.

Specifically, though conducted EMI traditionally covers the frequency range between 9 kHz (or 150 kHz depending on the standard) and 30 MHz, several EMC-related standards are expected to extend the range to lower and lower frequencies, owing to the massive use of the abovementioned devices.

Power converters enable the conversion of energy through fast switching, which leads to potential EMI issues. Under this circumstance, the prediction of converter-related sources of electromagnetic noise and the propagation of EMI along interconnects are crucial, especially as far as the development of troubleshooting techniques is concerned. In this respect, practical measurement considerations, and the possible interaction between power and data sub-systems are also worth investigating.

This paper presents a survey of the most recent modeling techniques, power/data coexistence issues, and measurement challenges related to the conducted EMI analysis in renewable energy systems, aiming to provide a brief overview of state-of-the-art research contributions. The summary does not purport to be exhaustive, but selected topics are intended to highlight the basic ideas of techniques and challenges of EMC analysis in renewable power systems, concerning conducted EMI generation, propagation, and susceptibility, as well as EMI measurement.

The remainder of this paper is structured as follows. Sec. II concerns EMI modeling of conducted emission sources. In Sec. III, the coexistence issue between power and communication lines will be discussed. In Sec. IV, relevant measurement challenges will be presented. Finally, conclusions are drawn in Sec. V.

II. EMI SOURCES: MODELLING TECHNIQUES FOR EMI PREDICTION

It is well known that power converters are the main source of EMI due to the fast-switching transients involved. Accurate modeling of power converters as EMI sources is necessary to predict conducted emissions in power systems. For this purpose, two types of modeling techniques are usually considered in the literature. The first one is the so-called circuit model or "white-box" model, in which all the inner components of the power converters, including parasitics, are properly modeled

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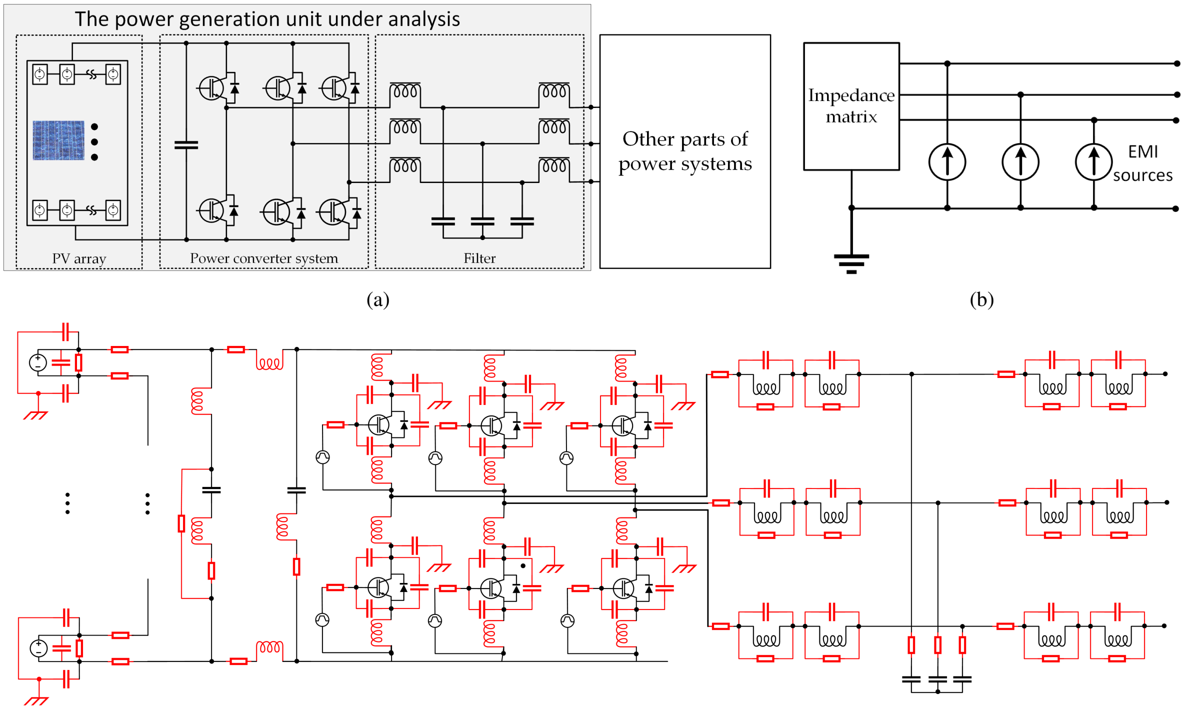

