Conducted Electromagnetic Emissions Analysis in Grid-tied PV System

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Abstract - **This paper focuses on the conducted electromagnetic interference emissions generated in a building grid-tied PV power system. It emphasizes on the inverter AC side, including the building power grid, as being the interference source and the PV side as the victim circuit, having the inverter as the coupling path. The applicable standards of the grid-tied PV system as being a fixed installation are discussed.**

The effect of the impedance variation on the performance of the inverter side EMI filter is investigated.

In-situ conducted emissions measurement of the PV system connected to the grid, at different points within the system, has revealed the existence of an excessive EMI noise, originating from the building power utility and propagating toward the DC side of the inverter. The conducted emissions waveforms are presented and the results are discussed.

***Key words*: Conducted EMI, EMC, Photovoltaic system, grid impedance**

I. Introduction

The discussion on the fossil energy depletion breeds a serious concern and paved the way for new alternative energy to compensate for the future energy demand. The emerging renewable energy such as solar energy has been a feasible solution for this energy dilemma. However, the solar energy exist as a raw energy and needs to be harnessed to a level at which the consumer can exploit it. This can be translated into a set of electronic sub-components which can be connected together to process this energy. The electrical power is produced using the photovoltaic cells found in solar panels

One critical subsystem of solar, or photovoltaic, installations is the solar inverter. These devices carry out the key step of feeding the newly generated power into the power grid. However, this "free" energy comes with a price tag resulting in electromagnetic pollution or interference, either being conducted to other sensitive equipment or radiated in free space. Of course, the next logical concern is preventing or mitigating this interference and achieving electromagnetic compatibility or EMC. Furthermore, the inherent concept of EMC involves defining certain limits that allow multiple devices and systems to function efficiently without causing problems or suffering impairment caused by interference.

Assuring the EMC compliance of solar inverters is preemptive approach before integrating this sub-component into the PV system. However, the PV system level compliance can not be guaranteed by looking only at the inverter as being the culprit component in the system. Therefore, the system level approach has to be adopted to ensure compliance with essential requirements of the EMC Directives.

There are a few contributed papers that have been published which points out the issues of the EMI emissions, either being conducted or radiated. However, it has been found that in a low power PV grid connected system, the DC wiring acts as antenna at resonance [1]. Preliminary suggestions on PV system testing methods for EMC compliance, were discussed in [2], however, the conclusion calls for the need for further investigations on the DC side behavior in terms of RF noise. In [3] the design of the line impedance stabilization network (LISN) and the conducted emissions limit lines have been proposed, and the values of the passive components have been given. However, the following points need to be addressed; 1) both the LISN design and the limits proposals, have been achieved based on laboratory measurements, rather than extrapolated using empirical field data to reflect the source impedance variations. 2) The production of the proposed LISN is difficult to implement, due to the DC side high current. 3) It is important to compare the actual value of the LISN to the existing 50 Ohms LISN as per EN61000-6-4. The EMC qualifications of the PV system components have been carried out by [4], using the LISN proposed by [3], the problem is that, the EMC compliance approach of each components, does not necessary converge into an EMC compliant at the system level .

This paper addresses the issues of the applicable standards in a grid-tied PV system, with the system being a fixed installation rather than an apparatus. It also, investigates the effect of the utility side impedance variations on the DC side of the PV system as a function of the insertion loss of the integrated EMI filter of the inverter. A complete conducted emissions testing as per EN61000-6-4 [5] was performed on a real time PV plant connected to a building power grid.

II. Applicable Standards

EMC regulations of grid-tied PV system have not been a straightforward application, due to the definition of its components being regulated separately or as an integral entity. At present, there are no specific standards regulating PV systems. In fact, there is no precise category for these devices. Currently, efforts are underway to come up with standards specific to the photovoltaic power generation systems. There are several assumptions as whether to classify the PV system as a single entity that can be individually tested in an EMC laboratory, or as a fixed installation that can be integrated into a large system.

According to the article 2, sections (a) & (b) of the official journal of the European Union [6], electronic equipment, can be any apparatus or fixed installation, defined as follows;

"Apparatus" means any finished appliance or combination thereof made commercially available as a single functional unit, intended for the end user and liable to generate electromagnetic disturbance, or the performance of which is liable to be affected by such disturbance.

