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Extraction of Equivalent Noise Source Model from Photovoltaic Systems

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Abstract—Photovoltaic (PV) systems have become popular as one of the renewable energy sources in recent years. With increasing number of PV systems, potential electromagnetic interference (EMI) issues from the PV systems cannot be ignored. In order to evaluate the EMI potential of a PV system, an in-circuit measurement method to extract its equivalent common-mode and differential-mode noise source models is described and validated. These noise source models serve as black boxes for further EMI analyses.

Index Terms— Electromagnetic Interference, Electromagnetic Compatibility, Photovoltaic System.

I. INTRODUCTION

THE use of solar photovoltaic (PV) systems as green energy source has increased significantly in recent years and is expected to rise further in the future [1]. On the other hand, the use of high frequency switching techniques in DC-DC converters and DC-AC inverters of the PV systems expects to generate more electromagnetic interference (EMI) issues [2]-[5]. Most of the EMI studies focus on AC output of the PV systems, as it connects to the power grid and the conducted emissions must comply with the relevant EMI regulation [6]. Although similar regulation does not apply on the DC input of a PV system, the high frequency switching DC-AC inverter with its DC input connected to the PV panel causes conducted emissions to be present in DC cable. These emissions can radiate through the DC cable and the PV panel, which serve as unintentional antennas [7]-[8]. Hence, an EMI filter on the DC side of a PV system is necessary to suppress the conducted emissions at the source before they radiate through the cable and the PV panel. As the size of the PV panel and the length of the DC cable vary in different installation sites, it is important to develop an efficient method to assess potential radiated EMI impact as well as to design an optimized EMI filter for mitigation. In order to do that, prior knowledge of noise source information at the DC input of a PV system that reflects its actual operation condition is the prerequisite. A full circuit model of a PV system to provide the noise source information requires detailed knowledge of the devices and components of the complete PV system, which can be computationally prohibitive. Beside this issue, the manufacturers of the PV

Fig. 1. In-circuit impedance extraction based on inductive coupling method: (a) basic measurement setup (b) cascaded two-port network representation.

systems are reluctant to provide circuit level information due to intellectual property protection. To overcome these constraints, we adopt an in-circuit measurement approach to extract the noise source model at the DC input of a PV system under its actual operating conditions, which provides adequate information for EMI modeling and mitigation purposes without the full knowledge of the internal circuit of the PV system. The noise source model allows us to evaluate the effectiveness of the filter for EMI mitigation without a trial-and-error process. This paper is organized as follows: Section II gives a brief introduction of the in-circuit measurement method based on a cascaded two-port network representation. Section III describes the procedures to extract both common-mode (CM) and differential-mode (DM) noise source models of a PV system. Section IV validates the CM and DM noise source models and the design of the respective EMI filters for noise suppression. Finally, Section V concludes the paper with recommended future work.

II. IN-CIRCUIT IMPEDANCE EXTRACTION METHOD

This section briefly describes the in-circuit impedance extraction method. Fig. 1(a) shows the basic in-circuit impedance measurement setup based on an inductive coupling method [9]. It consists of an injecting inductive probe, a receiving inductive probe and a vector network analyzer

Fig. 2. Measurement setup of the PV system (a) block diagram (b) actual setup

TABLE I
EQUIPMENT SPECIFICATIONS AND SETTINGS

Equipment	Model	Specifications
Micro-Inverter	TMSOLARUINVKIT	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

(VNA). Port 1 of the VNA injects an RF signal through the injecting probe into the circuit loop containing an unknown in-circuit impedance Z_X , which can be any electrical system connected and powered by a DC or AC source. Port 2 of the VNA receives the same RF signal via the receiving probe. Fig. 1(b) shows the two-port network representation of Fig. 1(a), where 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 S_X . The two-port network S_T in terms of $ABCD$ parameters between ports 1 and 2 of the VNA is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_T = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{TX} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_X \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{RX} \quad (1)$$

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 $ABCD$ networks of S_T , S_{TX} , S_X and S_{RX} respectively. The $ABCD$ parameters of the injecting and receiving probes are first obtained through a calibration test fixture, which is described in detail in [9] and will not be repeated here. Similarly, $ABCD$

Fig. 3. Measurement setup for extracting (a) CM noise source impedance (b) DM noise source impedance.

parameters of S_T are measured through two-port measurement by the VNA. Once S_T , S_{TX} and S_{RX} are determined, $ABCD$ parameters of S_X can be solved using (1). Parameter B of S_X is the in-circuit impedance Z_X .