(a)

(b)

(c)

Fig. 1. Principle drawings of modeling techniques of one PV-based power generation unit [1] connected to the power grid: (a) Functional structure, (b) Black-box model in the form of Norton equivalent (current sources), and (c) Circuit model: network topology with functional components (black) and main parasitics (red).

and simulated in a circuit solver. Conversely, in the second representation, only external voltages/currents at the input/output terminals are used to extract an equivalent representation of the power converter. Hence, this technique is known as "black-box" or "behavioral" modeling. As an illustrative example, black-box and circuit models of a photovoltaic (PV)-based power generation unit (see Fig. 1(a)) are presented in Fig. 1(b) and Fig. 1(c), respectively.

The circuit modeling procedure starts from the actual network topology with functional components (e.g., valves, capacitors, inductors, etc.) and then adds parasitics to account for their non-ideal behavior at radio-frequency, as shown in Fig. 1(c). This idea is quite straightforward and offers good flexibility. Indeed, by adding parasitics that are passive, this augmentation of the functional circuits can be easily simulated in any time-domain or frequency-domain solver, and be easily adapted if components and/or working conditions are changed. Since parasitic parameters are critical from the EMC viewpoint, accurate measurement/simulation procedures should be used to estimate these parameters. To this end, several analytical models, simulation tools, and measurement approaches have been developed. For instance, an experimental method to characterize insulated gate bipolar transistors (IGBTs)-based power converter modules is provided in [2]. In [3], the parasitics of AC filter components, DC-bus components, and IGBT modules are obtained by the combination of proper measurements using an impedance analyzer with curve fitting. Simulation tools for the extraction of broadband parasitic inductances are presented in [4] whereas [5] uses numerical EM analysis (finite element method) to extract parasitics of IGBT cells, the heat sink, and PCBs. Similar simulation tools are also employed in [6] to analyze common-mode noise generation due to unbalanced busbars. In general, as long as detailed geometrical and electrical parameters of all components are available, accurate circuit models can be developed. However, the complexity of modern power systems often represents an obstacle to the development of accurate circuit models. Indeed, each sub-system of the power grid usually involves multiple power converter units, which include many internal electrical and mechanical structures whose parasitics can be hardly estimated. In fact, accessing the internal structures of units and sub-systems is often impractical. Furthermore, even though all internal information is available, the extraction procedure will be extremely time-consuming, and the circuit simulation of complex systems may lead to convergence issues [7].

Due to such issues, black-box modeling is often preferred in complex systems. The power converter unit is treated as a black box that is characterized based on its terminal behavior. Specifically, the power converter under analysis is usually represented as a multiterminal Thevenin or Norton equivalent circuit, including a set of EMI sources and an impedance (or admittance) matrix, as shown in Fig. 1(b). To obtain the frequency-dependent values of these equivalent components in three-phase systems, two methodologies are presented in the literature:

- In the first method [8], [9], model parameters (sources, impedances) are treated as unknowns in nonlinear systems of equations. Several measurements are carried out with independent test benches in which terminals of the power converter(s) are connected to different networks. In this way, a set of terminal voltages and/or currents are collected and enforced in the aforementioned systems of equations to identify the unknown black-box model parameters.
- Alternatively, in the second method, EMI sources and the impedance matrix can be evaluated separately. To this end, the entries of the impedance matrix are directly measured by a Vector Network Analyzer (VNA) [10] or an Impedance Analyzer (IA) [11] connected to the power-converter terminals when the power converter is switched off. After the impedance matrix is known, CE currents or voltages of the active-state power converter are measured by using current probes [12] or line impedance stabilization networks (LISNs) [1], [13], respectively, to extract the EMI noise sources.