"Fixed installation" means a particular combination of several types of apparatus and, where applicable, other devices, which are assembled, installed and intended to be used permanently at a predefined location.

Based on the definitions cited above, grid-tied PV system should be classified as a fixed installation, if it is intended to be incorporated into utility grid to provide additional power to the grid system as shown on Figure 1.

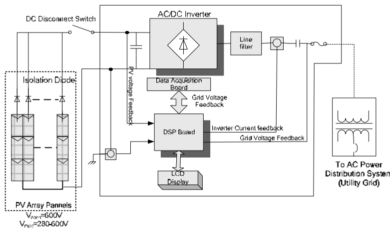

Fig. 1 PV power System in a Grid-tied Configuration

Hence, the generated electrical energy must be processed and converted down before it reaches the consumer appliances. In this case, the PV systems that are specially made to be incorporated into a given grid system or a fixed installation, must only meet the essential requirements set out in annex 1 of the new EMC Directives, 2004/108/EC which repeal the old EMC Directives 89/336/EEC. In the PV system, the compliance with the essential requirements is shown by in-situ EMC test results and documented using good engineering practices as spelled out in annex 1. Hence, the applicable standards for the fixed installation, such as the grid-tied PV system, are typically the generic standards: EN61000-6-2 for immunity and EN61000-6-4 for emissions. These refer to the basic standards that describe the actual test method to be performed. The case where the PV system is used as a stand-alone system, and requires in-situ testing, it is considered as apparatus and the whole system must show EMC compliance as such. Figure 2 shows the configuration where the PV power system is installed as a stand-alone system.

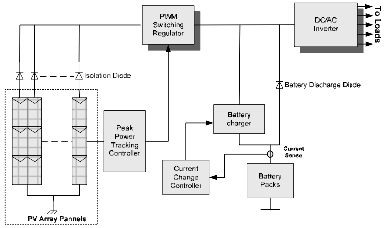

Fig. 2 PV power System in a Standalone Configuration

This paper consider the PV power system as being an integral part of an AC power distribution system, as shown in fig.1. Hence, only the generic standards will be applicable to show the compliance with the EMC Directives, in terms of conducted emissions.

III. System Components

In order to understand the source of propagation of the electromagnetic conducted emissions, it is important to describe the components that make up the PV power system. This helps to identify the source of the interference.

Figure 2 illustrate the necessary components of a stand-alone PV power system. The peak-power tracker senses the voltage and current outputs of the array and continuously adjusts the operating point to extract the maximum power under varying climatic conditions. The output power of the PV array is fed to the DC to AC inverter. The AC power is then injected into the utility grid as required by the load. A portion of the DC power is used to charge the battery. The battery charger is usually a DC–DC buck converter. When the sun is not available, the battery discharges to the inverter to supply the grid. The battery discharge diode is a protection feature to prevent the battery from being excessively charged. The isolation diode is used to prevent the PV array from acting as the load on the battery in dark conditions. The mode controller collects system parameters, such as the array and the battery currents and voltages and monitors the state of the battery. It uses this information to control the battery charger. Thus, in this configuration, the mode controller is the critical component of the entire system.

In the grid-connected system, as shown in Figure 1, all the DC power generated at the PV array is directly fed into the utility grid through the DC/AC inverter. Hence, only the inverter and its hardware are needed. The inverter module is the critical component in this configuration.

IV. Grid Impedance Variations

Most of the inverters in a grid-tied PV system are equipped with an EMI filter or line filter, to attenuate the EMI noise generated by the inverter, from being propagated towards the utility grid. However, these inverters do not have any filtering schemes on their DC side which represent very low impedance as seen from the AC side. Hence, most of the noise generated in the inverter and the noise inherent in the grid system due to switching loads is diverted towards the DC side. The DC side EMI conducted noise is converted into radiated emissions at half and quarter wavelength of the cable transmission, connecting the PV panels to the input side of the inverter. Furthermore, the variations of the grid impedance, seen by the inverter output have a significant influence on the performance of the line filter, in terms of its insertion loss. Most of off-the-shelf line filter, are evaluated assuming 50 ohms load impedance however, this assumption does not always hold, since the load (grid) impedance depends on the load capacity connected to power distribution and may vary from being resistive, capacitive or inductive. The following graphs show the insertion loss of the line filter as a function of frequency, at different types of load to demonstrate the issue of the grid impedance variations. The values of the inductor L and the capacitor C are extracted from the actual line filter used in PV system of the case study.