III. EXTRACTION OF NOISE SOURCE MODEL

To extract the in-circuit noise source impedance at the DC side of a PV system based on the method shown in Fig. 1, a PV system shown in Fig. 2 (a) is set up. It consists of a PV simulator to emulate the PV panel that provides DC input power to a DC-AC micro-inverter through a line impedance stabilization network (LISN). The AC output of the inverter connects to the 230V AC power grid and a resistive load of 200 Ω draws power from the inverter output. The LISN is to provide a well-defined termination for the subsequent conducted emissions measurement at the DC side of the PV system. For the actual PV system where the LISN is not present, the proposed method can still apply by pre-characterization of the impedance of the PV panel in accordance with the procedure described in [10]. Fig. 2 (b) shows the actual hardware setup in the laboratory. The micro-inverter, 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 micro-inverter 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 for a well-defined CM current return path. Table I provides the models and specifications of the micro-inverter, the PV simulator, the LISN and all the supporting test equipment.

Fig. 4. Extracted noise source impedance: (a) CM magnitude, (b) CM phase, (c) DM magnitude and (d) DM phase

Fig. 5. Extracted LISN impedance: (a) CM magnitude, (b) CM phase, (c) DM magnitude and (d) DM phase

Fig. 6. (a) CM and (b) DM emissions at LISN and at noise source

Fig. 7. Equivalent circuit of the measurement setup for extracting (a) CM noise source impedance (b) DM noise source impedance.

A. Extraction of Noise Source Impedance

In order to construct the CM and DM noise source models at the DC side of the PV system, we have to extract the respective noise source impedances of the PV system shown in Fig. 2 under its actual operating condition. Figs. 3 (a) and (b) show the setups for the extractions of CM and DM noise source impedances, respectively. Two current probes (Solar Electronics 9144-1N) and a VNA (OMICRON Lab Bode 100) are chosen to conduct the measurement. The values of bypass capacitors for CM and DM setups in Figs. 3 (a) and (b) have to be chosen such that their respective 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, the two 1 μ F capacitors provide a bypass impedance of 0.53 Ω for the CM setup and the 22 μ F gives a bypass impedance of 48 m Ω for the DM setup at the lowest frequency of 150 kHz. To account for the non-ideal behaviors of the bypass capacitors and the wire connections, their impedance frequency responses are

measured and plotted in Figs. 4 and 5 for comparison, which have shown that they serve as effective bypasses in the frequency range of interest. Hence, the respective noise source impedance dominates the in-circuit impedance to be measured. Figs. 4(a) and (b) show the magnitude and phase frequency responses of the extracted CM noise source impedance, respectively. Figs. 4 (c) and (d) show the magnitude and phase frequency responses of the extracted DM noise source impedance, respectively. For the case of CM setup, the impedance of the wiring and capacitor is significantly lower than that of the noise source impedance, and hence its impact on the measured noise source impedance is negligible. However, for the case of DM setup, although the impedance of the wiring and capacitor is low but still comparable to that the noise source impedance, it has to be de-embedded from the in-circuit measurement.

From the impedance response shown in Figs. 4 (a) and (b), the CM noise source impedance ($Z_{S,CM}$) can be modelled 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. Similarly, the DM noise source impedance ($Z_{S,DM}$) can be modelled by a 94 nH inductor. To determine the CM and DM noise source voltages, we need to know the respective CM and DM LISN termination impedances. Hence, the CM termination impedance ($Z_{LISN,CM}$) and DM termination impedance ($Z_{LISN,DM}$) are also extracted by placing the two inductive probes at the LISN side with similar setups. Figs. 5(a) and (b) show the magnitude and phase frequency responses of the extracted CM impedance of the LISN. Likewise, Figs. 5(c) and (d) show the magnitude and phase responses of the extracted DM impedance of the LISN. We can also simulate the CM and DM impedances of the LISN based on its circuitry provided by the manufacturer. Fig. 5 shows that the extracted CM and DM LISN impedances from the measurements agree rather well with those simulated. As a check for the agreement between the measured and the simulated LISN impedance magnitudes, the feature selective validation (FSV) technique is also applied to obtain the grade as a figures of merit (FOM) [11]-[13]. For a scale of 1-6, grade 1 is the best and grade 6 is the worst. Both the CM and DM