A comprehensive discussion of the aforesaid methods is presented in [14]. In general, black-box modeling is much simpler than white-box modeling, thus making it beneficial for model identification in complex systems. For instance, a three-phase four-line power converter unit requires to setup 4 different set benches or 2 sets of measurements in the aforesaid first and second methods, respectively.

As a preliminary requirement, black-box modeling assumes the power converters to be linear and time-invariant (LTI), which is not theoretically true. However, as long as conducted EMI emitted from the power converter is of interest, this LTI assumption can be considered approximately valid thanks to the presence of filters (functional input filters or EMI filters) that usually exist in real applications. Indeed, passive filters (composed of capacitors, inductors, common-mode chokes, etc.) provide a well-defined "mask" impedance at radio frequencies. In other terms, this impedance masks the time-variant and nonlinear behaviors of switching devices that are present after the filter, and provides a stable input impedance matrix regardless of the on/off state of the valves, which is essential for the aforesaid second method. The comparison between circuit and black-box models is summarized in Table I.

Furthermore, it is worth noting that to predict the EMI noise propagation in the systems, the EMI emission model can also be combined with circuit models of interconnects (cable networks). Since these interconnects are usually electrically long, researchers often resort to the multiconductor transmission line (MTL) theory [15] for modeling the noise propagation. For instance, [16] combines the use of black-box models of converters in a PV system and the distributed-parameter models of wiring harness, obtained by using MTL theory and a 2D electromagnetic solver (for evaluation of per-unit-length parameters), for investigating the propagation of conducted EMI in a low-voltage power network.

TABLE I
A COMPARISON BETWEEN CIRCUIT AND BLACK-BOX MODELS FOR RENEWABLE ENERGY SYSTEMS

	Circuit modelling	Black-box modelling
Idea	Functional circuits + Parasitics	Thevenin/Norton equivalence
Pros	· High flexibility · Adjustability	· Fewer elements · Faster simulation
Cons	· Extremely time-consuming · Some parasitics are not accessible/evaluable	· LTI assumption · Available only for EMI emitted to the outside

III. EMI SUSCEPTIBILITY: COEXISTENCE BETWEEN POWER AND DATA

Among several powerline communication (PLC) techniques, narrowband powerline communication (NB-PLC) technology, such as PRIME, G3-PLC, and IEEE 1901.2, is used in smart grid (SG) applications, offering the advantage of using existing power cables for both power and data transmission, thus minimizing cost and complexity. Despite the aforementioned advantages, PLC operation is possibly susceptible to conducted noise, which can be unintentionally generated by non-linear devices, especially, power electronic-based devices with switching frequencies and related harmonics in the PLC working frequency range [17], [18]. Indeed, most smart meters involved in the smart grid operate in the narrowband range of the CISPR A standard (from 9 kHz to 150 kHz) and specifically in the CENELEC-A band between 9 and 95 kHz, which is close to the switching frequencies of power converters. Meanwhile, few emission standards for this frequency range are currently available, with the result that an increasing number of interference cases are observed.

A principle diagram illustrating the aforementioned issues in an AC system is shown in Fig. 2, where a PLC transmitter (PLC Tx) and receiver (PLC Rx) operate in a system integrating distributed-generation (DG) sources, such as PV and wind generators, with different (possibly active) loads, such as smart buildings and electric vehicle chargers, which can behave as energy producers or consumers depending on time. The coexistence issues are introduced due to the communication signals over the power line. As one of the well-established parameters to indicate the PLC's performance, Frame Error Rate (FER) is calculated as the ratio between the erroneous frames and total received frames.

For the sake of simplicity, the system under analysis is generally divided into two separate parts in the literature: the converter circuit, which is usually in the form of a DC/DC converter that induces a significant amount of noise at the switching harmonics, and the communication circuit, i.e., the ideal AC power line system that enables data communication through the use of PLC modems. Such parts are usually coupled through an artificial circuit, either in the form of a capacitor or long transmission lines in close proximity. In a few cases (e.g., in [20]), a unified circuit is studied.

