Investigation of High Frequency Emissions (Supraharmonics) from Small, Grid-tied, Photovoltaic Inverters of Different Topologies

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***Abstract*—Due to the increasing number and capacity of grid connected power electronic interfaces associated with distributed generating systems, there is increasing concern on the associated power quality problems. Amongst these, high frequency (HF) emissions (referred to as Supraharmonics) in the range $2-150$ kHz has become a topic of growing interest within power quality research communities. An increasingly prominent grid connected devices which can contribute to these HF emissions are the photovoltaic (PV) systems. In this paper, HF emissions from seven small (output power $\leq$ 10kW), grid-tied, photovoltaic inverters (both single phase inverters and three phase inverter composed of three single phase inverters) are analysed using measurements carried out under controlled conditions in laboratory environments. It is shown that under fixed network conditions, these HF emissions are affected by the MPPT (Maximum Power Point Tracking) voltage and the output power level of the PV inverter. Moreover, a strong correlation between the behaviour of HF emissions and the topologies of inverters was observed; an important factor in developing high frequency models of PV inverters.**

***Index Terms*—Power quality, High Frequency (HF) emissions, Supraharmonics, PV inverters, Inverter topology**

I. Introduction

Due to the increasing number and power levels of power electronic interfaces and the use of power line communication (PLC) for smart meter reading, emissions in the frequency range 2-150 kHz (also referred to as high frequency (HF) emissions or supraharmonics) in electrical distribution systems are on the rise [1], [2]. As a result, the number of complaints relating to these emissions have gradually increased [3]. Amongst the possible repercussions of HF emissions, malfunctioning of equipment, interference with PLC communication and lifetime degradation of other connected equipment are prominent [3]–[5].

HF emissions can be categorized into two main types, namely, intentional emission and unintentional emission [3]. Whilst intentional emission is mainly related to PLCs, unintentional emissions correspond to HF emissions from power electronic interfaces such as PV inverters [6].

It is not long ago that an interest on HF emissions in electrical distribution systems was seen among the power quality research groups. So far, many research attempts have been taken to study the HF emissions from small, grid-tied PV inverters [7]–[9]. Many of these are based on field measurements and thus the scope of studies has been limited. In [10], the outcomes of controlled experiments carried out in laboratory environments using small, single phase, grid-tied PV inverters to investigate the factors affecting the HF emissions are presented. However, this study is limited only to three PV inverters and no attention is paid to the topology of the tested inverters.

The work presented in the paper is aimed at developing an understanding on the dependency of HF emissions from inverters of different topologies that presently exist. The results presented relating to seven small, grid-tied PV inverters tested under fixed network conditions are expected to be an important step towards modelling PV inverters for HF studies.

II. Theoretical Background

A. HF Emissions from PV Inverters

Almost all commercially available single phase, grid-tied PV inverters in the market today are of the self-commutated type and use PWM (Pulse Width Modulation) switching to produce a sinusoidal voltage at the output. This PWM switching is done at high frequencies releasing HF emissions into the grid. There are numerous types of PWM strategies available to date. However, the basics behind many PWM techniques are more or less similar. The output of a single phase inverter using natural, unipolar PWM is described in (1). The first term on the right hand side corresponds the desired output voltage from the inverter while the HF emissions are described by the second term [11].

$$V_{out} = V_{dc} M \cos(2\pi f t) + \frac{2V_{dc}}{\pi} \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \frac{J_{2n-1}(mM\pi)}{m} \cos((m+n-1)\pi) \cos[4\pi m f_s t + 2\pi(2n-1) f t] \quad (1)$$

