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UNIVERSITY**

SINGAPORE

**MODELING AND ANALYSIS OF EMI FROM
DC INPUT OF PHOTOVOLTAIC SYSTEMS**

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SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

2019

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SCHOOL OF ELECTRICAL AND ELECTRONIC
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A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2019

Statement of Originality

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Authorship Attribution Statement

This thesis contains material from the following two papers, one published in a peer-reviewed journal and one accepted at a conference, in which I am listed as an author.

Chapter 4 is published as M. Prajapati and K. Y. See, "Extraction of equivalent source model from photovoltaic systems," *IEEE Transactions on Electromagnetic Compatibility*, accepted for publication, to appear in 2019.

Chapter 5 is partly published as M. Prajapati and K. Y. See, "Extraction of equivalent impedance of photovoltaic panel under its actual operating conditions," *Joint IEEE International Symposium on Electromagnetic Compatibility and Asia-Pacific Symposium on Electromagnetic Compatibility*, Singapore, May 2018, pp. 1145-1149.

In both papers, the contributions of the co-authors are as follows:

- A/Prof See provided the initial project direction.
- I prepared the manuscript drafts. The manuscript was revised by A/Prof See.
- I co-designed the study with A/Prof See and performed all the laboratory work at the School of Electrical and Electronics Engineering. I also analyzed the data.
- All experimental set up and measurements were conducted by me in EMC lab, NTU for analysis, characterization, testing and simulation.

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Abstract

Electromagnetic compatibility (EMC) is a major technical challenge for solar photovoltaic (PV) systems. As the use of PV systems has increased in recent years, the problems of electromagnetic interference (EMI) from PV systems are becoming more evident. The main source of EMI in PV systems are the power converters, such as dc-dc converters and dc-ac inverters, which use high-frequency switching power electronic devices. The power converters transmit conducted noise emissions at the input side, where PV panels are connected, and at the output side, where loads and ac grid are connected. At the output side, the conducted emissions must comply with relevant EMI regulations to prevent interference to loads or the ac grid. Although similar regulation does not apply to the dc input of a PV system, the high frequency switching converters with its dc input connected to the PV panel causes conducted emissions to propagate along the dc cables. These emissions can then radiate through dc cable and PV panel, which serve as unintentional antennas.

Since PV systems are becoming widely accepted in both residential and industrial applications, EMI from these systems must be controlled. In such a task, an EMI model of the system can be a valuable tool as it provides insight into noise generation and propagation mechanisms. Moreover, EMI models are very useful to develop methods to mitigate noise emissions, such as designing EMI filters. However, it is challenging to develop accurate and efficient EMI model of a complex system such as of PV systems. Due to numerous components in power converters, several parasitic components and system specific couplings, conventional methods are inefficient to model such systems. PV systems provide an additional challenge since in addition to different complexity of power converters, noise propagation is influenced by operating condition of PV panel and long dc cables which vary in different systems. Therefore, a simple and efficient method is necessary which can provide a simple yet accurate way to analyze EMI in PV systems.

This thesis proposes to develop a measurement-based EMI model of DC input side of PV system. In this approach, the noise source of the system is represented by equivalent Thevenin voltage or Norton current source with equivalent noise source impedance in the frequency domain. Similarly, the noise propagation path is also modeled as equivalent impedance in the frequency domain. To develop an accurate EMI model, the noise source model of the power converters and impedance of PV panels should be extracted at operating conditions. For this purpose, an in-circuit measurement approach is used to extract the noise model at the dc input of a PV system under its actual operating conditions. The dc input side is mainly focused on this research to study the effect of PV panels and dc cables on EMI.

The proposed approach provides adequate information for EMI modeling and mitigation purposes without the full knowledge of the internal circuit of the PV system. Using the method, separate noise equivalent models for common-mode (CM) and differential-mode (DM) emissions of a PV system are developed. The model can then be used to study the conducted emissions and radiated emission from the system. The noise source model allows us to estimate noise emissions and evaluate the effectiveness of the filter for EMI mitigation without a trial-and-error process.

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List of Abbreviations

AC	Alternating Current
AF	Antenna Factor
CM	Common Mode
DC	Direct Current
DM	Differential Mode
DUT	Device Under Test
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FEM	Finite Element Method
IGBT	Insulated-Gate Bipolar Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MPPT	Maximum Power Point Tracking
PEEC	Partial Element Equivalent Circuit
PFC	Power Factor Correction
PV	Photovoltaic System
RF	Radio Frequency
SMPS	Switched Mode Power Supply
TDR	Time Domain Reflectometry
VNA	Vector Network Analyzer
VSD	Variable Speed Drive

Chapter 1

Introduction

Solar photovoltaic (PV) systems have increased rapidly as an alternative energy source in recent years and are expected to rise further in the future [1]. Considering the growing energy requirements and environmental concerns, PV has been considered as an important green energy source. However, in terms of power quality, PV systems have some technical issues to be resolved, such as power intermittency, poor conversion efficiency and electromagnetic compatibility (EMC). The focus of this research work is on EMC which is gaining more concern in recent years since electromagnetic interference from PV systems is becoming more evident.

1.1 Background

Electromagnetic Interference (EMI) in solar PV systems has been indicated in several studies in the past few years [2-10]. The cause of EMI in PV systems is due to high frequency switching in power converters used in these systems. Power electronic converters, such as DC-DC converters and DC-AC inverters, use high frequency switching for efficient power conversion. Most of the studies indicate conducted emissions in the range of 150kHz to 30MHz at output sides of PV systems. Several types of PV inverters are investigated on the basis of EMC and noise emissions in [11]. Significant noise flowing in different parts of a PV system is reported in [12]. The conducted emissions at the output side can cause interference to load and other electronic devices or to the ac grid if the system is Grid connected [13]. Consequently, different EMI mitigation techniques and regulations have been developed specifically for the load side [7, 8] to control the interference.

Although similar regulation does not apply on the dc input of a PV system, the high frequency switching converters with its dc input connected to the PV panel causes conducted emissions to be present in dc cable [2, 9, 10, 14, 15]. These emissions can radiate through the dc cable and the PV panel, which serve as unintentional antennas. It is important to regulate the noise emission at the input side of PV system as well since the radiated emissions can interfere with other electronic devices.

A model to analyze and regulate noise emissions from a system can be very useful. However, it is challenging to develop an accurate EMI model for a system. There are several modeling methods available which are good at converter level but not practical for system level EMI analysis [16-20]. Nevertheless, some methods have been applied for complex systems with reasonable accuracy [21-25]. In terms of PV system, a systematic method to model EMI for the system is lacking. Modeling of EMI in PV system is important because though a converter used in the system may comply with standard limits, the emissions from a system may exceed limits due to the presence of several converters and interactions within the system [12]. Such problems are revealed only after installation of the system and regulating the noise can be a time-consuming and costly operation. Moreover, measurements at site sometimes may not be accessible or practical, e.g. for radiated emissions due to the presence of other interfering sources. PV systems also present some unique challenges such as different types of system configuration, converter topologies, PV panels characteristics dependent on operation conditions and long dc cables with varying lengths. An efficient model of PV systems is therefore necessary to deal with EMI from the system.

In case of PV systems, which is similar to modeling EMI in power converters, there are generally two approaches to modeling: lumped circuit or device-based modeling [16, 26] and measurement-based equivalent noise source EMI modeling [27, 28]. While lumped circuit modeling has the advantage of scalability and adaptability, it becomes very complex with increasing number of components such as parasitic elements. Additionally, there could be issues with accuracy and convergence of the simulation for high-frequency analysis of a large number of components. Besides this issue, the manufacturers of the PV systems are reluctant to provide circuit level information due to intellectual property protection. As such, lumped circuit modeling

is inappropriate for system level EMI modeling. A more practical approach to model power converters for EMI analysis is the equivalent noise source EMI modeling approach.

Measurement-based EMI modeling approach is a black-box modeling technique where the converters are represented by Thevenin (or Norton) equivalent circuits with an independent noise source and noise impedance in the frequency domain [29, 30]. This approach has been applied to analyze EMI in motor drive systems [24, 25] and power converters such as power-factor-correction (PFC) devices [28, 31-33]. However, to estimate the noise source impedance, these studies use resonance method or insertion method which are prone to errors. In the case of resonance method, the process of choosing the right values of reactive components and then tuning for resonance especially at high frequencies is difficult and time-consuming. In case of insertion loss method, the impedances of inserted components must be much larger or smaller than the noise source impedances for better accuracy [34]. To improve the measurement of noise source impedance in switched mode power supply (SMPS), in-circuit impedance measurement based on inductive coupling method was proposed [35-37]. By using one current probe as an injection probe and another as a receiving probe, the method can obtain both magnitude and phase of the impedances accurately.

Once an accurate EMI model of a PV system is achieved, it can be used for various EMI analysis. The dominant modes of noise emissions can be identified and properly investigated. Models with noise source and termination impedances are very useful for EMI filter designs [38]. EMI filters are often required in electrical systems even after using other mitigation techniques. However, the design of the EMI filter is complicated since the noise and load impedances of the system changes according to operating conditions. The noise source model allows us to evaluate the effectiveness of the filter for EMI mitigation without a trial-and-error process. This helps for the systematic design of EMI filters thereby reducing the overall size and cost of EMI filters in the system.

1.2 Motivation and Objectives

As the solar PV systems become cheaper, they are gaining acceptance for widespread use in both residential and industrial applications. Hence, PV systems must be properly designed for EMC consideration, so that the electromagnetic interference (EMI) generated by the PV systems do not interfere with other electronics systems.

Since PV system comprises several components, detailed lumped circuit modeling is not suitable to study EMI of the system. Therefore, measurement-based equivalent noise source EMI modeling approach is proposed for PV systems in this thesis. Additionally, the two-port network based inductive coupling method is proposed to extract the in-circuit impedance required for the modeling. Using this approach, it will be possible to estimate separate CM and DM equivalent models for the system. This will be useful to analyze conducted emission in the system and to compare which component is significant for radiated EMI in PV systems. Similarly, the models will also be useful for developing optimum EMI filters for the system.

Therefore, the main objectives of this thesis are as following:

1. Develop a systematic method for modeling EMI from a PV system based on the measurement-based equivalent noise source model
2. Develop an efficient method to extract noise source and termination impedances for the models
3. Develop the model for a PV system, with a panel and dc cable, for actual operating condition.
4. Apply the model to test the effects of dc cable and EMI filters on conducted and radiated emission from the PV system.

1.3 Overview

This thesis is organized as follows:

Chapter 1 introduces the background, motivation and objective of the thesis.

Chapter 2 provides relevant literature review on Photovoltaic systems and EMI in PV systems.

Chapter 3 discusses in-circuit impedance extraction using inductive coupling method in details.

Chapter 4 presents the development of conducted noise emission model of PV system which includes LISN and PV simulator.

Chapter 5 presents the development of noise emission model of a PV system with PV panel and dc cable.

Chapter 6 concludes the thesis along with potential future works.

Chapter 2

Literature Review on Photovoltaic Systems and EMC

2.1 Introduction

Electromagnetic Interference (EMI) is becoming a major technical challenge in photovoltaic (PV) systems. EMI is electromagnetic disturbance that hampers normal operation and degrades the performance of electronics or electrical equipment [39]. EMI can induce undesired voltage and current in unintended devices and cause detrimental effects ranging from simple disturbance to catastrophe. While both electromagnetic compatibility (EMC) issues, emissions and susceptibility [40], are relevant in PV systems, the former is of bigger concern due to inherent capability of these systems to generate noise and transmit them to other devices. As the use of PV systems is increasing rapidly, EMI from these systems should be properly dealt with. The following sections discuss basic concepts of PV systems and EMI in these systems. This is followed by a review on available and proposed EMI modeling methods for PV systems.

2.2 Review on PV Systems and EMI

2.2.1 PV System

Solar photovoltaic (PV) system is a power system which generates electricity from solar energy. The energy conversion is done by the photovoltaic effect which is the creation of voltage and electric current when the light hits certain material, typically semiconductor materials. PV system consists of solar panels which utilize this effect to convert solar radiation to electricity directly. PV cells are semiconductor materials

that convert light into solar energy by using the photovoltaic effect. Several PV cells are connected and mounted on a frame to form PV panels. Several PV modules are wired together to form PV arrays. PV panels are connected in series and parallel to produce the amount of voltage and current required by a particular system.

Regarding power converters and other connected components, there are many similarities shared by PV systems with other power electronic systems, such as SMPS, PFC circuits or variable-speed drives (VSDs). However, it is the use of PV panels to harvest solar energy which separates the PV systems and distinguishes its technologies. Concerning EMC, PV panels present some peculiar problems due to their large modular size and operating condition depending characteristics. A review on the basics of PV cell will be helpful for later discussions on noise propagation in PV panels in later sections.

2.2.1.1 Photovoltaic Cell and Equivalent Circuit

Over the years there has been numerous development on different types of PV panels such as crystalline silicon and thin-film solar cells [41]. The works following in this thesis will primarily focus on crystalline silicon types as they are the most widely used solar panels. PV cells are p and n-type semiconductors placed together as in p-n diode. P-types are semiconductors doped with trivalent dopants (such as Boron) such that they can have excess holes. Holes are created when electrons from nearby silicon get transferred to Boron to complete one of the incomplete co-valent bonds. Similarly, n-type semiconductors are doped with pentavalent dopants (such as Phosphorus) such that they can have excess electrons. The loosely bonded extra electron of Phosphorus can be freed from due to internal thermal energy and flow in the semiconductor crystal. As shown in Fig. 2-1, when p and n-type semiconductors are combined p-n junction is formed [42]. Holes from p transfer to n and electrons from n to p region. This creates positive charge near n region and negative charge near p region. An electric field is now generated from the positive to negative charge. This electric field creates a barrier for any further holes and electrons to be transferred to opposite sides (minority sides).