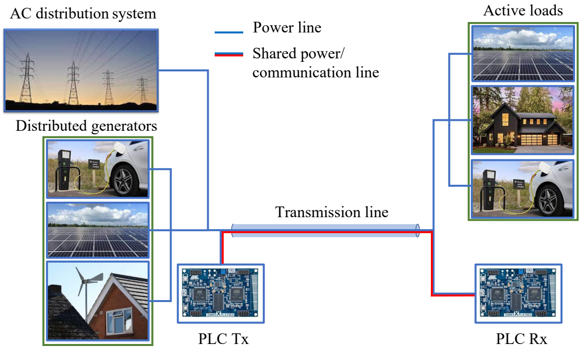

Fig. 2. Illustration of power and communication coexistence issues [19].

Initially, the influence of nonlinear loads or converters with conventional deterministic modulation on PLC effectiveness was mainly studied, with the experimental approach as the mainstream. For instance, In [21], LED lamps, which are typical nonlinear devices producing pulse currents during operation, are used to demonstrate their effect on the PLC. It was observed that increasing the number of LED lamps caused more frame drops; with a maximum of 32 LED lamps, the resulting FER reached 13.3%. Reference [22] studied the influence of Si-SiC-based converters on the performance of narrowband G3-PLC. A long DC cable (42 m) connected to the buck converter (working at 62 kHz switching frequency) was placed in proximity (1 cm) to the PLC signal cable in order to have an effective coupling, and the FER increased to over 30% when the converter supply voltage reached 200 V. The use of different semiconductor devices (Si or SiC) resulted in similar effects.

Recent studies [20], [23]–[25] have evidenced coexistence issues between NB-PLCs and power converters, focusing on G3-PLC systems and randomly modulated (or spread-spectrum modulated) power converters. Those modulation techniques introduce randomness in the modulated signal, leading to random carrier frequency modulation with a fixed duty cycle (RCFMFD), or random carrier frequency modulation with a variable duty cycle (RCFMVD). By such means, the converters achieve a lower EMI level at the harmonics of the switching frequency owing to the spread spectrum feature that spreads EMI power into a wider band of frequencies. However, this spreading can lead to a general increase in background noise in the frequency band of interest, and can worsen the frequency coexistence issue.

In [23], a SiC-based DC buck converter with a central frequency from 50 to 75 kHz, RCFMFD, and different levels of modulation spreading factor was used to generate interference in the communication loop that adopted two G3-PLC modems. The coupling was made by an artificial circuit to amplify the interaction. It was observed that with a larger spreading factor and input DC voltage, the FER steadily increased. The highest values of FER (over 50% for input DC voltages higher than 20 V) appear around the intermediate frequency of the communication bandwidth, between 56 and 69 kHz. Paper [24] investigated how the converters' modulation parameters and coding methods may affect PLC communication reliability, and compared the effects of deterministic and random modulations. The studied system resorts to the long DC cable for noise coupling. The results proved the increased FER when random modulation is used in place of the deterministic one. Reference [25] further studied the effects of two random modulation techniques, with an artificial coupling scheme from the DC/DC converter to the communication loop. Effects of parameters that influence random modulation schemes, such as the switching frequency of the RPWM, the modulation index, and the random number update rate (RNUR), have been discussed. Besides, results suggest that a better reduction effect of CE peak noise level can be achieved by random frequency modulation (RFM), but this would cause more influence and therefore FER on the communication loop than random pulse position modulation (RPPM). Finally, in [20], a comprehensive system mimicking the integration of renewable energy sources, where the DC/DC converter stage is connected in series with the DC/AC inverter stage, is studied through simulation. The conclusions are more complicated, depending on the switching frequencies of different converters, the modulation schemes used, and the PLC modem positions (if they are between two phases of the power line, or between a phase and ground).

Despite the wide variety of current studies, future research on the topic can be further performed, possibly focusing on 1) the analysis (both theoretical and experimental) of the coexistence issue in a more realistic and comprehensive system, 2) the development of related models (e.g., the black-box model of the converter in [19]) that facilitate the similar analysis, and 3) the proposal of efficient measures or standards to address the coexistence issue.