978-1-5386-0517-2/18/$31.00 2018 IEEE

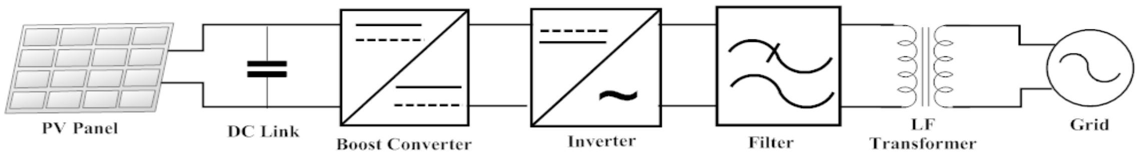

Fig. 1. Topology of a PV inverter with a Low Frequency Transformer

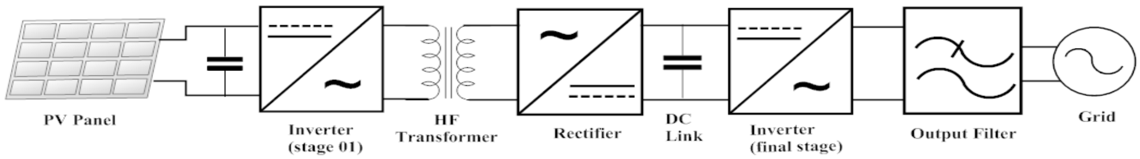

Fig. 2. Topology of a PV inverter with a High Frequency Transformer

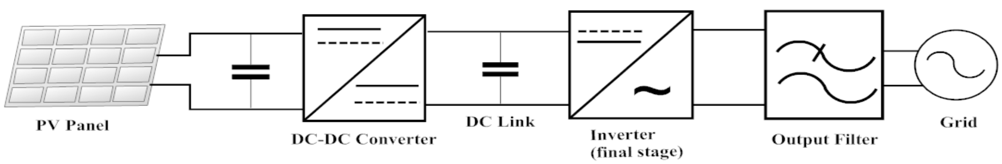

Fig. 3. Topology of a transformer-less PV inverter

$M \approx \frac{\sqrt{2}\ V_{grid}}{V_{dc}}$
V_{out} : output voltage
V_{dc} : DC link voltage
V_{grid} : grid voltage (RMS)
M : modulation index
f : grid frequency
t : time
J_{2n} : Bessel function of order 2
f_s : switching frequency

B. Topologies used in small, grid-tied photovoltaic inverters

1) PV inverters with low frequency transformers (LF inverters): As can be seen from Fig. 1, the DC power from the PV array is first boosted up by the boost converter (optional) before being converted into AC power at 50Hz or 60Hz using a low frequency (LF) inverter. The low frequency transformer provides galvanic isolation between the PV modules and the grid. Due to the use of this LF transformer, these inverters are large in size, heavy, more expensive and less efficient compared to other types of inverters [12]. However, they are considered durable, less likely to emit DC currents and feature a high peak power capacity making them more suitable for off-grid applications with high power requirements.

2) PV inverters with high frequency (HF) transformers (HF inverters): In this type of inverters (Fig. 2), the DC power from the PV array is first converted to high frequency AC. Then a HF transformer is used to boost the low voltage to a higher voltage. However, as the frequency of this AC voltage is much greater than that of the grid, a further conversion step is needed where it is converted to a DC voltage using a rectifier. The final inverter stage produces a waveform with a voltage and frequency suitable for grid connection. Due to the usage of the HF transformer, these inverters too provide galvanic isolation. Moreover, these are light, compact, inexpensive and feature a higher efficiency compared to the inverters with LF transformers.

3) Transformer-less PV inverters: In this topology (Fig. 3), a transformer is not used. Instead, a DC-DC converter is used to boost the DC voltage from the PV array to a voltage level greater than the peak-peak value of the nominal grid voltage. This DC voltage is then converted to an AC voltage that matches the grid voltage and frequency in the inverter stage. As no galvanic isolation is present, these PV inverters use other means to minimize the ground leakage current. Further, due to the absence of a transformer, this type of inverters are more efficient, light, compact and inexpensive compared to their counterparts [12]. Due to these advantages, the current market trend is towards transformer-less inverters. The other types described above, at least in the case of rooftop applications, can be expected to phase out over a period.

III. Experimental Framework

A. Experimental Setup

Due to their obvious advantages over on site field measurements, it was decided to conduct controlled experiments in laboratory environments. Seven commercially available small (output power $\leq \mathbf{10}$ kW), grid-tied PV inverters were selected covering all three PV inverter topologies described above. The objective of the experiments was to study the HF emissions from the PV inverters of different topologies.

TABLE I
DETAILS PERTAINING TO THE TESTED PV INVERTERS

Inverter Name	Inverter Topology	Output Power (kW)	Maximum Power Point Tracking Voltage Range (V)
Inverter A	LF Transformer	4.6 (1 phase)	260-585
Inverter B	HF Transformer	2.5 (1 phase)	230-500
Inverter C	HF Transformer	2.6 (1 phase)	175-560
Inverter D	Transformer-less	3.0 (1 phase)	200-500
Inverter E	Transformer-less	3.6 (1 phase)	165-530
Inverter F	HF Transformer	10 (3×1 phase)	230-500
Inverter G	Transformer-less	4.6 (1 phase)	175-500

Some measurements were carried out at the University of Wollongong (UOW), Australia, and some were carried out at the Technische Universitaet Dresden (TUD), Germany. The details of the PV inverters used in the experiments are given in Table I.