Fig. 2-1. PV Cell

In PV cell, due to light excitation, electron-hole pairs can form inside and outside the depletion region. If inside the depletion region, these pairs are usually ripped apart by the region's electrical field and the holes are transferred to the p-side and electrons to n side due to the electric field. Outside the electrical field, charge carrier pairs created by the light usually get lost by recombination. However, they may also reach the depletion region by diffusion due to thermal movements. Once inside the electric field, the electrons and holes are separated and transferred to n and p sides respectively. This creates an accumulation of positive charge in p region and negative charge in the n-region. This accumulation of charge continues as long as the potential created by the accumulating charge is not greater than the barrier potential of the depletion region. When it becomes greater, current will flow from p to n inside the PV cell as in the case of a p-n diode. So, the potential of a single PV cell can only be around 0.6-0.7V. In a PV panel, several PV cells are connected to obtain the desired voltage and current levels. If a load is connected to the PV cell, conventional current will flow from p to n in the wire.

PV panel characteristic is dependent on the operating condition of the panel. As such, this is important in terms of EMC consideration as well since it affects the noise propagation in the system. Since PV is essentially a p-n junction, as described in the previous section, it can be modeled using diodes with additional parasitic resistance,

capacitance and inductance as shown in Fig. 2-2 [43]. The dynamic photovoltaic model consists of photocurrent source (I_{ph}), forward-bias conduction diode (D_f), variable parallel capacitance (C_p), reverse-bias conducting diode (D_r) with a breakdown voltage offset (V_{bd}) (negative value), shunt resistance (R_{sh}), series resistance (R_s) and series inductance (L_s). D_f dominate when PV cell is under forward bias and D_r dominates when reverse biased beyond the breakdown voltage V_{bd} .

Fig. 2-2. PV equivalent model

Fig. 2-3 shows the non-linear I-V and power characteristics of a PV cell. The point where output power of PV cell is maximum is known as maximum power point. PV systems often have power converters to achieve this operating point by using maximum power point tracking (MPPT) algorithms. Fig. 2-3 also shows where D_f and D_r starts operating. During dc state R_s is mostly dominant when both diodes are operating. In the region where both diodes are not operating R_{sh} and R_s are both dominant. Parasitic components C_p and L_s are important when considering high frequency response for EMI analysis.

Fig. 2-3. PV I-V and power characteristics

PV power generation is mostly affected by illumination G and temperature T . The photocurrent I_{ph} is given by the following expression:

$$I_{ph} = \left[I_{scn} \left(\frac{R_s + R_{sh}}{R_{sh}} \right) + K_i(T - T_n) \right] \frac{G}{G_n} \quad (2.1)$$

Where I_{scn} is nominal short circuit current, K_i is current temperature coefficient, T_n is nominal temperature and G_n is nominal irradiance.

The forward diode D_f current I_{df} can be expressed as following:

$$I_{df} = I_s \left[\exp \left(\frac{V_d}{aV_t} \right) - 1 \right] \quad (2.2)$$

Where I_s is the diode saturation current is given as:

$$I_s = \frac{I_{scn} + K_i(T - T_n)}{\exp \left(\frac{V_{ocn} + K_v(T - T_n)}{aV_t} \right) - 1} \quad (2.3)$$

Where V_{ocn} is the nominal open-circuit voltage, K_v is voltage temperature coefficient, a is ideality factor between 1 and 2 and V_t is thermal voltage given as:

$$V_t = \frac{kT}{q} N_s \quad (2.4)$$

Where k is Boltzmann's constant, q is electron charge and N_s is the number of series cells.

The PV output dc current (I_{pv}) and voltage (V_{pv}) can be expressed as following:

$$I_{pv} = I_{ph} - I_s \exp\left(\frac{V_{pv} + I_{pv}R_s}{aV_t}\right) - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (2.5)$$

2.2.1.2 PV power converters and configurations

Fig. 2-4. Different PV system configurations: (a) Centralized technology, (b) String technology, (c) Multi-string technology and (d) AC-module technology

Besides the panels, PV systems can have several other components depending upon the area of application [41]. Since PV panels have non-linear VI characteristics, as discussed in Section 2.2.1.1, power converters are used with MPPT to extract optimum power from the panels [44]. Since most household and industrial appliances are ac powered, PV systems with inverters to convert generated dc to ac power are most common. The systems can either be stand-alone or grid-connected systems and their power generation range from few watts to several megawatts. Fig. 2-4 depicts different topologies commonly found in PV systems [45]. In a centralized configuration, a large number of PV panels, connected in series to provide adequate voltage amplification and in parallel to reach desired power level, are connected to a single centralized dc-ac converter. Despite reducing cost by using a single converter, such topology had issues such as power loss due to centralized MPPT, mismatch losses between MPPT modules and nonflexible design. The high-voltage along long dc cables also increases leakage current and degrades EMC performance. String technology is reduced version of centralized technology where a single string of PV panels is connected to their individual inverters. In multi-string technology, each individual string is connected to a separate dc-dc converter and a common dc-ac inverter is used. This reduces stress on the inverters as compared to centralized inverters and increases performance as individual MPPT can be used for a string of PV panels. The string and multi-string technologies may still need long dc cables to connect several panels, which can degrade EMC performance. In ac module or micro-inverter technology, each PV panel has its dedicated inverter. This can prevent the use of long dc cables and increase performance by using MPPT for individual panels.

Besides different configurations of PV systems, several types of power converter topologies are used in PV systems. However, going into details on types of topologies and evaluating their individual EMC characteristics is not in the scope of this thesis. The main focus is on developing a general method which can be used to evaluate noise emissions on different types of systems.

2.2.2 EMI in PV Systems

In terms of EMI generation, the power converters in the system, dc-dc converter and dc-ac inverters are of main importance. There are several different types and

topologies of power converters used in PV systems as discussed in 2.2.1.2. Despite the various types, the converters have power semiconductor switches, such as MOSFET or IGBTs, which operate at high frequency, from tens to few hundreds of kHz. Though the high-speed switching has several advantages such as high efficiency and shrinking the size of the converter, they become the source of electromagnetic noise. The high dv/dt and di/dt produced by these switches are the primary noise source of these systems [46]. Additionally, several parasitic components in the converters, such as capacitance between switches, heat sinks and ground, build unintentional paths for noise to circulate in the system [47]. EMI from these converters is primarily conducted emissions which flow from the converter to the external components via the power cables.

2.2.2.1 Noise generation

Fig. 2-5. Simplified illustration of EMI at input side of a PV system

Fig. 2-5 shows a simple PV system to illustrate different noise components in the system. As mentioned earlier, the semiconductor switch is the noise source in the system. The noise generation can be understood by considering the spectrum of a switching waveform due to the device. The voltage of the current waveform in the time domain due to the switch can be approximated by a trapezoidal waveform as shown in Fig. 2-6.

Fig. 2-6. Time-domain trapezoidal waveform

The waveform has amplitude A , time-period T and on-time represented by τ . The finite rise-time and fall-time are represented by τ_t and τ_f respectively. Assuming $\tau_f = \tau_t$, the frequency spectrum of the waveform is given as following [39]:

$$f(t) = A \frac{\tau}{T} + 2A \frac{\tau}{T} \sum_{n=1}^{\infty} \left[\frac{\sin(n\pi f_o \tau)}{n\pi f_o \tau} \right] \left[\frac{\sin(n\pi f_o \tau_r)}{n\pi f_o \tau_r} \right] \cos[2\pi f_o n t - n\pi f_o (\tau - \tau_r)] \quad (2.6)$$

where, $f_o = 1/T$ is the fundamental frequency.

Fig. 2-7. Frequency-domain spectrum of trapezoidal waveform

The magnitude spectrum of the trapezoidal waveform is depicted in Fig. 2-7. As shown, the asymptote of the spectrum has three slopes. The first corner frequency at $\frac{1}{\pi\tau}$, indicates that larger the on-time or duty-cycle of the waveform, lower the cut-off frequency. The -20 dB/dec slope is due to the first sin component in (4.1) which represents the harmonic response of the pulse width. Similarly, the -40 dB/dec slope is due to the second sin component in (2.6) and represents the harmonic response of the rise/fall time. The second corner frequency at $\frac{1}{\pi\tau_r}$, indicates that slower rise/fall

times provide additional roll-off of higher order harmonics. However, faster rise/fall time is preferred in power converters to prevent losses, which in turn increase noise spectrum.

The noise generation in power converters, therefore, can be understood by the above discussion. Some studies have therefore represented noise source in power converters by simply using sources with trapezoidal waveforms. This approximation, however, can be inaccurate since the rise/fall time of the waveforms in real systems are not constant [48]. In PV systems, a single power converter can have multiple switching devices. As such the spectral content of noise emission can be more complicated.

The generated noise then conducts to other components of the converter. The noise emission can then flow in the system in two modes: common-mode (CM) and differential-mode (DM), as shown in Fig. 2-5. DM noise emission flows between line and neutral of the system. Due to noise voltage existing between line/neutral and ground, CM noise flows between them through parasitic paths such as capacitance between the heatsink and ground.

2.2.2.2 *Noise propagation*

From the viewpoint of power converter devices, the emissions in PV systems can be seen from two sides: the input and the output of the converters. As shown in Fig. 2-5, there can be EMI at the input dc side of the power converters where the PV panels are connected. Similarly conducted noise emissions flow at the output ac side where the ac load or ac grid is connected. At the ac side, the conducted emissions could hamper connected loads and if the emission is above the existing limits, they cannot be connected to the ac grid. Consequently, there have been numerous studies on conducted emissions at ac side of the PV systems [2-4, 7]. Most of the studies deal with mitigation of conducted emissions at ac side but do not concern with emissions at dc side of PV systems.

In contrast to the output side of the PV system, the input side which is dc, presents a different problem. Like the output side, the input side is also affected by conducted EMI. However, there is generally no load, or any other equipment connected to the input side for the conducted EMI to interfere. However, several papers have shown excessive conducted emission at the input side and reported it to be the cause of

radiated emission from the PV systems [2, 10, 14, 49, 50]. The PV panels due to their size are mostly capacitive and the long dc cable used to connect converters and PV panels can have distributed capacitance and inductance. Together, they form a resonant circuit for several frequencies and radiated electromagnetic fields can occur between 150kHz – 30MHz [51].

Several study and measurement results on emissions from the input and output sides of PV systems are reported in [2]. The study shows measurement results for radiated emissions between 150kHz to 30MHz due to both CM and DM currents in PV systems separately. This indicates that both components of the noise should be investigated. The study examined several high-end inverters and charge controllers and reported that most complied with existing standards in terms of conducted emission at ac sides. However, with respect to emission from the dc sides, most of the devices failed existing standards. It has also been indicated that PV systems, in general, lack specific standards and regulations for proper investigation of EMI. This is depicted in Table 2-1. Some relevant limits are discussed in [2, 13] and new DC-LISN for emission measurement is suggested in [52]. Some new emission limits have been proposed for dc side of PV systems, but it remains to see if they will be implemented in standards [5].

Table 2-1. Consideration of utility connected PV inverters in EMC standards.
(Green: Sufficiently regulated in related standards. Yellow: Demand for regulation.)

Propagation of interference via		Frequency			
		9kHz-150kHz	150kHz-30MHz	30MHz-300MHz	300MHz-1GHz
AC-lines	Disturbance variable	Disturbance Voltage	Disturbance Voltage	Generally not relevant	Generally not relevant
DC-lines	Disturbance variable	Disturbance Voltage	Disturbance Voltage	Disturbance Power	Disturbance Power
Housing	Disturbance variable	Generally not relevant	Generally not relevant	Disturbance Field Strength	Disturbance Field Strength

Similarly, several studies [5, 6, 9, 10, 14, 15], have presented radiated emission studies in PV systems. While some have only considered PV panel in their studies, it is necessary to consider the long dc cables as well. Reference [14] is a study on radiation noise from PV panel with 1.5m long cable connected between the power

converters and the PV panel. The study shows that radiation noise is significantly higher than that using the model without the cable. References [9, 15, 53] have developed a simple antenna model of PV panels to model the radiation from the panels. However, the use of these models in real systems at operating conditions is not considered. In general, a systematic approach to consider different components of noise generation and propagation to accurately model conducted and radiated noise emissions in PV systems is lacking.

There have also been several studies to mitigate noise emissions in PV systems. Different topologies have been investigated [54-57] to reduce leakage currents in these systems. Similarly, new topologies [58-60] and modulation techniques [8, 58, 61, 62] have also been suggested. Besides, these methods investigated for PV systems, several methods developed for SMPS [63, 64] could also be applicable to PV systems. However, despite having several techniques to mitigate noise emission at the source, there is often need of EMI filters to further reduce the noise levels. Consequently, several studies are available on EMI filters for PV systems [7, 65-68]. Some studies [69, 70] have presented filter development for dc side of PV systems but have not considered the noise source impedance. [71] has presented filter design for the dc side by considering PV array parameters, dc side cable impedance, inverter parasitic capacitance and the unbalance of ac side impedance. However, the approach is based on lumped circuit modeling of the system and is time-consuming and prone to error.