A. Resistive Impedance

Figure 3 shows the equivalent circuit of the harmonic noise generated at the inverter AC side and interfacing with the power grid, having variable resistive impedance. The line filter, with the cut-off frequency of 10 KHz, is inserted between the inverter AC side and the power grid.

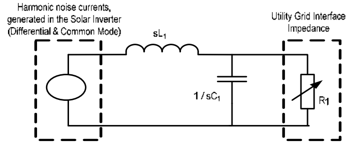

Fig.3 Grid impedance variations: Resistive load

To observe the effectiveness of the line filter, the insertion-loss transfer function is plotted versus frequency. This is illustrated In Figure 4.

In the frequency domain, the insertion loss $IL_R(\omega)$ of the line filter can be derived as:

$$IL_R(\omega) = \sqrt{\left(1 - \frac{\omega^2}{\omega_0^{\ 2}}\right)^2 + \frac{(\omega L_1)^2}{R_1^{\ 2}}} \qquad (1)$$

Where ω_o is the self-resonant frequency of the LC circuit, ω is the angular resonant frequency of the circuit, L_1 is the inductance of the line filter, and R_1 is the load resistive impedance.

It can be seen that the insertion loss does not change dramatically above the desired frequency of interest (10 KHz) which corresponds to a minimum insertion loss. However, a large dip below zero magnitude (negative region) appears due to the resonance of the LC circuit. As a result, the EMI noise in this region will be amplified instead of suppressed. The amplified EMI noise sees very low impedance looking to the inverter DC side, hence, the conducted EMI noise, originating from the power grid will flow through the inverter circuit and the DC bus, connecting the inverter input to the array panels.

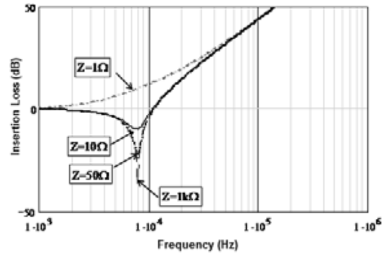

Fig. 4 Insertion-loss versus frequency at different resistive load impedance

B. Inductive impedance

The equivalent circuit of the harmonic noise generated at the inverter AC side and interfacing with the power grid, having variable inductive impedance, is shown in Figure 4.

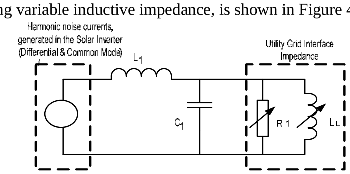

Fig. 5 Grid impedance variations: Inductive load

The resonant frequency of the inductor load, in terms of ω_o is given by:

$$\omega_L^{\ 2} = \omega_o^{\ 2}\left(1 + \frac{L_1}{L_L}\right) \qquad (2)$$

Where L_1 is the inductance of the Line filter and L_L is the inductive grid impedance.

The frequency domain, the insertion loss $IL_{RL}(\omega)$ of the line filter can be derived as:

$$IL_{RL}(\omega) = \left(\frac{\omega_L}{\omega_0}\right)^2 \sqrt{\left(1 - \frac{\omega^2}{\omega_L^2}\right)^2 + \frac{(\omega L_1)^2}{R_1^2} \times \frac{\omega_0^2}{\omega_L^2}} \qquad (3)$$

Figure 6 illustrates the effect of the inductive load impedance on the insertion-loss of the line filter. Comparing with Figure 4, it can be seen that the resonant frequency of the circuit has increased beyond the desired cut-off frequency of the line filter (10 KHz) and the EMI noise amplification can occur in this region. This is the worst case degradation the line filter performance.