The experimental setup used at UOW is shown in Fig. 4. Each PV inverter was connected to a programmable waveform generator, while the waveform generator was operated in the regenerative mode. In this mode, the waveform generator provides a 50Hz/230V reference signal while absorbing the generated power of the PV inverter (the waveform generator acts as an ideal grid). A PV emulator was used to provide the necessary DC supply to the inverter. A similar experimental set-up was used at TUD.

The entities that could affect the HF emissions from the PV inverters were identified as the Maximum Power Point Tracking (MPPT) voltage, power output of the inverter, grid voltage magnitude and frequency, grid impedance at the emission frequencies and the background distortion levels of the grid. Since the objective of the experiments were to study the HF emissions from PV inverters governed by their topology, it was decided to maintain uniform network conditions across all the inverters.

A sinusoidal reference voltage of 230V/50Hz with low distortion levels was maintained at the output of all the inverters (less than 2mV at all HF emission frequencies of the inverters). The impedance introduced between the programmable generator and the PV inverter is based on the line-to-neutral loop impedance as defined in IEC 60725 for low voltage installations rated less than 75A (i.e.$(0.4 + j0.25)\Omega$ at 50Hz) [13]. However the reactive part would significantly change for different switching frequencies and would result in unrealistic high values at higher frequencies. For instance, it would yield an impedance of $(0.4 + j80)\Omega$ at 16kHz and $(0.4 + j100)\Omega$ at 20 kHz. In order to keep the impedance for different tested inverters as constant as possible, only the resistive part of reference impedance was used to ensure consistency in the test outcomes. With this, aim was to ensure that the HF emissions measured are not influenced by the frequency dependent inductive reactance.

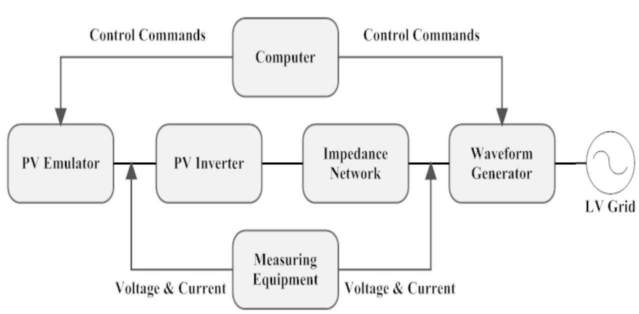

Fig. 4. Measurement and Control Setup

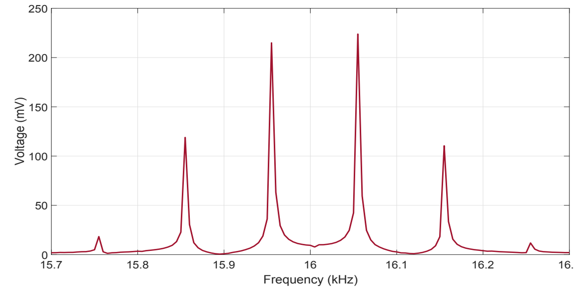

Fig. 5. The first HF emission band of inverter C

In the first set of experiments, each inverter was operated at its rated power under varying MPPT voltages. The MPPT voltage was varied in the full range as specified in the technical data sheet of each inverter. In the second set of experiments, the output power of each inverter was gradually varied keeping the MPPT voltage constant. This was repeated for different MPPT voltages equally separated in the full range.

B. Measurements and Data Analysis

The input voltage, current and power to PV inverters were monitored throughout the experiment using a power quality data logger. The output voltage and current were recorded using a transient recorder (Fig. 4). The sampling rate and measurement time period were selected to be 1MS/s and 200ms respectively [14]. After being high pass filtered to remove the low frequency emissions, data was analysed using Fast Fourier Transform (FFT) that resulted in a 5Hz spectrum [15].