IV. EMI MEASUREMENT CHALLENGES

For both EMI modeling and verification, accurate measurement of CE is essential. In high-power applications such as power systems, the fundamental switching frequency of power electronic devices starts from a few kHz [26], [27]. Therefore, the electromagnetic pollution in the frequency range 2 kHz - 150 kHz is of great interest from both power quality (PQ) and EMC viewpoints. Indeed, traditional PQ analysis covers the range from 50 Hz up to 2 kHz, while EMC starts at 9 kHz or 150 kHz [17], [28]. There is a gap between 2 kHz and 9 kHz, especially for the conducted EMI measurement.

As a matter of fact, in conducted EMI measurement standards CISPR 16 (9 kHz - 30 MHz) and CISPR 22 (150 kHz - 30 MHz), proper circuit layouts of LISNs have been defined for ensuring repeatable CE measurements. Specifically, the main objectives of a LISN are as follows. Firstly, it presents a stable terminal impedance seen from the power converter side. Secondly, it blocks noises that do not come from the power converter under analysis (such as those coming from the power grid) to a certain level, which is quantified by the decoupling factor (DF). Thirdly, it provides an additional measurement port for measuring conducted EMI with a low voltage division factor (VDF). However, since LISNs are designed to be used

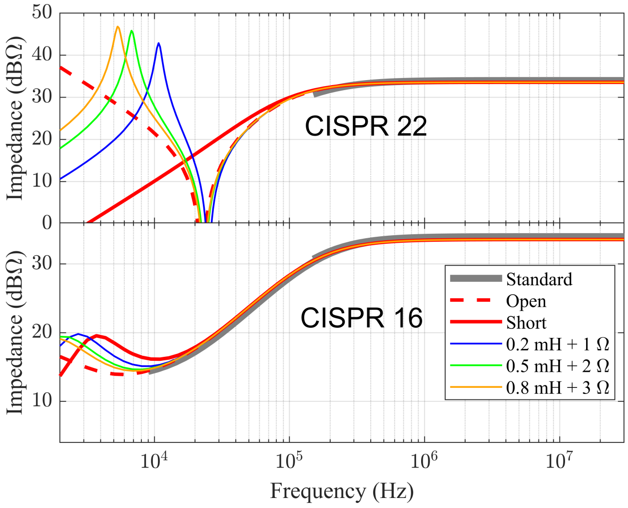

Fig. 3. Impedance response of CISPR 22 and CISPR 16 LISNs connected to different grid networks.

for measurements starting at 9 kHz / 150 kHz, using those LISNs for accurate conducted EMI measurements down to 2 kHz is questionable.

Indeed, as noticed in [1] and [29], the LISNs compatible with CISPR 16 and CISPR 22 cannot provide stable impedance in different grid networks, sufficiently high DF between grid and power converters, or sufficiently low VDF in the frequency range between 2 and 9 kHz. This makes conducted EMI measurements unrepeatable and unreliable. For instance, based on [29], Fig. 3 shows the impedance responses of the CISPR 16 LISN connected to different grid impedances, showing a LISN impedance value that varies with the grid impedances at low frequencies.

Another challenge related to conducted EMI measurement is the number of measurement ports. The capability of traditional LISNs is limited to enabling EMI measurement on one line at a time (even if the power circuits of several phases are simultaneously in effect), which is enough for EMI verification but not very helpful for EMI analysis. In fact, some black-box modeling procedures and modal-domain analyses (such as common-mode quantity extraction) require the simultaneous measurement of EMI voltages on all lines, demanding a LISN providing multiple EMI measurement ports. Currently, several LISNs are used to conduct simultaneous measurements on different channels (e.g., measurements in [19]), with each LISN working on a single-phase sub-system.

The aforesaid challenges call for a new design of wide-band LISNs that can cover the frequency range starting at 2 kHz and have multiple measurement ports.

V. CONCLUSION

This paper summarized several state-of-the-art techniques and challenges in conducted EMI analysis in renewable energy systems. Circuit and black-box EMI models were reviewed and compared. Several electromagnetic coexistence issues in PLC systems and the corresponding possible solutions were discussed. The main challenges related to LISNs in EMI measurement were also highlighted.

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