A systematic model for analyzing EMI in PV systems can be very useful. It would also allow us to investigate the CM and DM currents separately and find the dominant component. The noise source and termination impedances available in such a model can be useful in designing optimized EMI filters. In order to properly investigate the noise, it is, therefore, necessary to incorporate noise sources and noise impedances on the converters side. In the following sections, possible methods for modeling EMI are described.

2.3 Review of EMI Modeling in PV systems

As mentioned earlier, inverters used similar circuits used in today's power-factor-correction (PFC) circuits and variable-speed drives (VSDs). Therefore, their circuits and topologies are not entirely different. This provides the opportunity to apply existing EMI modeling and mitigation technologies to PV systems. Consequently, many studies relating to EMI modeling in PV systems are similar to modeling techniques in other power converter systems. Moreover, a significant number of literature is available on EMI modeling for other systems as compared to that of PV systems. It is therefore relevant and necessary to review modeling concepts used in other power systems besides PV systems for a better understanding of the problem. Appropriate modeling method can then be suggested which is suitable for the problems presented by PV systems. The following sections discuss on different methods commonly used for modeling noise propagation path and noise generating source in conducted noise emissions.

2.3.1 Modeling of Noise Propagation Path

Noise generated in power converters is conducted towards PV panels via the dc cables in PV systems. EMI filters and device parameters are also considered in the propagation path. The noise path can be complicated so proper identification and modeling of the propagation path are necessary to model the system accurately. There are several methods of modeling propagation path available in the literature which can be classified into two categories: Theoretical models and Experimental models.

2.3.1.1 Theoretical models

Theoretical models are based on solving Maxwell's equations for a given physical structure and material property. Finite element method (FEM) and partial element equivalent circuit (PEEC) have been used in such studies [17, 72-75]. Commercial software are also available to extract circuit parasitics such as Ansoft Maxwell Q3D, Maxwell 2D etc. [16, 17]. In PV systems theoretical models have been applied to obtain parasitic capacitance and leakage current in PV modules [76, 77]. An analytical model of dc cable is suggested in [78]. The theoretical method can provide

path parameters before the actual device fabrication; however, they can be very complex depending on the type and number of components.

2.3.1.2 *Experimental models*

Noise propagation paths can also be represented by experimental methods which involve measurement of device-under-test (DUT) to obtain path parameters. The models can be obtained by measuring individual components or measuring path network characteristics. Individual component method is usually done using impedance analyzer [79, 80] or using time domain reflectometry (TDR) method [81, 82]. Inductive coupling methods have also been developed which can extract in-circuit impedance [83]. An experimental model for noise propagation path in PV systems is considered in some studies [4]. In [69] EMI filters are modeled as individual components with parameter values as provided by the manufacturer. However, the parasitic elements of the system are not considered. Individual component measurement approach can provide accurate physical characteristics of the components but can be time-consuming if there are several components. Another experimental method is based on representing paths as a multi-port network [84, 85]. This method can accurately represent small parasitics but it may not provide clear insight into the characteristics of the system.

For PV systems, PV panels and dc cables must be considered in propagation path models. PV panel characteristics can vary according to operating condition as discussed in Section 2.2.1.1. It is therefore important to extract the model at actual operating condition of the PV panel. For this purpose, the inductive coupling method which is discussed in the next chapter. The dc cables of PV panels can be several meters long. A transmission line model will be used to represent the dc cables in this thesis. Besides these, individual component measurement is done to represent other components such as EMI filters.

2.3.2 Modeling of Noise Generating Source

As discussed in Section 2.2.2, the semiconductor switching devices used in PV converters are the main source of noise existing in the system. Modeling of the noise source is one of the main challenges in EMI analysis. The method for modeling

should be accurate as well as efficient such that it is easy to develop and computationally efficient. The method should also be applicable to different configurations and topologies. Available noise source modeling methods can be classified into two categories: Device-based models and Measurement-based equivalent models

2.3.2.1 Device-based Modeling Approach

This approach is based on modeling semiconductor switching devices by considering their physical concepts. The devices are modeled as individual components which represent the source of noise emissions. Besides modeling the noise source, other circuit components and parasitic components present in the power converter must be modeled separately and included in the overall converter model. The semiconductor components can be represented as device models in three different ways: Physics-based model, device model as provided by the manufacturer and ideal switch with impedance approximation.

Physics-based models are developed by considering physical equations that govern the characteristics of the switching device. This approach is applied in EMI models in [82, 86] based on Hefner's IGBT model [87]. Physics-based models consider all major physics involved in the device and can be very insightful. While these models can be very accurate if sufficient model parameters are obtained. However, the parameter extractions need sets of experiments which can be complicated and often the parameters need to be tuned by a trial-error process to reach accepted accuracy level.

Since it is time-consuming and complicated to develop a physics-based model from basics, device models provided by the manufacturer are often used [16, 17]. These models are also physics-based models but with parameters derived at certain conditions and provided by the manufacturer to the users. This type of noise source model is mostly used in the study of EMI from PV converters and systems [4, 7, 69, 78]. While device-based models provided by manufacturers are very convenient to use, the models may not be accurate under actual operating conditions for EMI analysis. Extra steps need to be taken to verify that the available parameters are valid under the actual experimental conditions [17]. A major limitation of this approach

can be the unavailability of the device model. Identifying the right semiconductor device model for a given power converter is often difficult and, in many cases, not available.

Some studies have applied simplification of noise source by representing them as ideal switches with some approximate impedance such with RLC parasitics [18-20] or as time-varying resistance during switching transitions [80, 88]. The noise sources are generally represented as trapezoidal waveforms with some finite rise and fall-time. Similar approach is used to model EMI in complex systems [21-23]. While this approach simplifies detailed physics-based device modeling and could be accurate to few MHz, it cannot represent varying slew rates of source waveforms accurately [48]. This can greatly affect the accuracy of the model, particularly at high frequencies.

The device-based modeling approach is mostly useful for power electronics simulations for analyzing control strategies, stability etc. The main advantages of this method are adaptability and scalability. Each component such as control, gate drives, filters etc. can be modeled separately and integrated together. It is very easy to add new components or make parametric changes in the system. For simple converters, this approach could also be useful for EMI predictions. However, with an increasing number of components in the system and for high-frequency analysis the lumped parameter modeling can become very complex. Particularly with physics-based models the simulation could take a long time and could have convergence issues when the details of the model which is generally required for high-frequency analysis is too high. Even with simplified source approximations, the computational requirement can be high due to several system and parasitic components. It has been noted that the accuracy of such a modeling approach is good only up to 10MHz [28, 82]. Some studies have also represented the noise sources by directly measuring the voltage across the switches [89-91]. While this approach simplifies the modeling of a semiconductor device and has shown better accuracy, it still requires extraction of the complete lumped circuit model of the converter. The development time of device-based model is long and in some cases the device models may not be available.

2.3.2.2 Measurement-based Equivalent Models

It was pointed out in the previous section that device-based modeling has limitations and is not suitable for system level EMI simulations. Circuits with a large number of components require large computational resources and time. It may also pose a problem for simulation convergence when there are a lot of components [28]. Moreover, for an integrated complete system, it may not be possible to get required device models from the manufacturer or it may be difficult to extract the parameters without disintegrating the product. In such a case, lumped circuit modeling will not be possible. A more practical approach to modeling power converters for EMI analysis would be the measurement-based equivalent modeling approach.

This approach is a black-box modeling technique where the converters are represented using one-port or two-port network with independent sources [29, 30]. This implies representing the circuit using Thevenin (or Norton) equivalent in the frequency domain. With this approach, the CM and DM equivalent circuits can be represented separately as shown in Fig. 2-8. $Z_{X,CM}$ and $Z_{X,DM}$ can be CM and DM impedances of external devices such as LISN, Mains, PV panels etc. $V_{X,CM}$ and $V_{X,DM}$ are the respective CM and DM noise voltages at these devices. To develop the model, it is therefore necessary to obtain the noise source and noise impedances.

Fig. 2-8. Measurement-based (a) CM and (b) DM models

Most of the developments in this approach are applied in other converter systems, such as PFC circuits and VSDs, [24, 25, 28, 31-33]. However, these early developments are not accurate mostly because of improper measurement approach and over-simplification of motor drive model. Other studies have implemented this technique by indirectly calculating the noise source and noise impedances using two or more conditions and then simultaneously solving the network equations [31, 32]. However, to estimate the noise source impedance or generating conditions, these studies either use resonance method or insertion method which is prone to errors. In the case of resonance method, the process of choosing the right values of reactive components and then tuning for resonance can be difficult and time-consuming. Especially at higher frequencies, the input impedance may have several resonances within a small frequency range which makes it difficult to be precise. In case of insertion loss method, the impedances of inserted components must be much larger or smaller than the noise source impedances [34]. If the condition is not met, the accuracy of the measurement degrades. Moreover, the method only provides the magnitude of the noise source impedance and the phase can only be estimated with the Hilbert transform process [92].

In order to improve the measurement of noise source impedance in SMPS inductive coupling method has been proposed [35-37]. By using one current probe as an injection probe and another as a receiving probe, the method is able to measure CM and DM impedances using different measurement configurations. Additionally, both magnitude and phase of the impedances can be achieved. With proper calibration of the measurement setup, good accuracy has been shown by this method. The next chapter explains the inductive coupling two probes method in detail.

Since PV system comprises of several components as described in Section 2.2.1.2, detailed lumped circuit modeling is not suitable to study EMI of the system. Therefore, measurement-based behavioral EMI modeling approach is proposed for PV systems in this report. No previous studies have proposed this approach for modeling EMI from PV systems. Additionally, the inductive coupling method will be used to extract the noise source impedance required for the modeling. Using this approach, it will be possible to estimate separate CM and DM equivalent models for

the system and analyze them separately. The models will also be useful for developing optimum EMI filters for the system.

2.4 Summary

As discussed in this chapter, EMI is a growing concern in photovoltaic systems. Noise generated from PV power converters are conducted at both input and output sides of the converters. At the input dc side, noise emissions are conducted towards PV panels through the long dc cables and are potentially radiated by these components. To be able to systematically deal with the noise emissions, an efficient method to develop the EMI model of the PV system must be developed. This involves developing accurate models for both noise propagation path and noise generating sources. Different methods of noise propagation path are available in the literatures. Among these experimental models are proposed for a PV system in this thesis. Similarly, measurement-based equivalent model is proposed for noise source modeling. For extraction of noise source model and PV model at an actual operating condition, the inductive coupling method is proposed.

Chapter 3

Inductive Coupling Method for Extracting In-circuit Impedance

In order to develop an accurate equivalent noise model of the PV system for EMI analysis, the noise source model must be extracted at operating conditions. For this purpose, the in-circuit impedance extraction using inductive coupling method is proposed. This chapter discusses the proposed model in detail.

3.1 Introduction to Inductive Coupling Method

Fig. 3-1. Basic measurement setup of in-circuit impedance extraction

The basic measurement setup for in-circuit impedance extraction using inductive coupling method is shown in Fig. 3-1. It consists of two current probes - injecting and receiving probes, clamped on to the electric circuit which consists of the unknown impedance component. The two current probes are connected to Vector Network Analyzer (VNA). Port 1 of VNA injects RF signal into the circuit loop containing unknown impedance Z_X and the same signal is received at Port 2 of VNA. The unknown impedance Z_X can be any electrical system and powered by dc or ac electrical source. By using this setup and applying two-port network ABCD

parameter analysis in-circuit impedance of a system can be extracted accurately at operating conditions. In the following sections, the basic theories involved in the method are discussed.

3.2 Fundamental Concepts

Basic theories about inductive coupling method are discussed below as they are necessary for later discussion on the topic.

3.2.1 Inductive Coupling Probes

Current probes are the basic instrument used in the proposed method which forms inductive coupling for measurement purpose. Current probes are commonly used for current measurement and diagnostics purposes [93, 94]. The ac current probes work on the principle of Ampere's law and Faraday's laws [95]. It can be used to inject ac signals into an electrical circuit or receive ac signals from the circuit without a direct connection with the circuit.

Fig. 3-2. Current probe equivalent circuit

The equivalent circuit of a current probe is shown in Fig. 3-2 [96]. The current probe is clamped onto an electric circuit, with current I , which acts as a one turn primary winding. C_P represents the primary side stray capacitance. According to Ampere's law, the current I produces a circular time-varying magnetic field mostly confined within the magnetic component of the probe. The n -turn secondary winding is wound around the magnetic component of the current probe. According to Faraday's law, the magnetic field induces a voltage V_S across the terminals of the secondary winding.

The magnetic core is represented by a magnetic inductance L_M in parallel to a core loss resistance R_C . L_L , R_S and C_S represent the secondary side leakage inductance, winding resistance and stray capacitance respectively. The secondary side of the current probe is terminated with a burden resistor R which has equivalent series inductance L_R . V_R represents the output voltage of the current probe.