HF emissions from PV inverters occur in frequency bands each containing further side bands. Here, only the first emission band was considered as it accounts for more than 90% of the total HF emission of single phase inverters [10]. As illustrated in Fig. 5, the first HF emission bands of the tested

TABLE II
CENTER FREQUENCIES AND THE MAXIMUM OBSERVED HF EMISSIONS FROM THE TESTED PV INVERTERS

Inverter name	Inverter topology	Centre frequency of the first emission band (kHz)	Maximum HF emission observed during the test (mV)
Inverter A	LF Transformer	8	17
Inverter B	HF Transformer	20	263
Inverter C	HF Transformer	16	380
Inverter D	Transformer-less	21	1122
Inverter E	Transformer-less	25	1225
Inverter F	HF Transformer	20	454
Inverter G	Transformer-less	16	931

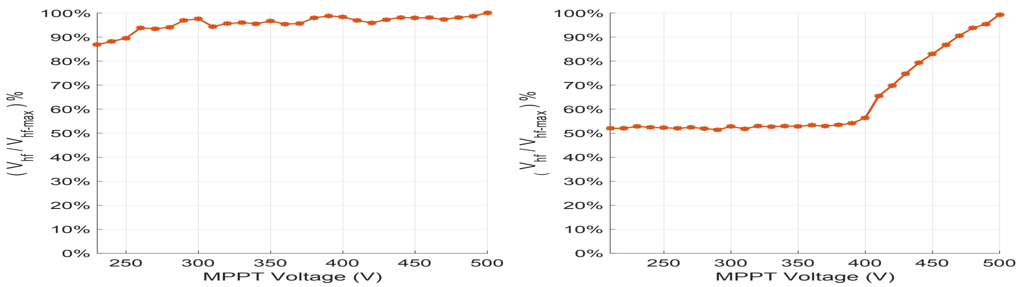

Fig. 6. Left: V_{dc} - type 01 behaviour, Right: V_{dc} - type 02 behaviour (Graphs are based on data for inverter C and E, respectively)

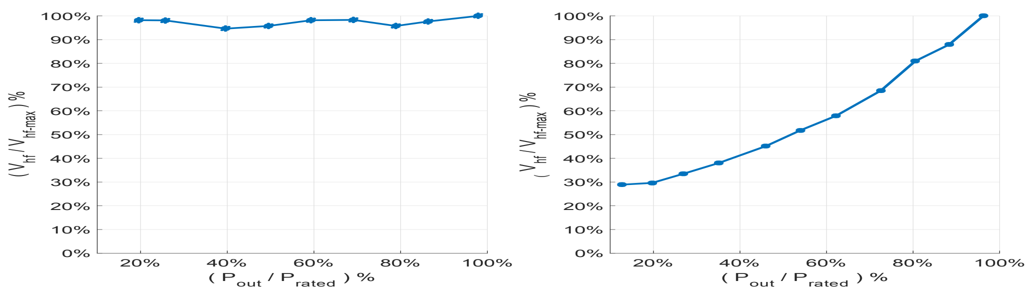

Fig. 7. Left: P_{out} - type A behaviour, Right: P_{out} - type B behaviour (Graphs are based on data for inverter C and E, respectively)

inverters were visible as distinct frequencies symmetrically distributed around one frequency that will henceforth be referred to as the centre frequency. For the ease of further analysis, these emissions were aggregated into one frequency band with a bandwidth of 800Hz centred at this frequency (for instance, the centre frequency of Fig. 5 is 16 kHz). For an inverter with a centre frequency of f_{hf} kHz, the aggregated HF voltage emissions can be calculated according to (2) [15]. A 5Hz margin was kept at the lower frequency limit to centre the frequency band at f_{hf}.

$$V_{hf} = \sum_{f=f_{hf}-395}^{f=f_{hf}+400} |V_f|^2 \tag{2}$$

IV. Experimental Results

Table II shows the maximum HF emission observed from each PV inverter during the experiment. As expected, based on the high frequency attenuation properties of transformers, the least HF emissions were observed from the low frequency inverter, moderate HF emissions from the high frequency inverters and the highest HF emissions from the transformer-less inverters.

A. Relationship between HF emissions and the MPPT voltage

The HF emissions from the tested PV inverters demonstrated two different types of behaviours with varying MPPT voltage level. In the first type of behaviour observed (henceforth referred to as V_{dc} - type 01 behaviour), the HF emissions are more or less constant throughout the entire MPPT voltage range.

In contrast to the first type of behaviour, the second type of behaviour (henceforth referred to as V_{dc} - type 02 behaviour) demonstrates a high dependency of HF emissions on the MPPT voltage. The HF emissions are constant upto a certain MPPT voltage level, and then increases linearly with the increasing MPPT voltage. The change of HF emissions throughout the entire MPPT voltage range is around 50% of the highest HF emission of the inverter (Fig. 6).