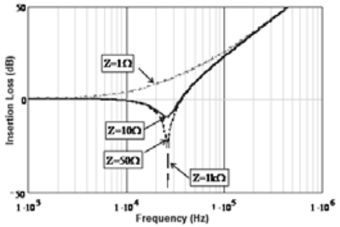

Fig. 6 Insertion-loss versus frequency at different inductive load impedance

C. Capacitive Impedance

The third case, of the power grid impedance variations is the capacitive load impedance, in which the solar inverter and the line filter are interfaced with capacitive grid impedance. The equivalent circuit of the harmonic noise is shown in Figure 7.

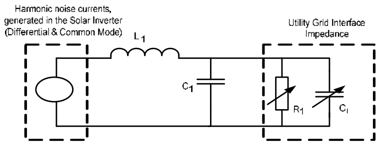

Fig. 7 Grid impedance variations: Capacitive load

The resonant frequency of the capacitive load impedance, in terms of ω_o is given by:

$$\omega_c^2 = \frac{\omega_0^2}{1+\dfrac{C_L}{C_1}} \tag{4}$$

Where: C_L is the load capacitance.

The line filter insertion-loss for capacitive grid load impedance is given by:

$$IL_{RC}(\omega) = \sqrt{\left(1-\frac{\omega^2}{\omega_c^2}\right)+\frac{(\omega L_1)^2}{R_1^2}} \tag{5}$$

Figure 8 shows the insertion loss of the EMI filter as a function of frequency for different values of the capacitive impedance load.

As a result of the load being capacitive in nature, the resonant frequency is decreased compared with the resistive impedance load of Figure 4. Thus the insertion loss at the desired cut-off frequency (10 KHz) has increased.

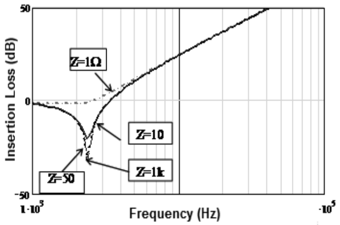

Fig. 8 Insertion-loss versus frequency at different capacitive load impedance

V. Conducted Emissions Measurements Case Study

To demonstrate the validity of the arguments that were pointed out in the previous sections, a complete conducted emissions testing has been carried out on the grid-tied façade mounted PV power system of the Queens University engineering building (www.queensu.ca) using generic EMC standards for conducted emissions, namely EN61000-6-4.

There are 12 sets of PV solar array, each set is made up of 22 PV panels connected in series, and mounted on four floors of the building façade. Each floor has 3 sets, for a total of 264 solar panels. Each set produce an open circuit voltage of 350 Volts and short circuit current of 4 Amps. Since the voltage is configured in parallel and the current in series, the total generated current is about 40 Amps in a sunny day. The open circuit voltage is kept constant at 350Volts. The total power generated at the DC side of the inverter is given by:

264 panels at 75W per panel yield a total of 19.8kW. The electrical specifications of the inverter are given in table 1.

TABLE 1 INVERTER SPECIFICATIONS

Continuous AC Output Power	20kW
Full Load Efficiency	Greater than 95%
Nominal Line Frequency	50/60 Hz +/- 0.5Hz
Nominal Line Voltage	208Vac –12%, +10% (per UL1741 & IEEE929)
Power Factor	Unity +/-0.02
AC Current Distortion	Less than 5%
PV Array Configuration	Monopole-Negative, Grounded, Bipolar-Neutral Grounded, or Floated
Maximum PV Array Voltage	600Vdc
PV Peak Power Point Window	300* - 600Vdc
*Minimum PV Peak Power Voltage	280–330Vdc dependant upon actual AC line voltage at inverter
PV Array Maximum Input Current	71.4Adc
PV Ripple Current	Less than 5%
Temperature	-20 ^{0}C to +50 ^{0}C
Relative Humidity	90% Non-Condensing

VI. Measurement Set-up

To measure the conducted EMI noise, the following equipments are mandatory;

1. Line Impedance Stabilization Network (LISN). A 50 Ohms impedance was selected as per EN61000-6-4
2. A ground plane with sufficient geometry to provide a good earth grounding for the LISN
3. Compliant spectrum analyzer used to display the measured noise spectrum in frequency domain.
4. A software application that interface the spectrum analyzer for data logging and processing.