Transfer impedance (Z_T) is an important parameter of current probes, which is defined as:

$$Z_T = \frac{V_2^-}{i_1} \quad (3.1)$$

Where V_2^- is the reflected voltage wave of the current probe and i_1 is the primary current flowing through a 50Ω termination and it can be expressed as:

$$i_1 = \frac{V_1}{50\Omega} = \frac{V_1^+(1 + S_{11})}{50\Omega} \quad (3.2)$$

Where voltage reflection coefficient (S_{11}) is the ratio of reflected voltage wave (V_1^-) to incident voltage wave at primary side (V_1^+). From equation (3.1) and (3.2) transfer impedance can be expressed as follows:

$$Z_T = \frac{50\Omega \cdot V_2^-}{V_1^+(1 + S_{11})} = \frac{50\Omega \cdot S_{21}}{1 + S_{11}} \quad (3.3)$$

Where the forward voltage gain coefficient (S_{21}) is the ratio of V_2^- to V_1^+ .

Current probes are usually designed to have constant frequency response within the selected operating range of frequencies. Beyond this range, probe's hysteric and magnetizing current causes non-linearity of frequency response. Hence the current probes cannot represent a linear circuit model over a wide frequency range.

Fig. 3-3. (a) Current Probe 9144-1N, (b) Calibration Fixture

For experiments discussed in the thesis, Solar 9144-1N current probes, shown in Fig. 3-3 (a), were used as injection and receiving probes. In Fig. 3-3 (b) the calibration fixture is shown which can be used to measure the transfer impedance of the current probe. By using the measurement setup shown in Fig. 3-4 and from equation (3.3), the transfer impedance can be determined.

Fig. 3-4. Measurement setup to extract transfer impedance of current probes

The extracted transfer impedances of Solar 9144 current probes used as injection and receiving probes are shown in Fig. 3-5. Since the same type of current probe is used as injection and receiving probes their transfer impedances are similar. The results show that the probes are suitable to be used for our concerned measurement frequency range of 150kHz – 30MHz.

Fig. 3-5. Extracted transfer impedance of (a) Injection probe and (b) Receiving probe

3.2.2 Two-port Network Analysis

The basic theory of inductive coupling method using two current probes was introduced in [35]. An improved approach based on two-port ABCD network was given in [97] which improved the calibration method and accuracy of the method. Basic concepts of a two-port network are therefore briefly discussed below.

Since a VNA is used for the proposed method, as shown in Fig. 3-1, the measurements obtained from the setup are in terms of scattering or S-parameters. S-parameters are determined in terms of incident, reflected and transmitted waves.

Fig. 3-6. Two-port network with incident and reflected waves

A two-port network is shown in Fig. 3-6, where V_1^+ and V_1^- are incident and reflected voltage waves at port 1 respectively. Similarly, incident and reflected current and

voltage waves are shown for the two ports in the figure. The relationship between the voltage waves can be expressed in terms of S-parameters as following [98]:

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} \quad (3.4)$$

Where the S-parameters, S_{11} , S_{12} , S_{21} and S_{22} are input voltage reflection coefficient, reverse voltage gain, forward voltage gain and output voltage reflection coefficient respectively. For two-port networks, it is useful to represent the network in terms of ABCD parameters since they deal with voltage and current directly and can be cascaded.

Fig. 3-7. Single two-port ABCD network

Fig. 3-7 shows a single two-port ABCD network. The input and output voltage and currents for the network can be expressed as:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (3.5)$$

A, B, C and D parameters are open-circuit voltage transfer ratio, short-circuit transfer impedance, open-circuit transfer admittance and short-circuit current transfer ratio, respectively.

Fig. 3-8. Cascaded two-ports ABCD network

For a cascaded two-port network, as shown in Fig. 3-8, individual networks can be expressed as follows:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (3.6)$$

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} V_3 \\ I_3 \end{bmatrix} \quad (3.7)$$

From (3.6) and (3.7), we can obtain,

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} V_3 \\ I_3 \end{bmatrix} \quad (3.8)$$

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_3 \\ I_3 \end{bmatrix}$$

Where $\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}$. Therefore, the ABCD parameters of the cascaded network can be represented as the product of ABCD parameters of individual two-port networks.

To convert S-parameters obtained from VNA to ABCD parameters the following expressions can be used.

$$A = \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{2S_{21}} \quad (3.9)$$

$$B = Z_0 \frac{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}} \quad (3.10)$$

$$C = \frac{1}{Z_0} \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2S_{21}} \quad (3.11)$$

$$D = \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}{2S_{21}} \quad (3.12)$$

Where, Z_0 is the characteristic impedance of the VNA.

3.3 In-circuit Impedance Extraction using Inductive Coupling Method

Fig. 3-9 shows the inductive coupling measurement setup to extract impedance from an online or operating system. The system consists of an ac power supply V_S with source impedance Z_S . Alternately, the circuit can also be powered by a dc power supply. Z_C represents the impedance of the electric cable of the circuit. Z_L is the impedance, of the equipment or load, which is to be extracted. In most cases, Z_L dominates the impedance of the circuit such that the measurement shows the impedance of the equipment under test. In case, Z_L is comparable to Z_C and Z_S it is necessary to deduct their impedance to obtain Z_L .

Fig. 3-9. In-circuit impedance measurement of online system

The measurement setup in Fig. 3-9 can be represented as a cascaded two-port network as shown in Fig. 3-10. In the figure, S_{TX} and S_{RX} are the two-port networks of injecting and receiving probes, respectively. S_T is the overall two-port network measured by the VNA, which is the cascaded two-port networks of the injecting probe, the receiving probe and the unknown impedance network S_X which contains the unknown impedance Z_X . If the device under test (DUT) is an online system, as shown in Fig. 3-9, Z_X will be combination of Z_S , Z_C and Z_L .

Fig. 3-10. Cascaded two-port network representation of inductive coupling method

The two-port network S_T in terms of ABCD parameters between ports 1 and 2 of the VNA is as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_T = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{TX} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_X \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{RX} \quad (3.13)$$

where,

$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_T$, $\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{TX}$, $\begin{bmatrix} A & B \\ C & D \end{bmatrix}_X$ and $\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{RX}$ are the two-port ABCD parameters of S_T , S_{TX} , S_X and S_{RX} respectively. ABCD parameters of the unknown impedance network S_X can be obtained if ABCD parameters of S_{TX} and S_{RX} are known. These parameters are usually obtained prior to the actual measurement by characterizing the probes.

The characterization of the inductive probes is done using a calibration fixture shown in Fig. 3-3 (b). For characterizing the probe, it is clamped onto the inner conductor of the calibration fixture. The outer frame of the fixture serves as a ground reference for the VNA.

Fig. 3-11. Characterization of injection probe (a) schematic diagram, (b) equivalent circuit

Fig. 3-12. Characterization of receiving probe (a) schematic diagram, (b) equivalent circuit

Fig. 3-11 shows the setup for injection probe characterization. As shown in Fig. 3-11(a), port 1 of VNA, which is connected to the injection probe, injects the RF signal. The RF signal is received back at port 2 of the VNA which is connected to one end of the calibration fixture, while the other end is shorted. The equivalent circuit of the setup is shown in Fig. 3-11(b). For characterizing receiving probe, ports 1 and 2 connections are simply interchanged as shown in Fig. 3-12. The S-parameters obtained from these measurements can be converted to ABCD parameters as explained in Section 3.2.1.

Once ABCD parameters of the probes are obtained, the parameters of the unknown impedance network S_X can be obtained from equation (3.13). Since S_X is a series impedance model, the parameter B indicates the unknown impedance Z_X .

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_X = \begin{bmatrix} 1 & Z_X \\ 0 & 1 \end{bmatrix}_X \quad (3.14)$$

3.4 Extraction of Noise Source Impedance

In this thesis, we propose to model conducted noise from a PV system using separate CM and DM measurement-based equivalent models. As such, both CM and DM noise source impedance should be extracted for the purpose. CM noise currents flow through Line/Neutral wire to Ground as shown in Fig. 3-13. DM noise currents flow through Line and Neutral wire of the system.

Fig. 3-13. Conducted CM and DM noise emissions

The noise voltage developed at LISN contains both CM and DM components and is defined as:

$$V_{LG} = 50(I_{CM} + I_{DM}) \quad (3.15)$$

$$V_{NG} = 50(I_{CM} - I_{DM}) \quad (3.16)$$

The CM and DM noise voltages can then be expressed as:

$$V_{DM} = 50I_{DM} = \frac{V_{LG} - V_{NG}}{2} \quad (3.17)$$

$$V_{CM} = 50I_{CM} = \frac{V_{LG} + V_{NG}}{2} \quad (3.18)$$

Similarly, the noise currents in the system can be given as:

$$I_L = I_{CM} + I_{DM} \quad (3.19)$$

$$I_N = I_{CM} - I_{DM} \quad (3.20)$$

The phase and neutral currents can then be used to calculate CM and DM currents as:

$$I_{DM} = \frac{I_L - I_N}{2} \quad (3.21)$$

$$I_{CM} = \frac{I_L + I_N}{2} \quad (3.22)$$

It is, therefore, possible to represent conducted noise emissions using separate CM and DM noise sources. The individual noise source impedances can be extracted using inductive coupling approach by confining the RF excitation to the desired noise current paths. Such an approach was first proposed in [35]. The method used a signal generator and a spectrum analyzer instead of VNA, which limited the measurement to extract only magnitude but not the phase of the unknown impedance. Also, the method required the use of additional chokes to isolate source impedance which introduced some errors in the measurement. A revised version of the method was introduced in [37]. While the study could extract both magnitude and phase of the source impedance, the accuracy of the measurement is influenced by the choice of standard resistor for calibration [97]. Besides the measurement setup for extraction of DM impedance is questionable since it introduces parasitic capacitance between the two wires which hampers the accuracy of the measurement. To overcome these limitations the proposed measurement setups for extraction of noise source impedances are shown in Fig. 3-14.

Fig. 3-14. Proposed setup for extraction of (a) CM and (b) DM noise source impedances

Fig. 3-14 (a) and (b) shows setups for extracting CM and DM noise source impedances respectively. The capacitors are connected in the setup to provide low resistance paths to the RF signal so that the noise source impedance dominate the overall impedance of the system.

In the case of CM noise source impedance extraction, the injected RF signal is confined within the path of CM noise current. This implies that the total CM impedance measured is given by:

$$Z_{total,CM} = Z_{DUT,CM} + Z_{wire+capacitor,CM} \quad (3.23)$$

Similarly, for the case of DM noise source extraction, the RF signal follows the path of DM noise current and therefore the total DM impedance is given by:

$$Z_{total,DM} = Z_{DUT,DM} + Z_{wire+capacitor,DM} \quad (3.24)$$

In both cases, the noise source impedances generally dominate the total impedance such that impedances of capacitor and cable can be neglected. However, if their impedances are comparable to that of the noise source, then they should be deducted from the total impedance. It is important to note that the case where $Z_{wire+capacitor} \gg Z_{DUT}$ should be avoided in both cases. In such condition, Z_{total} is dominated by $Z_{wire+capacitor}$ and Z_{DUT} cannot be extracted. It is therefore necessary to check the impedance for wire and capacitor with that of DUT in every measurement.

The LISN in the setups is connected to provide a standard load impedance for the network. Also, it prevents noise from a power supply to contaminate the DUT and facilitates the measurement of noise from DUT. Further details on the use of LISN with PV simulator as power supply are discussed in Chapter 4. However, the method is not only limited to the use of LISN. In Chapter 5, LISN and PV simulator are replaced by an actual PV panel. The same method is then applied to extract the noise source and PV impedances at operating conditions.

3.5 Summary

This chapter has proposed an inductive coupling method for extraction of in-circuit impedance and its use to extract noise source impedance at actual operating conditions. This is required to extract noise source impedance from PV system power converters to model the noise source models correctly. By using two current probes and VNA, it is possible to get the frequency response of in-circuit impedance. The

basic theory of the proposed method was discussed. It was shown that by using two-port ABCD network analysis, the unknown impedance can be extracted with good accuracy. Since the method uses clamping probes, it is easy to set up and requires minimal modification to the DUT system. The method is therefore applied to extract the noise source model of PV system which is discussed in the next chapter.

Chapter 4

Conducted Noise Model of PV System with LISN and PV simulator

In this chapter development of a measurement-based EMI model of a PV system is discussed in detail. For developing and testing the model, a PV simulator and LISN is used instead of PV panel such that the measurements can be taken at stable operating conditions. The inductive coupling method, described in Chapter 3, is used to extract the required in-circuit impedances for the model. The measurement results and the proposed models are provided. Based on the developed model, CM and DM EMI filters are tested.

4.1 Experimental Setup

For the development of the proposed modeling approach, a PV system shown in Fig. 4-1 is set up. Fig. 4-1 (b) shows the actual experimental setup and Table 4-1 shows the specifications of the equipment used. The setup consists of a PV simulator to emulate the PV panel that provides dc input power to a dc–ac microinverter through a line impedance stabilization network (LISN). The PV simulator can be operated at a stable operating point which is useful for developing and testing the proposed method. The LISN provides a well-defined termination for the subsequent conducted emissions measurement at the dc side of the PV system. The ac output of the inverter connects to the 230 Vac power supply and a resistive load of 200 Ω draws power from the inverter output.

Fig. 4-1. Measurement setup of the PV system with LISN and PV simulator (a) Block diagram. (b) Actual setup.