B. Relationship between HF emissions and the output power of the inverter

The behaviour of HF emissions from the tested PV inverters with the varying output power level too can be categorized into two types, henceforth referred to as P_{out} - type A behaviour and P_{out} - type B behaviour. In P_{out} - type A behaviour, no significant change of HF emissions can be seen with the varying output power. However, the PV inverters demonstrating P_{out} - type B behaviour shows a significant variation of HF emissions with the changing output power levels (Fig.7). In both cases, the MPPT voltage was maintained at the maximum value permitted for each inverter.

The PV inverters that show no change in HF emissions with the varying output power at the highest MPPT voltage do not show any appreciable variation of HF emissions at other MPPT voltages as well. However, the curves of $(V_{hf}/V_{hf-max})\%$ which illustrate the variation of HF emissions with the MPPT voltage of other inverters demonstrate that high output power levels lead to higher emission levels as evident from Fig. 8.

V. Discussion

Table III presents a summary of experimental results for all the tested PV inverters.

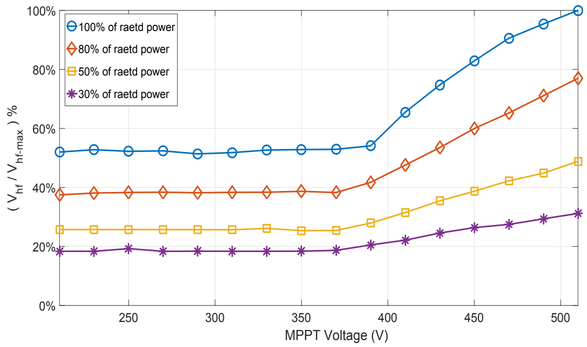

Fig. 8. Behaviour of HF emissions from inverter E (Belonging to V_{dc} -type 02) at varying MPPT voltage and output power levels

A. Analysis of experimental results

1) Behaviour of HF emissions with varying MPPT voltage: An important observation can be made based on the results presented in Table III. The PV inverters exhibiting V_{dc} - type 01 behaviour are inverters with transformers. All the other PV inverters with V_{dc} - type 02 behaviour are transformer-less inverters. This sheds light to an important question as to whether the topology of the PV inverter has an impact on the behaviour of its HF emissions.

Obviously, the HF emissions from a PV inverter is largely governed by its final inverter stage. The HF emissions which arise as a result of this final inverter stage depends heavily on the DC voltage it receives as the input. Moreover, the damping provided by the output filters or any other components of the PV system too plays an important role in determining the level of HF emissions propagating into the grid.

Regarding transformer-less inverters, when the MPPT voltage is low, the DC-DC converter boosts the DC voltage to a constant value. Once the MPPT voltage exceeds this value, the operation of the DC-DC converter is no longer required, thus the voltage supplied to the final inverter stage steadily increases with the increasing MPPT voltage. This increase in DC voltage to the final inverter stage is reflected as an increase in the HF emissions giving rise to V_{dc} - type 02 behaviour.

In contrast, the final inverter stage of PV inverters with HF transformers receive a reasonably constant DC supply due to the operation of the HF transformer, thus producing more or less constant HF emissions throughout the entire MPPT voltage range demonstrating V_{dc} - type 01 behaviour.

TABLE III
BEHAVIOUR OF HF EMISSIONS FROM PV INVERTERS WITH MPPT VOLTAGE AND OUTPUT POWER OF THE INVERTER

Inverter name	Inverter topology	Behaviour related to the MPPT voltage	Behaviour related to the output power of the inverter
Inverter A	LF Transformer	Vdc_type_01	Pout_type_A
Inverter B	HF Transformer	Vdc_type_01	Pout_type_B
Inverter C	HF Transformer	Vdc_type_01	Pout_type_A
Inverter D	Transformer-less	Vdc_type_02	Pout_type_A
Inverter E	Transformer-less	Vdc_type_02	Pout_type_B
Inverter F	HF Transformer	Vdc_type_01	Pout_type_B
Inverter G	Transformer-less	Vdc_type_02	Pout_type_A

Only one PV inverter with a LF transformer was available for testing. It exhibited a very close resemblance to V_{dc} - type 01 behaviour, however the HF emissions were very low due to the use of a low frequency transformer (less than 20 mV).

2) Behaviour of HF emissions with varying output power of the inverter: The HF emissions from the tested PV inverters showed two types of behaviours with varying output power, namely P_{out} - type A behaviour and P_{out} - type B behaviour. This can be due to the characteristics of the internal impedance of the PV inverter at HF emission frequencies. A PV inverter having a non-linear internal impedance at high frequencies could show a high dependency of HF emissions with the output power of the inverter (P_{out} - type B behaviour), while another inverter with a fairly constant internal impedance at high frequencies would simply exhibit P_{out} - type A behaviour. However, no relationship between the topology of the inverter and the behaviour of its HF emissions with the varying power level was observed.