The measurement setup is shown in Figure 9

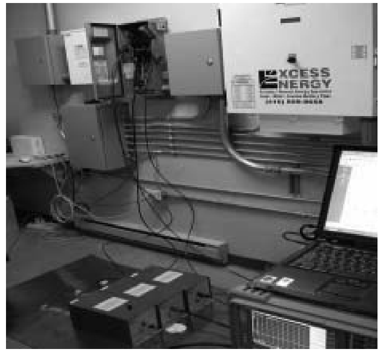

Fig. 9 Conducted emissions Test setup

VII. Experimental Results and Discussion

First measurements were conducted on the PV system to measure the conducted ambient noise at the disconnect box of the DC side of the inverter with the following test conditions

- LISN is placed on the inverter DC side.
- The input DC power to the inverter is disconnected.
- The inverter module is idle.
- The AC side (grid side) is disconnected.

The corresponding result of the EMI noise spectrum, as per EN61000-6-4 standards, is shown in Fig. 10.

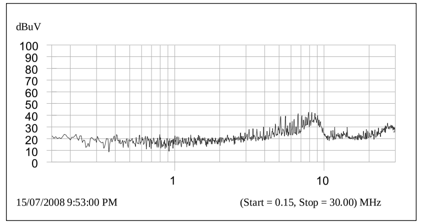

Fig. 10 Ambient EMI noise at the inverter DC side

As it can be seen from the graph, the swept frequency spectrum shows background noise up to 4MHz. however, there are some peaks 8 MHz, which are originated from DC cable external EMI noise coupling, at half and quarter wavelength resonance frequencies.

The second measurement was taken at the grid side, specifically, at the primary of the isolation transformer, with the inverter shutdown, but the main breaker to the grid power network was kept closed, the LISN is connected on the inverter AC side. This is shown in Figure 11.

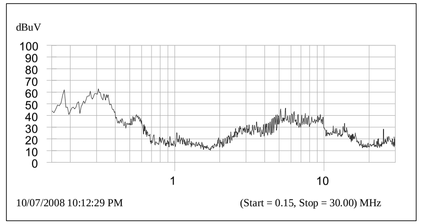

Fig. 11 Conducted EMI spectrum at the grid side with inverter shutdown and DC side disconnected

The frequency spectrum of Figure 11 shows low frequency interference conducted noise coming from the AC power grid due to switching load s in the power network. Note that the noise picked up by the DC external cables, seen in Figure 10, is amplified, due to the mismatch impedance between the line filter and the power grid, as detailed in section 4 of this paper.

Third measurement was taken at the inverter DC side to see the EMI noise that is coming from the inverter module and the power grid, with the following conditions

- LISN is placed on the DC bus of the PV system.
- The input DC power to the inverter is connected.
- The inverter module is operational.
- The AC side (grid side) is connected.
- Maximum PV power throughput.

The corresponding result of the EMI noise spectrum, as per EN61000-6-4 standards, is shown in Figure 12.

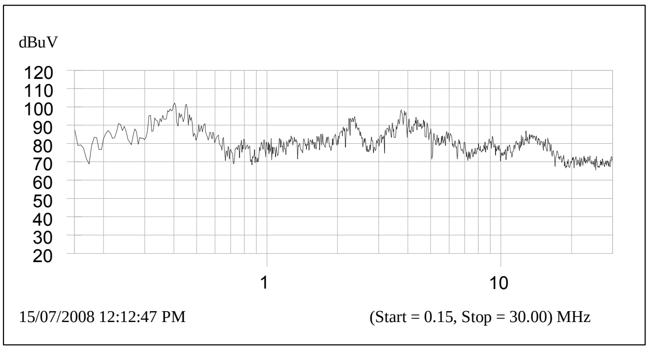

Fig. 12 EMI noise spectrum with PV system fully operational; LISN placed at the DC side of the inverter

The noise frequency spectrum measurement reveals significant conducted EMI noise that is generated within the power grid and the inverter module and exceeds the applicable generic emission standards for fixed installation. The installation of the line filter at the output of the inverter provides a poor noise attenuation performance, due to the impedance variations of the power grid which results in the amplification of the EMI noise which is propagated in the PV system. However, an EMI filter at the DC side of the inverter is required to attenuate excessive conducted electromagnetic noise.