Table 4-1. Equipment specifications and settings

Equipment	Model	Specifications
Micro-Inverter	TMDSOLARUINVKIT	Input: 24-40VDC, 4A Output: 220V, 50Hz Switching Frequency: 50kHz
PV Simulator	AMETEK ETS 1000	Open Circuit Voltage: 40V Maximum Power Point Voltage: 30V Short Circuit Current: 5.2A Maximum Power Point Current: 4A
AC Supply	Chroma 61504	220V 50Hz
Load	Resistive	200 Ω
LISN	Electro-Metrics MIL 5-25/2	25A max continuous current 220VAC Line-Ground

For the experiment, a micro-inverter development kit (TMDSOLARUINVKIT) by Texas Instruments was used. The device has a dc-dc converter at the input for voltage amplification, an inverter for producing ac output voltage and an EMI filter at the ac side. The circuit layout of the micro-inverter without parasitic elements is shown in

Fig. 4-2. The device has several components and to develop a detailed lumped circuit model for the entire PV system including the micro-inverter with parasitics, as described in Section 2.3.2.1, would be time-consuming and computationally demanding. Therefore, the proposed method is to develop a measurement-based equivalent model of the inverter as discussed in Section 2.3.2.2. For this approach, the actual layout and details of the device parameters of the microinverter are not necessary.

Fig. 4-2. Circuit diagram of micro-inverter

The microinverter, which operates at a switching frequency of 50 kHz, causes conducted emissions at 50 kHz and its harmonics at the dc side. The cable between the LISN and the microinverter is made as short as possible so that the impact of the cable's impedance on the measurement is minimized. The length of the cable is 25 cm to give provision for the clamping of the probes. A 1 m by 1.5 m metal ground plane is placed below the measurement setup at a uniform distance of 5 cm. This provides a well-defined path for the CM noise to flow.

To develop a measurement-based EMI model of the system, as described in Section 2.3.2.2, model parameters need to be extracted from the system at operating conditions. The in-circuit impedances of the noise source, LISN and wire can be measured using the inductive coupling method. The noise source voltage can be measured from the LISN. Effectively we can construct the EMI model of the input side of the PV system using the extracted results. Each of the extraction processes is explained in the following sections.

4.1.1 Extraction of In-circuit Impedance of LISN

Fig. 4-3. Circuit diagram of LISN

For the experiment, Electro-Metrics MIL 5-25/2 LISN was used. The circuit diagram of the LISN, as provided by the manufacturer, is shown in Fig. 4-3. The function of the LISN is twofold. First is to block conducted noise flowing from PV simulator towards the DUT, which is the micro-inverter, so that the measurement results are not polluted by external noise. The noise from the power source is diverted by capacitors C_{L1} and C_{N1} , as well as blocked by inductors L_{L1} and L_{N1} . The second function of the LISN is to maintain a well-defined impedance at the power source side. Capacitors C_{N1} and C_{N2} prevent overloading of the test receiver by input dc power. The 1 kΩ resistors provide static charge paths to discharge the capacitors if 50 Ω resistors are not connected. The 50 Ω resistors are connected in parallel to the 1 kΩ when the test ports are connected to a noise discriminator network or a test receiver (spectrum analyzer). It is necessary to connect a 50 Ω dummy load to the remaining one port which is not connected to test receiver. This setup then ensures a well-defined impedance at the power source side for taking noise measurements.

Fig. 4-4. Extraction of LISN (a) CM and (b) DM in-circuit impedances

To obtain a better estimate of the model of the system, the in-circuit impedance of the LISN is extracted at the operating condition, using the inductive coupling method. Figs. 4-4. (a) and (b) show the setup to extract CM and DM impedance of LISN respectively. Two current probes (Solar Electronics 9144-1N) and a VNA (OMICRON Lab Bode 100) were used to conduct the measurement. The total impedance measured during the process can be expressed as follows:

$$Z_{total,CM} = Z_{LISN,CM} + Z_{wire+2\mu F} \quad (4.1)$$

$$Z_{total,DM} = Z_{LISN,DM} + Z_{wire+22\mu F} \quad (4.2)$$

Where, $Z_{total,CM}$ and $Z_{total,DM}$ are the total impedance obtained for CM and DM measurements respectively. $Z_{LISN,CM}$ and $Z_{LISN,DM}$ represents the actual CM and DM impedances of LISN respectively. $Z_{wire+2\mu F}$ is the impedance of the short wire used for clamping the two probes and impedance of two $1 \mu F$ capacitors in parallel used for providing a low impedance path for the RF signals. Similarly, $Z_{wire+22\mu F}$ is the

impedance of the short wire and capacitor used for DM measurement with a similar purpose.

Fig. 4-5. Extracted CM impedance of LISN: (a) magnitude, (b) phase

As mentioned in Section 3.4, the values of bypass capacitors for both setups are chosen such that their impedances are sufficiently lower than those of the noise source and LISN in the frequency range of interest (150 kHz to 30 MHz). As a quick estimation, two 1 μ F capacitors provide a bypass impedance of 0.53 Ω for the CM

setup and the 22 μF gives a bypass impedance of 48 m Ω for the DM setup at 150 kHz. To account for the non-ideal behaviors of the bypass capacitors and the wire connections, their impedance frequency responses are also measured and plotted for comparison in the following results. The LISN impedances are obtained after deducting the impedance of wire and capacitor from the total measurement result.

Fig. 4-6. Extracted DM impedance of LISN: (a) magnitude, (b) phase

Figs. 4-5 (a) and (b) show the magnitude and phase frequency responses of the extracted CM impedance respectively. Likewise, Figs. 4-6 (a) and (b) show the magnitude and phase responses of DM impedance of the LISN. It is also shown that the impedance of wire and capacitor is less than that of LISN in both cases signifying that they aid as effective bypasses in the frequency range of interest. The measured results are also compared with modeled results obtained from the circuit layout provided by the manufacturer. The figures show that the two results match closely.

4.1.2 Extraction of Noise Source Impedance

Fig. 4-7. Extraction of noise source (a) CM and (b) DM in-circuit impedances

The setup for extracting impedances of the noise source is similar as for LISN in the previous section. The two probes are now clamped at the microcontroller side as shown in Fig. 4-7. Details on the process are explained in Section 3.4. The total impedances measured in this case can be expressed as follows:

$$Z_{total,CM} = Z_{noise,CM} + Z_{wire+2\mu F} \quad (4.3)$$

$$Z_{total,DM} = Z_{noise,DM} + Z_{wire+22\mu F} \quad (4.4)$$

Where, $Z_{noise,CM}$ and $Z_{noise,DM}$ represents the actual impedances of CM and DM noise sources respectively. $Z_{wire+2\mu F}$ and $Z_{wire+22\mu F}$ are the impedances of wire and capacitors for the two cases, similar to the previous section.

Fig. 4-8. Extracted CM impedance of noise source: (a) magnitude, (b) phase

The magnitude and phase responses of extracted CM impedances of noise source are shown in Figs. 4-8 (a) and (b) respectively. Similarly, Figs. 4-9 (a) and (b) show the results for DM noise source impedances. The figures also show the impedance of wire and capacitance which confirms that the bypass capacitors are effective for the frequency range of interest. From the obtained impedance response, the CM noise source impedance can be modeled by a series RLC circuit ($R = 36.8 \Omega$, $L = 12 \mu\text{H}$ and $C = 0.5 \text{ nF}$) in parallel with a 0.25 nF capacitor. It is well known that CM impedance of simple power converters is capacitive as determined by the capacitance between the heat sink of semiconductor device and ground. The micro-inverter in the experiment consists of several semiconductor devices with a flyback transformer in the dc-dc converter. These components together can affect the CM frequency to have multiple resonances as shown by the results.

The DM noise source impedance can be modeled by a 94 nH inductor. This is accordance with other studies since DM impedance is mostly affected by the lead connections at the input of the power converters. The frequency responses of the lumped circuit estimation are also shown in the figures, which show close agreement with the measured results.

Fig. 4-9. Extracted DM impedance of noise source: (a) magnitude, (b) phase

4.1.3 Noise Source Estimation

Fig. 4-10. Measurement of noise at LISN

After CM and DM noise source and termination (LISN) impedances are determined, the two probes and the bypass capacitor can be removed. The CM and DM conducted emissions are then measured with the LISN and a CM/DM discrimination network [99], as shown in Fig. 4-10. To account for the short cable impedance, used to connect LISN and the micro-inverter, the measured CM cable impedance ($Z_{cable,CM}$) and DM

cable impedance ($Z_{cable,DM}$) are found to be dominated by inductance. Their respective inductances are $0.351 \mu\text{H}$ and $0.172 \mu\text{H}$.

Fig. 4-11. (a) CM and (b) DM emissions at LISN and at noise source

Using the extracted LISN and cable impedances and the measured conducted emissions, the CM and DM noise source voltages can be computed as follows:

$$V_{noise,CM} = V_{LISN,CM} \times \frac{Z_{noise,CM} + Z_{cable,CM} + Z_{LISN,CM}}{Z_{LISN,CM}} \quad (4.5)$$

$$V_{noise,DM} = V_{LISN,DM} \times \frac{Z_{noise,DM} + Z_{cable,DM} + Z_{LISN,DM}}{Z_{LISN,DM}} \quad (4.6)$$

The calculated noise source emissions using (4.5) and (4.6) and the measured CM and DM conducted emissions at the LISN are shown in Figs. 4-11 (a) and (b), respectively. For the case of CM noise source, $Z_{noise,CM}$ is much higher than $Z_{LISN,CM}$ in lower frequency range and therefore CM noise source emission ($V_{noise,CM}$) is significantly higher than that at the LISN ($V_{LISN,CM}$). At frequencies above 10 MHz, $Z_{LISN,CM}$ becomes comparable to $Z_{noise,CM}$ and $V_{noise,CM}$ approaches $V_{LISN,CM}$.

Fig. 4-12. Equivalent circuit of the measurement setup for extracting (a) CM noise source impedance (b) DM noise source impedance.

In the case of DM noise, the DM noise source impedance ($Z_{noise,DM}$) is very small and the DM LISN impedance ($Z_{LISN,DM}$) dominates the total DM impedance of the

PV system. This makes the DM noise source emission ($V_{noise,DM}$) nearly equal to DM noise at LISN ($V_{LISN,DM}$)

Using the extracted noise source CM and DM impedances and the respective noise source voltages, the frequency-domain CM and DM noise models are constructed, as shown in Figs. 4-12 (a) and (b), respectively. The conducted noise models show that CM noise voltage at the dc side of the PV system can be very high. This can lead to significant CM current propagating through the dc cable between the PV panel and the dc input of the PV system. If the CM noise at the source is not controlled using proper EMI filter, the system can radiate significant emissions. Similarly, the DM emissions should also be controlled as it can also generate radiated emissions from the large PV panel, which acts as unintentional radiating antennas.

The CM and DM noise source models at the dc input of the PV system under its actual operating condition are thus constructed. The models are validated by using external CM and DM EMI filters and predicting their effect on noise emissions.

4.2 Validation using CM and DM filters

In this section the conducted emissions with CM and DM EMI filters will be simulated based on the CM and DM noise source models developed in the previous section and then validated through measurement.

4.2.1 CM Filter

Fig. 4-13. Connection of CM filter

For the CM filter, two 1 nF capacitors (C_Y) and a 10 mH CM choke (L_C) are connected at the dc input of the micro-inverter, as shown in Fig. 4-14. Comparing V_{LISN} without the filter in 4-11 and with the filter in 4-16 shows that CM emission is reduced as expected. Additionally, due to the effective DM impedance offered by the CM filter, DM emission is also reduced. In order to estimate the conducted emissions, the impedances of the filter components are measured and plotted in Fig. 4-14. The figure shows that Z_{C_Y} can be modeled by a series RLC circuit ($R = 6.34 \Omega$, $L = 0.082 \mu H$ and $C = 1.08 \text{ nF}$). The effective CM and DM impedances of Z_{C_Y} will be two C_Y in parallel and two C_Y in series, respectively.

Fig. 4-14. Magnitude of impedance versus frequency of CM filter components

The effective CM and DM impedances of the CM choke are also measured separately and plotted in Fig. 4-14. It is shown that the CM impedance of the choke is well above its self-resonant frequency and is capacitive in the frequency range of interest. It can be modeled by a 0.079 nF capacitor. Similarly, the effective DM impedance of the choke can be modeled by a parallel RLC circuit ($R = 1.75 \text{ k}\Omega$, $L = 44.92 \mu H$ and $C = 0.025 \text{ nF}$).

Fig. 4-15. (a) CM and (b) DM equivalent noise models with CM filter

Fig. 4-15 shows the equivalent noise model with the CM filter and the LISN. Using the extracted noise model and the measured impedance, the conducted emission of the system with the filter can be computed by:

$$V_{LISN} = V_{noise} \times \frac{Z_{LISN} Z_{CY}}{Z_t Z_{CY} + Z_t Z_{noise} + Z_{CY} Z_{noise}} \quad (4.7)$$

where, $Z_t = Z_{LISN} + Z_{cable} + Z_{LD}$, the terms are replaced by the respective CM and DM values. The comparisons of calculated and measured CM and DM conducted emissions at LISN after inserting the CM filter are shown in Figs. 4-16 (a) and (b) respectively. For both cases, the calculated emission agrees rather well with the measured emission. Hence, they demonstrate the validity of the extracted noise model.