B. Future Work

HF emissions measured at equipment terminals fall into two basic types; primary emission generated by the equipment itself, and secondary emission drawn from the neighbouring equipment [1]. In the work reported in this paper, only the primary HF emissions generated from the selected PV inverters were explored. Regarding this particular experiment, the first emission bands of the tested PV inverters did not coincide with the peaks of the secondary HF emissions (noise) arising from the waveform generator. However, this may not be the case in other situations or in different experimental platforms. Thus, it is important to determine the specifications of a standard test set-up to perform accurate and reliable laboratory measurements to determine primary emission levels.

All inverters were tested under fixed network conditions for the ease of comparison. However, when connected to a real low voltage network, many factors such as the variations in grid voltage and frequency, existing waveform distortion levels and network impedance at the point of connection should be taken into consideration in determining the level of HF emissions propagating into the grid.

In the experiment conducted, only single phase inverters (In addition to a three phase inverter formed using three single phase inverters) were tested to explore their HF emissions. As was described earlier, the majority of HF emissions from single phase PV inverters occur at their first emission band. However, HF emissions from three phase inverters differ from that of single phase inverters [11]. They can emit significant HF emissions at other emission bands as well (Fig. 9). Therefore, one important future work is quantifying and analysing the HF emissions of three phase PV inverters.

Moreover, it was suggested that the behaviour of HF emissions from a PV inverter at varying output power levels could be due to the linearity/non-linearity of the internal impedance

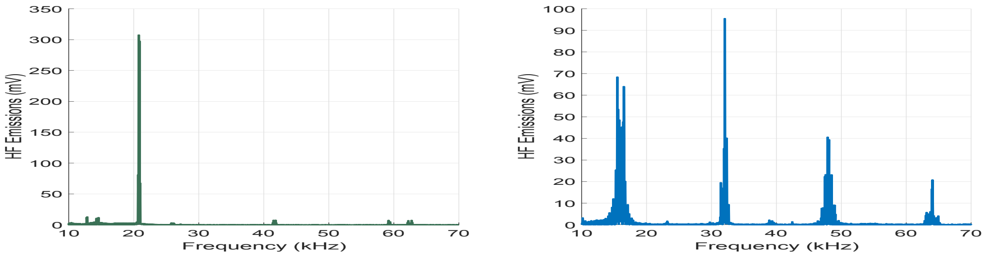

Fig. 9. HF emissions from a single phase PV inverter (left) and a three phase PV inverter (right)

at its emission frequencies. This has to be further explored before drawing any rigorous conclusions.

VI. Conclusion

In this paper, results of laboratory experiments carried out to determine the behaviour of HF emissions from small (output power $\leq$ 10kW), grid-tied single phase PV inverters under fixed supply conditions were presented. The HF emissions were found to be lowest in the case of low frequency inverters, and are moderate for high frequency inverters and highest in the case of transformer-less inverters. These observations are in line with the high frequency attenuation properties of transformers.

Furthermore, the HF emissions from the tested PV inverters demonstrated two types of behaviours with varying MPPT voltage levels, one constant (V_{dc} - type 01 behaviour) and one varying (V_{dc} - type 02 behaviour). They also exhibited two distinctive behaviours with the varying output power level of the inverter referred to as P_{out} - type A behaviour (constant HF emissions) and P_{out} - type B behaviour (varying HF emissions).

Further, the analysis of results suggested that there exists a relationship between the topology of the inverter and the behaviour of HF emissions with the MPPT voltage. All inverters with transformers (HF inverters and LF inverters) show a reasonably constant HF emission level throughout the entire MPPT voltage range (V_{dc} - type 01 behaviour). All transformer-less inverters exhibit V_{dc} - type 02 behaviour, where there is a strong dependency of HF emissions on the MPPT voltage.

No relationship could be found between the topology of the inverter and the behaviours of HF emissions with the varying output power level. However, it is suggested that this can be attributed to the linearity or non-linearity of the internal impedance of the PV inverter at its HF emission frequencies and should be explored further.

This work was mainly aimed at better understanding the HF emissions from small, grid-tied, single phase PV inverters. The analysis of results can be further utilised in developing HF models of PV inverters. Based on the observations made, it is recommended that the maximum MPPT voltage and the rated output power are accommodated in determining the maximum allowable HF emission limits for standardisation purposes.

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