A final measurement was done at the grid side, to see the amount of EMI noise generated from the inverter. The measurement was done under these conditions.

- LISN is placed on the AC side of the inverter, specifically, at the primary side of the isolation transformer.
- The input DC power to the inverter is connected.
- The inverter module is operational.
- The AC side (grid side) is connected.
- The time of testing was done at maximum PV power throughput.

The results are shown in Figure 13.

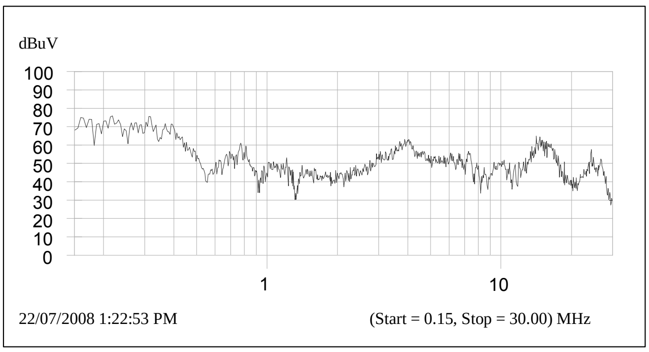

Fig. 13 EMI noise spectrum with PV system fully operational; LISN placed at the AC side of the inverter

The frequency sweep of the EMI noise at the AC side of the inverter indicates that there is a significant EMI noise generated in the inverter and reflected back to the grid system. This performance degradation is due to the poor design or selection of the line filter. Hence, a good evaluation of the grid impedance is important, in selecting the proper line filter.

VIII. CONCLUSION

The classification of the PV system for EMC testing is a debatable issue. However, by knowing the type of configuration of the PV system as being a stand alone or a grid-tied, the PV system can be classified as a fixed installation or a set of apparatus as defined by the new EMC Directives. In this paper the PV system is a grid-tied configuration and it is considered as a fixed installation. Therefore, the generic emissions standards were applied.

The effect of the grid impedance on the line filter performance is significant and it must be evaluated when selecting the line filer. The conducted EMI measurements reveal significant emissions generated by the inverter module and propagated back to DC side of the PV system. This requires an additional EMI filter at the input side of the inverter.

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REFERENCES

[1] M.C. Di Piazza, C. Serporta, G.Tine, G. Vitale, "Electromagnetic compatibility characterization of the DC side in a low power photovoltaic plant", IEEE ICIT '04, IEEE International Conference on Industrial Technology, 2004. Volume 2, 8-10 Dec. 2004 Page(s):672 - 677 Vol. 2

[2] C. Bcndel, T. Degner, N. Heme, Jorg Kirchhof, G. Klein, H. Lange, C. Trousseau, W. Enders, C. Halter, P. Scheibenreiter, P. Wurm, P. Clam, C. Metzger, A. Schulbe, H. Daub, K. Stanley, "EMC and Safety Design for Photovoltaic Systems", ESDEPS, Publishable Final Report, Version 28. March 2002,

[3] H. Uarberlin, "New DC-LISN for EMC Measurements on the DC side of PV systems", Realization and first measurements at inverters", 17th European Photovoltaic Solar Energy Conference, Munich, Germany, Oct 22-26 2001.

[4] N. Henze, G. Bopp, T. Degner, H. Haberlin and S. Schattner, "Radio Interference on the DC Side of PV Systems Research Results and Limits of Emissions" 17th European Photovoltaic Solar Energy Conference, Munich, Germany, Oct 22-26 2001.

[5] IEC EN61000-6-4:2006 Electromagnetic Compatibility generic emission standard part 6-4: Generic Standards – Emission standard for industrial environments.

[6] Official Journal of the European Union, Directive 2004/108/EC of the European Parliament and of the Council, 15 December 2004