Fig. 4-16. Comparison of conducted emissions at LISN with CM filter: (a) CM emission, (b) DM emission

4.2.2 DM Filter

The model is also investigated by adding a DM filter, which consists of one $0.1 \mu\text{F}$ capacitor (C_X) and two $5 \mu\text{H}$ DM chokes (L_D), as shown in Fig. 4-17. The process for calculating conducted emission is similar to the case of adding CM filter. Comparing

the respective emissions with and without the DM filter Fig. 4-20 and Fig. 4-11, respectively, shows that the DM filter is effective in reducing the DM emission. to the effective CM impedance contributed by the DM chokes, the CM emission has also reduced to a lesser extent.

Fig. 4-17. Connection of DM filter

The measured impedance frequency response of the DM filter components is shown in Fig. 4-18. The figure shows that Z_{L_D} can be modelled by a $5.4 \mu\text{H}$ inductor and Z_{C_X} can be modelled by a series RLC circuit ($R = 1.48 \Omega$, $L = 0.597 \mu\text{H}$ and $C = 0.112 \mu\text{F}$). The effective CM and DM impedances of Z_{L_D} will be two L_D in parallel and two L_D in series, respectively. Z_{C_X} has a negligible impact on CM emission.

Fig. 4-18. Magnitude of impedance versus frequency of DM filter components

Fig. 4-19 shows the equivalent noise model with the DM filter and LISN. The DM emission can be computed by:

$$\begin{aligned}
 V_{LISN,DM} &= V_{noise,DM} \\
 &\times \frac{Z_{LISN,DM} Z_{C_X}}{Z_t Z_{C_X} + Z_t (Z_{noise,DM} + Z_{L_D,DM}) + Z_{C_X} (Z_{noise,DM} + Z_{L_D,DM})}
 \end{aligned} \tag{4.8}$$

where, $Z_t = Z_{LISN,DM} + Z_{cable,DM}$

Since C_X is ineffective in the case of CM noise, CM emission is calculated by:

$$V_{LISN,CM} = V_{noise,CM} \times \frac{Z_{LISN,CM}}{Z_{noise,CM} + Z_{cable,CM} + Z_{LISN,CM} + Z_{L_D,CM}} \tag{4.9}$$

The calculated and measured emissions at the LISN after inserting the filter are shown in Fig. 4-20. It shows that both the calculated CM and DM emissions agree closely with the respective measured emissions.

Fig. 4-19. (a) CM and (b) DM equivalent noise models with DM filter

Fig. 4-20. Comparison of conducted emissions at LISN with DM filter: (a) CM emission, (b) DM emission

4.3 Summary

The chapter has demonstrated that both CM and DM noise source models of a PV system can be extracted accurately using an in-circuit impedance measurement approach. The constructed noise models allow us to assess the EMI impact of the PV

system efficiently. The modeling approach does not need the full details of the internal circuitry of power converters. The effectiveness of the CM and DM filters can also be assessed with the noise source models for EMI mitigation purpose. For an actual PV system without the LISN, the proposed method can be applied by replacing the LISN impedance with the impedance of the PV panel and cable. This is discussed in the following chapter.

Chapter 5

Conducted and Radiated Noise Model of PV System with PV Panel and DC Cable

In this chapter, an EMI model of a PV system with PV panel and dc cable is developed. Besides extracting the noise source impedance of the system, as described in the previous chapter, it is also necessary to extract the impedance of PV panel at the operating condition. As described in Section 2.2.1.1, PV characteristics are dependent upon operating conditions. It is, therefore, necessary to understand and develop the PV model for EMI analysis.

5.1 Small Signal Model of PV panel

The full equivalent model of a PV panel, shown in Fig. 2-2, is explained in Section 2.2.1.1. In the model, the dc parameters are photo-current source (I_{ph}), reverse breakdown voltage offset (V_{bd}), forward-biased diode (D_f) and reverse-biased diode (D_r). These dc parameters can be ignored, at frequency range of 150 kHz to 30 MHz, for EMI consideration. These parameters along with shunt resistance (R_{sh}) can be replaced by an equivalent parallel resistance (R_p). Hence, the model can be simplified to the small signal model as shown in Fig. 5-1 [100]. As shown in the figure the remaining parameters: equivalent parallel capacitance (C_p), series inductance (L_s) and series resistance (R_s) are included in the simplified model. For the small signal mode, the impedance of the panel is given by:

$$Z = \left[R_s + \frac{R_p}{\alpha + 1} \right] + j \left[L_s \omega - \frac{\omega R_p^2 C_p}{\alpha + 1} \right] \quad (5.1)$$

where $\omega = 2\pi f$ and $\alpha = \omega^2 R_p^2 C_p^2$.

Fig. 5-1. PV AC small signal model

At lower frequencies the impedance is dominated by R_p and R_s . However, at EMI concerned frequencies, R_p may not be dominant, as it is shunted by C_p . R_s , however, affects the overall impedance at the resonant frequency. Therefore, C_p , R_s and L_s are significant for the impedance characteristics of the PV panel at the concerned frequency range. While, R_s and L_s are relatively constant while C_p varies with the operating conditions. During operation of the PV panel, C_p is mainly affected by two terms: transition or junction capacitance (C_j) and diffusion capacitance (C_d) [43]. The charge stored in the depletion region determines C_j . It affects small positive and negative voltages when the junction is not conducting with a significant current. Similarly, C_d is due to charge stored in the neutral region outside the depletion region. It dominates the capacitance when the junction carries significant current. Due to these parameters, the impedance of the PV panel is dependent on its operating condition. It is therefore important to know the equivalent impedance of the panel at that specific operating condition.

5.1.1 Extraction of PV Equivalent Model at Different Conditions

In this section, the equivalent small signal model of a PV panel is extracted using in-circuit impedance measurement method. The purpose of the experiment is to demonstrate the dependence of model parameters to different operating conditions and the applicability of the proposed method to extract the parameters. The measurement setup for extracting the impedance of the PV panel is shown in Fig. 5-2. OMICRON Lab Bode100 VNA and two Solar Electronics Type 9144-1N current probes are used for the measurement. A 32-cell 60W PV panel is chosen and halogen

lamps are used as a controlled light source to illuminate the PV panel. The light intensity is fixed at 1000 W/m^2 and the ambient temperature is maintained at 50°C . A connected variable resistor is used to change the operating point of the PV panel. A 1.1 mF capacitor is connected in parallel to the resistor to provide a low impedance path for the RF signal. The impedance frequency response of the panel is measured using inductive coupling approach from 5 kHz to 30 MHz .

Fig. 5-2. Extraction of the equivalent impedance of the PV panel (a) Schematic diagram and (b) actual experimental setup

5.1.1.1 Impedance under Dark and Illuminated Conditions

The magnitude and phase of the extracted impedance of the PV panel under dark and illuminated conditions are shown in Fig. 5-3. The impedance of the short wire used to connect the PV panel with the variable resistor and the capacitor can be measured first and de-embedded to achieve good measurement accuracy. The results show that the load variation does not affect the PV panel's impedance for dark condition, as expected.

PV impedance under dark and illuminated conditions - Magnitude

(a)

PV impedance under dark and illuminated conditions - Phase

(b)

Fig. 5-3. Comparison of (a) magnitude and (b) phase of PV impedance under dark and illuminated conditions

Table 5-1. PV small signal model parameters under dark and illuminated conditions

Case	C_p (μF)	R_s (Ω)	L_s (μH)
$Z_{PV,dark}$	0.12	0.76	1.09
$Z_{PV,illum,short}$	1.01	0.68	0.79
$Z_{PV,illum,open}$	~11.9	0.63	1.13

Table 5-1 shows that the equivalent parallel capacitance for the dark condition is much lower than those for the two illuminated conditions. Since R_p and R_s dominate C_p for open circuit condition, it is not possible to accurately estimate the capacitance. For the dark condition, the voltage across the PV cells is very small and insignificant current flows across the depletion region. Therefore, the capacitance is small since it is mostly dominated by the junction capacitance (C_j). During the illuminated condition, voltage across the cells increases and higher current flows across the depletion region. Therefore, the capacitance increases as diffusion capacitance (C_d) dominates the parallel capacitance. The series resistance and inductance are relatively constant for all three conditions. At higher frequencies above 10 MHz, there is an additional capacitive effect which is due to the parasitic capacitance of the connector leads of the PV panel.

5.1.1.2 Impedance under Illuminated and Various Load Conditions

The impedance of the panel is extracted at different load conditions as shown in Fig. 5-4. For clarity, only the magnitude is shown here. The results show that C_p dominates the impedance of the PV panel below 100 kHz. Above 100 kHz, the impedance becomes inductive as L_s starts to dominate. At resonance near 100 kHz, the impedance is determined by the series resistance (R_s). At higher frequencies above 10 MHz, connectors of the PV panel introduce another capacitive effect due to the parasitic capacitance.

Table 5-2 lists the estimated values of model parameters (C_p , L_s , R_s) obtained from the measurement. As panel voltage increases, the parallel capacitance increases since C_j , which increases slightly with increasing voltage, is dominated by larger C_d . As panel voltage increases, the voltage bias across the depletion region also increases. This causes more current flow across the depletion region which causes an increase in diffusion capacitance. The panel voltage and consequently the parallel capacitance increases further for loads below 7.4 Ω , which is near maximum power point (MPP) of the panel, such that the impedance is dominated by resistors R_p+R_s . Therefore, it is not possible to get an accurate estimation of C_p for cases with smaller loads, as shown in Table 5-2. The results also show that series resistance and inductance are relatively constant for different illuminated conditions.

Fig. 5-4. Comparison of PV impedance under illuminated and various load conditions

Table 5-2. PV small signal model parameters under illuminated and different load conditions

Case			Model Parameters		
<i>Load</i>	<i>V_{pv}</i>	<i>I_{pv}</i>	<i>C_p</i>	<i>R_s</i>	<i>L_s</i>
(Ω)	(V)	(A)	(μF)	(Ω)	(μH)
Short	0	3.16	1.01	0.68	0.79
1.8	3.08	1.8	1.19	0.72	0.80
2.6	5.8	3.1	1.91	0.76	0.79
7.4	15.5	2.96	2.29	1.10	1.13
8.5	17	2.88	~2.82	1.19	1.15
10	18.1	2.6	~5.71	0.99	1.15
13	17.7	2	~8.30	0.79	1.15
19	19	1.75	~9.10	0.76	1.16
Open	20.7	0	~11.90	0.63	1.13

The impedance of the PV under various operating conditions is therefore extracted using the in-circuit measurement method. If load is replaced by a power converter, the same method can be used to extract the impedance of the PV panel under the actual operating condition, which is essential for developing accurate noise models.

5.1.1.3 Lumped Circuit Model Construction

The impedance model of the PV panel can be constructed for a specific operating condition from the obtained results discussed earlier. However, some changes to the model illustrated in Fig. 5-1 is needed to estimate the impedance at higher frequencies. The modified equivalent circuit used for modeling is shown in Fig. 5-5. To consider the effect of PV connection leads at higher frequencies, the external parallel capacitor (C_{ext}) and resistor (R_{ext}) are added. Their values can be obtained from measurement results shown in Fig. 5-4. Fig. 5-6 shows the simulation results for two illuminated conditions with short and open circuits at the load end. The model parameters (C_p, L_s, R_s) for short circuit condition are obtained from Table 5-2. Parallel resistance (R_p) is not included since it is not effective at the concerned frequency range. The parameters $C_{ext} = 0.12nF$ and $R_{ext} = 498.9\Omega$ are obtained from measured results shown in Fig. 5-4. As for open circuit condition, L_s and R_s are obtained from Table 5-2. R_p can be obtained from dc measurement and C_p can be estimated analytically. The parameters used for the case of open circuit are $C_p = 1.3\mu F$, $R_p = 0.3\Omega$, $C_{ext} = 70pF$ and $R_{ext} = 1.3k\Omega$. Fig. 5-6 shows that the simulated and measured results are in good agreement.

Fig. 5-5. Modified PV small signal impedance model for simulation

Fig. 5-6. Comparison of simulated and measured impedance of PV under illumination

The section uses an in-circuit impedance measurement method to extract the equivalent circuit model of the PV panel under its actual operating condition. The extraction of the equivalent impedance of the panel is important since it determines the DM impedance of the panel. The CM impedance is influenced by a type of grounding and placement of the panel. It is, therefore, necessary to extract these impedances for a system at operating conditions. The extracted impedance in the frequency range of interest can then be used to evaluate the EMI impact from a PV system when it is connected to a high frequency switching power converter.

5.2 Conducted Emissions

In this section, the EMI model of a PV system with actual PV panel is developed at its operating condition. The experimental setup of the system is shown in Fig. 5-7. To characterize the effect of PV panel and DC cables at the input side, the output side AC grid connection is avoided in the setup. For the intended purpose and simplicity, it is adequate to consider the dc-dc converter which forms input part of most PV converters as discussed in Section 2.2.1.2. In the setup, a dc-dc buck converter is used

with its output connected to a resistive load. The input is connected to a 32-cell 60W PV panel. The PV panel and buck converter are placed 5 cm above a copper plate of 3 m x 1 m dimension. The metal plate serves as the ground for the system and provides a well-defined path for CM noise current to flow. The actual experimental setup is shown in Fig. 5-7 (b) and device specifications are shown in Table 5-3. The entire setup is placed inside a shielded room to facilitate radiated emission measurements.