Fig. 8. Connection of (a) CM filter and (b) DM filter

Fig. 9. Magnitude of impedance versus frequency (a) CM filter components (b) DM filter components

LISN impedances achieved a FOM of grade 2, which suggests there is indeed reasonably good agreement between the datasets.

B. Extraction of Noise Source Voltage

With the CM and DM noise source and termination impedances determined, we remove the two probes and the bypass capacitor and measure the CM and DM conducted emissions with the LISN and CM/DM discrimination network [14]. To account for the cable impedance between the 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 μ H and 0.172 μ H.

Since CM and DM LISN and cable impedances have been determined, with the measured CM and DM conducted emissions, the CM and DM noise source voltages can be computed as follows:

$$\begin{aligned}
 V_{noise,CM} &= V_{LISN,CM} \times \frac{Z_{noise,CM} + Z_{cable,CM} + Z_{LISN,CM}}{Z_{LISN,CM}} \\
 V_{noise,DM} &= V_{LISN,DM} \times \frac{Z_{noise,DM} + Z_{cable,DM} + Z_{LISN,DM}}{Z_{LISN,DM}}
 \end{aligned} \quad (2)$$

The measured CM and DM conducted emissions at the LISN and the calculated noise source emissions using (2) are shown in Figs. 6(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, $Z_{LISN,CM}$ has become comparable to $Z_{noise,CM}$ and $V_{noise,CM}$ approaches $V_{LISN,CM}$. For the case of DM noise source model, the DM noise source emission ($V_{noise,DM}$) is nearly equal to DM noise at LISN ($V_{LISN,DM}$) because 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.

Once the extracted noise source CM and DM impedances and their respective noise source voltages are known, the frequency-domain CM and DM noise models can be constructed, as shown in Figs. 7(a) and (b), respectively. The noise source models reveal that CM noise voltage at the DC side of the PV system is very high and can lead to significant CM current flowing through the DC cable between the PV panel and the DC input of the PV system. Without controlling the CM noise at the source with proper EMI filter, the DC cable can radiate significant emissions. Similarly, the DM noise emissions can also generate radiated emissions from the large PV panel, which acts as unintentional radiating antennas. In this section, we have described the procedures to construct the CM and DM noise source models at the DC input of the PV system under its actual

Fig. 10. (a) CM and (b) DM equivalent noise models with CM filter

operating condition. These models allow us to access the CM and DM radiated emissions through the DC cable and the PV panel so that we can design optimal EMI filters to suppress conducted emissions at the source and eventually radiated emissions from the DC cable and the PV panel. Both the designs of CM and DM EMI filters will be discussed in the next section.

IV. EMI FILTER DESIGN USING THE NOISE SOURCE MODEL

The CM and DM filters are designed in accordance with the procedure described in [15] to suppress the CM and DM emissions at the DC input of the PV system. Based on the CM and DM noise source models developed in the previous section, the CM and DM emissions with the respective filters will be simulated first and then validated through measurement.

A. CM Filter

For the CM filter at the DC input of the micro-inverter, it consists of two 1 nF capacitors (C_Y) and a 10 mH CM choke (L_C), as shown in Fig. 8(a). Comparing V_{LISN} without the filter in Fig. 6 and with the filter in Fig. 12, as expected, CM emission is reduced. However, DM emission is also reduced due to the effective DM impedance offered by the CM filter. In order to know the effective attenuation of the CM filter on CM and DM emissions, the impedance frequency responses of the filter components are measured and plotted in Fig. 9(a). It shows that Z_{C_Y} can be modeled by a series RLC circuit ($R = 6.34 \Omega$, $L = 0.081 \mu H$ and $C = 1.09 \text{ nF}$). The effective CM and DM impedances of Z_{C_Y} will be two C_Y in parallel and two C_Y in series, respectively.