Fig. 5-7. Measurement setup of PV system (a) Block diagram (b) Actual setup

Table 5-3. Equipment specifications and settings

Equipment	Specifications
PV Panel	Nominal Peak Power (W_p): 60 W Nominal Voltage (V_{mp}): 18.3 V Nominal Current (I_{mp}): 3.27 A Open Circuit Voltage (V_{oc}): 22 V Short Circuit Current (I_{sc}): 3.67 A Dimensions: 685×670×35 mm
Buck Converter	Input: 10-40VDC, 5A Switching Frequency: 50kHz
Load	2.2 Ω

For operating the system, the PV panel is illuminated by halogen lamps. The panel is operated at a light intensity of 1000 W/m^2 and ambient temperature of 50°C . DC power is then supplied by the panel to the buck converter which operates at 50 kHz switching frequency. The duty cycle of the switch is set manually and fixed at 0.55 to operate the system at the specific operating point. At this state, the output voltage and current of the panel are $V_{PV} = 18.1 \text{ V}$ and $I_{PV} = 2.6 \text{ A}$ respectively during operation.

In order to model EMI noise in the system, the noise source and termination impedances are extracted at operating condition using the in-circuit measurement approach. The noise current in the system is then measured using current probes to estimate the noise source current. A proper model of the DC cable is also necessary for the noise propagation path. These processes are discussed in detail in the following sections.

5.2.1 Extraction of Noise Source and PV Equivalent Impedances

The process of extraction of noise source impedance is similar to the process described in Chapter 4, for a PV system with LISN and PV simulator. The measurement setups to extract CM and DM impedances of the noise sources, with actual PV panels, are shown in Figs. 5-8 (a) and (b) respectively. Details of the inductive probe setup is discussed in Section 3.4. For the measurements, two Solar Electronics Type 9144-1N current probes and OMICRON Lab Bode100 VNA were used. The $1 \mu\text{F}$ and $22 \mu\text{F}$ capacitors are connected to provide a low impedance path for the RF signals. The total impedances, $Z_{total,CM}$ and $Z_{total,DM}$, measured for the setup are then given as following:

$$Z_{total,CM} = Z_{noise,CM} + Z_{wire+2\mu F} \quad (5.2)$$

$$Z_{total,DM} = Z_{noise,DM} + Z_{wire+22\mu F} \quad (5.3)$$

where, $Z_{noise,CM}$ and $Z_{noise,DM}$ are the actual CM and DM noise source impedances. $Z_{wire+2\mu F}$ and $Z_{wire+22\mu F}$ are the impedances of wire and bypass capacitors for the two cases.

Fig. 5-8. Measurement setup for extracting (a) CM (b) DM noise source impedances

After extraction of noise source impedance, the impedance of PV panel is extracted by clamping the inductive probes at panel side of the PV system, as shown in Fig. 5-9. Since the characteristic of the PV panel is dependent on operating point, as described in Section 2.2.1.1 and demonstrated in Section 5.1.1; its impedance has to be extracted at the operating condition. Although DM impedance of the panel is mainly affected by the operating condition, both CM and DM impedances are extracted at the operating condition. The total impedances extracted in this case of PV are given as follows:

$$Z_{total,CM} = Z_{PV,CM} + Z_{wire+2\mu F} \quad (5.4)$$

$$Z_{total,DM} = Z_{PV,DM} + Z_{wire+22\mu F} \quad (5.5)$$

where, $Z_{PV,CM}$ and $Z_{PV,DM}$ are the actual CM and DM impedances of the PV panel.

Fig. 5-9. Measurement setup for extracting (a) CM (b) DM impedances of PV panel

The extracted magnitude and phase of CM impedances are shown in Figs. 5-10 (a) and (b) respectively. The figures also show that the bypass capacitors work effectively for the frequency range of interest. The total impedances measured in (5.2) and (5.4) are therefore dominated by $Z_{noise,CM}$ and $Z_{PV,CM}$ respectively. The results show that $Z_{noise,CM}$ can be estimated by a 0.02 nF capacitor. This is as expected since CM impedance is noise source is dominated by the parasitic capacitance between converter and ground. Similarly, $Z_{PV,CM}$ can be estimated by 0.07 nF capacitor. The higher capacitance is as expected since it is determined by the parasitic capacitance between ground and panel structure which is larger in size.

Fig. 5-10. Extracted CM impedance: (a) Magnitude, (b) Phase

Figs. 5-11 (a) and (b) show the extracted magnitude and phase of DM impedances respectively. The results show that the bypass capacitor works effectively for the DM case as well. The total impedance in (5.5) is dominated by $Z_{PV,DM}$ and $Z_{wire+22\mu F}$ can be neglected. However, $Z_{wire+22\mu F}$ must be de-embedded from total impedance in

(5.3) since it is close to $Z_{noise,DM}$. After de-embedding, it is observed that $Z_{noise,DM}$ can be represented by 0.055 μH inductor.

Fig. 5-11. Extracted DM impedance: (a) Magnitude, (b) Phase

In the case of $Z_{PV,DM}$, the result follows a similar characteristic as observed in Fig. 5-4. The equivalent PV model as illustrated in Fig. 5-5 can therefore be constructed

from the obtained result. At the operating point of $V_{PV} = 18.1 \text{ V}$ and $I_{PV} = 2.6 \text{ A}$, the parallel capacitance C_p , parallel resistance R_p and series resistance R_s are insignificant and can be neglected for the concerned frequency range. The equivalent PV model can then be estimated with series inductance $L_s = 1.5 \mu\text{H}$, external parallel capacitor $C_{ext} = 50 \text{ pF}$ and resistor $R_{ext} = 840 \Omega$.

The CM and DM impedances of noise source and PV panel are therefore extracted at operating conditions using the inductive coupling approach. The impedances allow us to estimate the noise source of the PV system, which is essential for complete noise model of the system. Estimation of the noise source is discussed in the following section.

5.2.2 Noise Source Estimation

Fig. 5-12. Measurement of (a) CM and (b) DM conducted noise current

Since the PV system does not have a LISN as with the setup in Chapter 4, the noise current in the system is measured using a current probe and spectrum analyzer, as shown in Fig. 5-12. The CM noise current $I_{PV,CM}$, is measured by clamping the current probe onto both line and neutral wire of dc cable, as shown in Fig. 5-12 (a). With this

setup, the DM noise current in the wires produce an opposite magnetic flux in the core of the probe, which effectively cancels their effect. The resultant magnetic flux in the probe and the signal generated in spectrum analyzer is due to CM current. Similarly, the DM noise current $I_{PV,DM}$, can be measured by clamping the probe onto both wires but with one of the wires wound in opposite direction, as shown Fig. 5-12 (b). In this case, the CM currents create opposite magnetic flux in the probe which effectively cancels their effect. DM current can therefore be measured by the spectrum analyzer.

The current measured is then obtained as follows:

$$I[dB\mu A] = V_{receiver} + K \quad (5.6)$$

where, $V_{receiver}$ is the voltage obtained from spectrum analyzer in $dB\mu V$ and K is transfer admittance of current probe in dB .

The equivalent noise source currents $I_{noise,CM}$ and $I_{noise,DM}$ are obtained from the measured currents as following:

$$I_{noise,CM} = I_{PV,CM} \times \frac{Z_{noise,CM} + Z_{cable,CM} + Z_{PV,CM}}{Z_{noise,CM}} \quad (5.7)$$

$$I_{noise,DM} = I_{PV,DM} \times \frac{Z_{noise,DM} + Z_{cable,DM} + Z_{PV,DM}}{Z_{noise,DM}} \quad (5.8)$$

The short cable between PV panel and buck converter is accounted by measuring CM cable impedance ($Z_{cable,CM}$) and DM cable impedance ($Z_{cable,DM}$) which are dominated by inductance. Their respective inductances are $0.351 \mu H$ and $0.172 \mu H$.

The measured CM and DM conducted emissions and the estimated noise source emissions using (5.7) and (5.8) are shown in Figs. 5-13 (a) and (b), respectively. For the case of CM noise source, $Z_{noise,CM}$ is much higher than $Z_{PV,CM}$, therefore CM noise source emission ($I_{noise,CM}$) approaches $I_{PV,CM}$. For the case of DM noise source model, $Z_{noise,DM}$ is smaller than $Z_{PV,DM}$, therefore the DM noise source emission ($I_{noise,DM}$) is much higher than $I_{PV,DM}$.

Fig. 5-13. (a) CM and (b) DM emissions at PV and at noise source

With the extracted CM and DM impedances and the estimated noise source, the frequency-domain CM and DM noise models of the PV system can be constructed, as shown in Figs. 5-14 (a) and (b), respectively. Similar to the model developed in Chapter 4, the models provide insights on conducted noise generation and propagation in the PV system. The results show that both CM and DM noise

generation in a PV system can be significant. The effect of the noise source and termination impedances on noise propagation can also be visualized from these models. Without the use of filters, noise propagates towards PV panels and give rise to radiated emission, which is discussed in Section 5.3. In the following section, the effect of longer cables is incorporated into the models.

Fig. 5-14. Equivalent circuit of the measurement setup for extracting (a) CM noise source impedance (b) DM noise source impedance.

5.2.3 Models with Longer DC Cable

In this section, longer lengths of DC cable are considered by using the transmission line model of the cables. In the PV system setup described in the previous section, shown in Fig. 5-7, longer DC cable is connected between PV panel and the buck converter. Fig. 5-15 (a) illustrates the cross-section of the type of DC cable used for the experiment. The conductor radius (r) of the DC cable used in the experiment is 1.2 mm and the distance between the wires (d) is 2.6 mm. Two cases with cable lengths of 1 m and 3 m are studied. In both cases, the cable is maintained at a height (h) of 5 cm above the ground plane of the system. The equivalent CM and DM models

with long DC cable are shown in Fig. 5-15 (a) and (b) respectively. The other components of the model, such as noise source and termination impedances, are obtained as described in the previous section.

Fig. 5-15. PV system noise model with DC cable: (a) Cross-section of DC cable, (b) CM and (c) DM noise model

For a two-conductor cable above a ground plane, the CM characteristic impedance ($Z_{c,CM}$) of the transmission line is obtained as following [101]:

$$Z_{c,CM} = 30 \ln \left[\frac{2h}{r} \sqrt{1 + \left(\frac{2h}{d} \right)^2} \right] \quad (5.9)$$

Similarly, the DM characteristic impedance ($Z_{c,DM}$) is given as follows:

$$Z_{c,DM} = 120 \ln \left[\frac{d}{r} \sqrt{\frac{1}{1 + \left(\frac{d}{2h} \right)^2}} \right] \quad (5.10)$$

Using (5.9) and (5.10), the obtained $Z_{c,CM}$ and $Z_{c,DM}$ for the setup are 218.98Ω and 92.78Ω respectively. Once the characteristic impedances are obtained, the noise emission $I(L)$ at the end of the transmission line, which is the input of the PV panel, can be obtained using [95]:

$$I(L) = \frac{V_0}{Z_c} \left[\frac{1 - \Gamma_L}{1 + \Gamma_L e^{-j2\beta L}} \right] \quad (5.11)$$

where, phase constant $\beta = 2\pi/\lambda$ and λ is the wavelength. The input voltage of the transmission line is V_0 and the characteristic impedance Z_c is replaced by $Z_{c,CM}$ and $Z_{c,DM}$ for CM and DM case respectively. Load reflection coefficient is given as $\Gamma_L = \frac{Z_L - Z_c}{Z_L + Z_c}$, where Z_L is the load at the end of the transmission line.

The estimated and measured noise emissions with 1 m DC cable are shown in Fig. 5-16. The estimated results show close agreement with measured results in both CM and DM noise emissions. Comparing the noise emission with that of the system with 25 cm cable in Fig. 5-13, reveals that both CM and DM emissions have increased at higher frequencies. The increased conducted noise emission can cause an increase in radiated emission, especially for CM emissions.

Fig. 5-16. Comparison of noise emission with 1 m DC cable

Fig. 5-17 shows close agreement with estimated and measured noise emission for the system with 3 m DC cable. Comparing with results in Fig. 5-13 and Fig. 5-16, shows that use of longer DC cable increases both CM and DM noise emissions. This increment is caused due to multiple resonances introduced by using the longer cable in the system. Fig. 5-17 (a) shows that the increment of noise is more severe in the case of CM emission which is problematic for radiated emissions.

Fig. 5-17. Comparison of noise emission with 3 m DC cable

5.3 Radiated Emissions

To measure the radiated emission from the PV systems at a frequency range of 150 kHz to 30 MHz, a loop antenna is used. The measuring antenna is placed at 1 m distance and 1 m height in front of the PV panel, as shown in Fig. 5-18. As mentioned in the previous section, the entire experimental setup is placed inside a shielded room. This prevents external noise to pollute the radiation measurements taken from the loop antenna. The signal received by the loop antenna, when the PV system is turned on, is first amplified and then measured by a spectrum analyzer. Both the amplifier and the spectrum analyzer are placed outside the shielded room.

Fig. 5-18. Radiated emission measurement setup

The electric field strength of the radiation noise (E_{noise}) is defined by

$$E_{noise}[dB\mu V/m] = V_{receiver} - G + AF \quad (5.12)$$

where, $V_{receiver}$ is the voltage measured by the spectrum analyzer in $dB\mu V$, G is the amplifier gain in dB and AF is the antenna factor of the loop antenna in dB/m .

Before the measurement of radiated emission from the PV system, the individual effect of CM and DM conducted noise on generating radiated emission is first studied. This will allow us to determine the dominant mode for radiated noise emission from the panel and to determine separate antenna factor for CM and DM models.

5.3.1 Dominant Mode and Antenna Factor

To characterize the effect of CM and DM conducted noise emissions, the antenna factor of the PV panel is determined for each case. Antenna factor (AF) is the ratio of radiated electric field intensity to the voltage across the terminals for an antenna. In decibels it can be expressed as:

$$AF[dB/m] = E[dB\mu V/m] - V[dB\mu V] \quad (5.13)$$

Fig. 5-19. Radiation measurement with (a) CM and (b) DM source excitation

Since PV panel characteristics changes with operating condition, it is necessary to determine its AF at the specific operating condition. The measurement setups to determine the AF for CM and DM radiated emissions from PV panel are shown in Figs. 5-19 (a) and (b) respectively. For both cases, a variable resistor is connected to the PV panel and the panel is operated at $V_{PV} = 18.1 V$ and $I_{PV} = 2.6 A$ to match the operating point with previous setups.

For determining the antenna factor ($AF_{PV,CM}$) for CM radiated emissions, a current probe is clamped onto line and neutral wire of DC cable. Two bypass capacitors are connected to each wire and to the ground plate of the system. A signal generator is then connected to the probe to inject CM current into the system. Similarly, for determining the antenna factor ($AF_{PV,DM}$) for DM radiated emissions, the injecting probe is clamped unto one of the wires of the DC cable. A bypass capacitor is connected across the line and neutral wire and a 30 mH CM choke is placed between

the probe and the PV panel to suppress CM currents. DM current can therefore be injected into the system using the signal generator.

In both cases, the actual amplitude of noise currents, $I_{PV,CM}$ and $I_{PV,DM}$, in the system are measured using another probe by similar setup as shown in Fig. 5-12. Since $Z_{PV,CM}$ and $Z_{PV,DM}$ are known (Section 5.2.1), the voltage across the PV panel for each case can be determined. The electric field strength of the radiated emissions is measured using the loop antenna and obtained from (5.12). Finally, $AF_{PV,CM}$ and $AF_{PV,DM}$ are determined using (5.13).

Fig. 5-20. CM and DM antenna factor of PV panel

The extracted AFs of PV panel for CM and DM radiated emissions are shown in Fig. 5-20. The results clearly show that CM is the dominant mode for generating radiated emissions. This implies that for a similar level of CM and DM conducted noise, radiated emission due to CM emission will dominate the noise spectrum. Radiated emissions due to DM conducted noise can be dominant only if DM conducted noise is significantly higher than CM noise. For low power PV systems, this is usually not the case as shown by previous results.

Since $AF_{PV,CM} \gg AF_{PV,DM}$, the radiated emission from the PV panel can be estimated from the CM noise emission, if DM noise is not significantly higher than CM noise. Therefore, the radiated emission from PV panel (E_{PV}) can be estimated by

$$E_{PV}[dB\mu V/m] = AF_{PV,CM}[dB/m] + V_{PV,CM}[dB\mu V] \quad (5.14)$$

5.3.2 Radiated Emission with Different Lengths of DC Cable

In this section, the measurement results of radiated emission from the PV system with different lengths of dc cable are presented. The measurement setup is as shown in Fig. 5-18 with different dc cables replaced between PV panel and buck converter for the measurements. Additionally, the radiated emission is also estimated as discussed in the previous section using (5.14).

Fig. 5-21. Radiated emission from PV system with 25 cm DC cable

The radiated emission from PV system with short 25 cm dc cable is shown in Fig. 5-21. The figure also shows the background noise, when halogen lamps are switched on but without operating the PV system. For the measurements, it is ensured that the background noise is below the radiation measurements. The measured emission is compared with estimated results obtained from conducted emission, shown in Fig. 5-12, by using (5.14). The good agreement between measured and estimated emission implies that the radiated emission is mostly dominated by CM emission. The results

show that there can be considerable radiated emission from PV system at both low and high frequency.

Fig. 5-22. Radiated emission from PV system with DC cables: (a) 1 m and (b) 3 m

Figs. 5-22 (a) and (b) show radiated emission results for the system with 1 m and 3 m dc cables respectively. Both results show good agreement between measured and estimated emissions. The estimated results are obtained from estimated CM

conducted emission shown in Fig. 5-16 and Fig. 5-17. With 1 m dc cable, the emission has increased at higher frequencies, particularly around 25 MHz. This agrees with the CM conducted emission with 1 m dc cable. Similarly, for the system with 3 m cable, the emission has worsened at high frequencies since the longer cable causes an increase in CM emission as shown in Fig. 5-17.

This section has presented radiated emission results for different lengths of dc cable in the PV system. The results show that emissions can rise with longer lengths of dc cable. It is also shown that the radiated emissions can be estimated from conducted emission using (5.14). The close agreement with the measured results shows that the approach can be used to study emissions from further variation in the PV system such as longer dc cables or use of EMI filters. The use of EMI filters and their effect on the noise emissions are discussed in the subsequent section.

5.4 EMI Filter Effect on Noise Emissions

The previous sections have shown that conducted and radiated noise emission generated from the PV system can be significant. In order to reduce the noise emissions, EMI filter can serve as valuable tools. The effects of using CM and DM filters on noise emissions from the PV systems are investigated in this section.

5.4.1 CM Filter

Fig. 5-23. Connection of CM filter

A CM LC filter consisting of one 10 mH DM choke (L_c) and two 1 nF capacitors (C_Y) is connected to the PV system as shown in Fig. 5-23. The filter is same as the one used for the system, with LISN and PV simulator, in the previous chapter. The

impedance frequency responses of the CM filters are shown in Fig. 4-14 and the lumped parameter models of the components are discussed in Section 4.2.1.

The equivalent noise model of the PV system with the CM filter is shown in Fig. 5-24. Using the measured impedance and the extracted noise model, the conducted emission of the system with the filter can be computed by:

$$I_{PV} = I_{noise} \times \frac{Z_{noise}Z_{CY}}{Z_tZ_{CY} + Z_tZ_{noise} + Z_{CY}Z_{noise}} \quad (5.15)$$

where, $Z_t = Z_{PV} + Z_{cable} + Z_{LD}$, the terms are replaced by the respective CM and DM values.

Fig. 5-24. (a) CM and (b) DM equivalent noise models with CM filter

The calculated and measured CM and DM conducted emissions after inserting the CM filter are plotted in Figs. 5-25 (a) and (b) respectively. Comparing the results with emissions without the filters in Fig. 5-13 shows that the CM emission is considerably reduced. DM emission is also reduced in this case due to effective DM impedance of the CM filters.

Fig. 5-25. Comparison of conducted noise emission with CM LC filter: (a) CM emission, (b) DM emission

Radiated emission is also measured for the system with the CM filters. The measured and estimated emissions, shown in Fig. 5-26, show good agreement. The estimated emission is obtained from estimated CM conducted emission shown in Fig. 5-25 (a) and by using (5.14). Since the CM conducted emission is well reduced using the CM

filter, the radiated emission is also effectively reduced. Therefore, CM filters are effective to reduce radiated emissions from the system.

Fig. 5-26. Radiated emission from PV system with CM LC filter

5.4.2 DM Filter

Fig. 5-27. Connection of DM filter

For the case of DM filter, an LC filter consisting of one $0.1 \mu\text{F}$ capacitor (C_x) and two $100 \mu\text{H}$ DM chokes (L_D), is connected to the PV system as shown in Fig. 5-27. The conducted emission with DM filter shown in Fig. 5-29 shows that DM emission is mainly reduced compared to emissions without the filter in Fig. 5-13. Due to the effective CM impedance of DM chokes CM emission is also reduced to some extent. The impedance magnitude of the DM filters used in the setup is shown in Fig. 5-28. According to the measurement results, Z_{C_x} can be modelled by a series RLC circuit

($R = 1.08 \, \Omega$, $L = 0.09 \, \mu\text{H}$ and $C = 0.1 \, \mu\text{F}$) and Z_{L_D} can be modelled by parallel RLC circuit ($R = 2.82 \, \text{k}\Omega$, $L = 100.7 \, \mu\text{H}$ and $C = 0.02 \, \mu\text{F}$). Z_{C_X} has a negligible impact on CM emission. The effective CM and DM impedances of Z_{L_D} will be two L_D in parallel and two L_D in series, respectively.

Fig. 5-28. Magnitude of impedance versus frequency of DM filter components

Fig. 5-29. (a) CM and (b) DM equivalent noise models with DM filter

Fig. 5-30. Comparison of conducted noise emission with DM LC filter: (a) CM emission, (b) DM emission

The equivalent noise model with the DM filter is shown in Fig. 5-29. The DM emission at PV panel can be computed by:

$$\begin{aligned}
 I_{PV,DM} &= I_{noise,DM} \\
 &\times \frac{Z_{noise,DM} Z_{C_X}}{Z_t Z_{C_X} + Z_t (Z_{noise,DM} + Z_{L_D,DM}) + Z_{C_X} (Z_{noise,DM} + Z_{L_D,DM})}
 \end{aligned} \tag{5.16}$$

where, $Z_t = Z_{PV,DM} + Z_{cable,DM}$

In the case of CM noise, C_X is ineffective. Therefore, CM emission is calculated by:

$$I_{PV,CM} = I_{noise,CM} \times \frac{Z_{noise,CM}}{Z_{noise,CM} + Z_{cable,CM} + Z_{PV,CM} + Z_{L_D,CM}} \tag{5.17}$$

The calculated and measured emissions are shown in Fig. 5-30. It shows that both the calculated CM and DM emissions agree well with the measured emissions.

Fig. 5-31. Radiated emission from PV system with DM LC filter

The measured and estimated radiated emissions after inserting DM filter are shown in Fig. 5-31. As discussed earlier, DM filter does not reduce CM conducted emission significantly. Therefore, comparing with the radiated emission in Fig. 5-21, the emission is not effectively reduced after insertion of the DM filter.

5.5 Summary

In this chapter, a measurement-based equivalent EMI model of a PV system is developed under actual operating conditions. It was shown that a small-signal model of PV panel can be developed for EMI analysis. The parameters of the model can be extracted using the in-circuit measurement approach. The noise source impedances are also extracted using the same approach. After extracting the impedances and estimating the noise source, the CM and DM conducted noise models of the PV system are developed. The model is also extended to include longer dc cables using a transmission line model. The radiated emission measured from the system revealed that CM emissions dominated the noise spectrum. The CM antenna factor of the PV panel is therefore used to estimate radiated emissions under different conditions and good agreement was achieved with that of measured results. Finally, different CM and DM EMI filters were tested using the model. It showed that CM filters are most effective to reduce radiated emissions from the system. For longer dc cables, it may be necessary to use higher valued CM filters to achieve the same attenuation of noise emissions.

Chapter 6

Conclusion

6.1 Conclusion

In this thesis, a measurement-based equivalent EMI model of input dc side of a PV system is developed. An in-circuit measurement approach using inductive coupling probes is proposed to extract the CM and DM noise source and termination impedances at operating condition. This allows estimation of the noise source and allows the development of accurate noise emission models of the system. Unlike the conventional device-based models, this approach does not require detailed information on the internal structure of PV power converters and is not computationally demanding. The proposed method is easy to implement, efficient and provides adequate information for EMI analysis.

The proposed modeling approach is applied to two cases of PV systems. Initially it is developed for a system consisting of PV simulator, LISN and micro-inverter. The obtained results show the proposed approach is good for modeling PV system for EMI analysis. The method is then applied to a system with an actual PV panel. The in-circuit measurement approach is used to extract the PV small-signal model parameters. The model is also extended to include longer dc cables by considering a transmission line model.

Developing both CM and DM models of the PV system provides good information on dominant noise in the system. The effects of EMI filters on the two modes of noise can also be easily investigated. Without EMI filters significant conducted noise can propagate in the system. Furthermore, noise emissions can increase with longer dc cables due to resonance. Similarly, it was shown that radiated emission from the PV system is dominated by CM emission. The antenna factor of the PV panel is

determined to estimate the radiated emission in different cases. To reduce radiated emission from a PV system, CM EMI filters can be most effective.

6.2 Future Work

The proposed modeling approach has been applied for a low power PV system under laboratory conditions. The same approach can be extended to other PV systems with different converters and multiple PV panels.

The model can also be further extended by developing two-port noise equivalent model of the PV converter. This will allow for investigating the noise at both input and output side of the PV system.

Author's Publications

Journal Paper

- **M. Prajapati** and K. Y. See, "Extraction of equivalent source model from photovoltaic systems," *IEEE Transactions on Electromagnetic Compatibility*, accepted for publication, to appear in 2019.

Conference Papers

- **M. Prajapati** and K. Y. See, "Extraction of equivalent impedance of photovoltaic panel under its actual operating conditions," *Joint IEEE International Symposium on Electromagnetic Compatibility and Asia-Pacific Symposium on Electromagnetic Compatibility*, Singapore, May 2018, pp. 1145-1149.
- S. B. Rathnayaka, K. Y. See, **M. Prajapati**, K. Li, N. B. Narampanawe and F. Fan, "Inductive coupling method for on-line frequency response analysis (FRA) for transformer winding diagnostic," *IEEE Region 10 Conference*, Penang, Nov 2017, pp. 88-92.
- S. B. Rathnayaka, K. Y. See, **M. Prajapati**, K. Li, N. B. Narampanawe and F. Fan, "Influence of temperature on transformer's winding defect analysis using inductive probes," *Progress in Electromagnetics Research Symposium*, Singapore, Nov 2017, pp. 2285-2289.

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