For the CM choke, the effective CM and DM impedances are also measured separately and plotted in Fig. 9(a). It shows that the CM impedance of the choke is well above its self-resonant frequency and is capacitive in nature in the frequency range of interest. It can be modelled by a 0.079 nF capacitor. Similarly, the effective DM impedance of the choke can be modelled by a parallel RLC circuit ($R = 1.75 \text{ k}\Omega$, $L = 44.93 \mu H$ and $C = 0.025 \text{ nF}$).

Fig. 11. (a) CM and (b) DM equivalent noise models with DM filter

The equivalent noise model with the CM filter and the LISN is shown in Fig. 10. Using the measured impedance and the extracted noise model, the conducted emission of the system with the filter can be computed by:

$$V_{LISN} = V_{noise} \times \frac{Z_{LISN} Z_{C_Y}}{Z_t Z_{C_Y} + Z_t Z_{noise} + Z_{C_Y} Z_{noise}} \quad (3)$$

where, $Z_t = Z_{LISN} + Z_{cable} + Z_{L_D}$, the terms are replaced by the respective CM and DM values. Figs. 12(a) and (b) show the comparisons of calculated and measured CM and DM conducted emissions at LISN after inserting the CM filter, respectively. The calculated emission agrees rather well with the measured emission for both CM and DM. Hence, they demonstrate that the validity of the extracted noise model.

B. DM Filter

The model is further investigated by adding DM filter, which consists of one 0.1 μF capacitor (C_X) and two 5 μH DM chokes (L_D), as shown in Fig. 8(b). The process to calculate conducted emission is similar to the case of adding CM filter. Comparing the respective emissions without and with DM filter in Fig. 6 and Fig. 13, respectively, it shows that the DM filter is effective in reducing the DM emission. The CM emission has also reduced but to a lesser extent, which is due to the effective CM impedance contributed the DM chokes. The measured impedance magnitude versus frequency of the DM filter components is shown in Fig. 9(b). It shows that Z_{C_X} can be modelled by a series RLC circuit ($R = 1.49 \Omega$, $L = 0.598 \mu H$ and $C = 0.112 \mu F$) and Z_{L_D} can be modelled by a 5.4 μH inductor. Z_{C_X} has 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.

The equivalent noise model with the DM filter and LISN is shown in Fig. 11. Similarly, DM emission can be computed by:

Fig. 12. Comparison of conducted emissions at LISN with CM filter: (a) CM emission, (b) DM emission

Fig. 13. Comparison of conducted emissions at LISN with DM filter: (a) CM emission, (b) DM emission

$$V_{LISN,DM} = V_{noise,DM} \times \frac{Z_{LISN,DM} Z_{C_X}}{Z_t Z_{C_X} + Z_t (Z_{noise,DM} + Z_{L_D,DM}) + Z_{C_X} (Z_{noise,DM} + Z_{L_D,DM})} \quad (4)$$

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

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

$$V_{LISN,CM} = V_{noise,CM} \times \frac{Z_{LISN,CM}}{Z_{noise,CM} + Z_{cable,CM} + Z_{LISN,CM} + Z_{L_D,CM}} \quad (5)$$

The calculated and measured emissions at the LISN are shown in Fig. 13. It shows that both the calculated CM and DM emissions agree quite well with the respective measured emissions.

V. CONCLUSION

Based on an in-circuit impedance measurement approach, we demonstrate that both CM and DM noise source models of a PV system can be extracted accurately. The noise source models allow us to assess the EMI impact of the PV system efficiently without the need to know its full details of the internal circuitry.

With the known noise source models, it also allows us to assess the effectiveness of the CM and DM filters for EMI mitigation purpose. For the actual PV system without the LISN, the proposed method can still be applied by replacing the LISN impedance with the impedance of the PV panel and cable. The modeling of system with actual PV panels without the LISN will be the focus for further works.

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