Harmonic Content of Power Grids with Distributed PV Systems

IEEE PES DLP

Panama Chapter

Research Seminar

9:00-10:00 hrs

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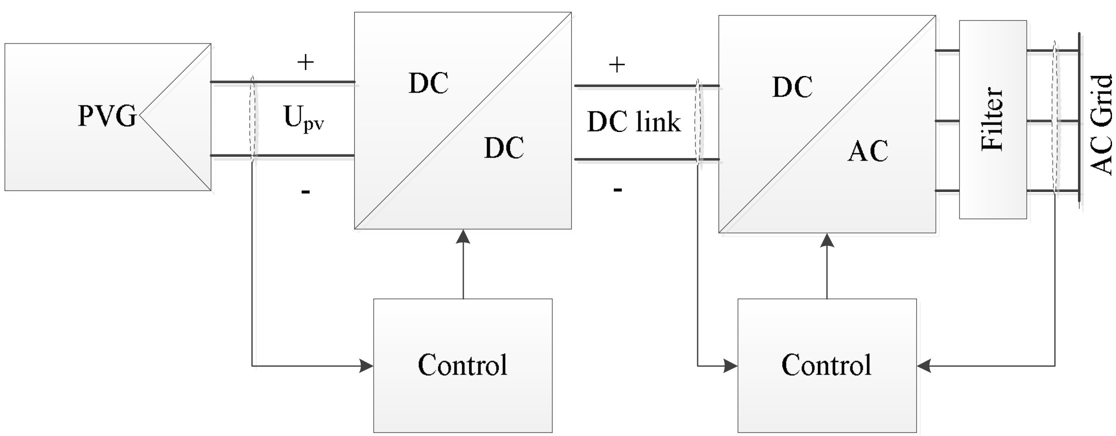
The Photo-Voltaic Generator

- A photovoltaic system transforms solar radiation into electrical energy using so-called PV panels. Power electronics equipment is used to enable connection to the AC power grid as well as to facilitate maximum power extraction from the available solar irradiation
- However, an undesirable characteristic of the equipment used is that the current and voltage waveforms at the point of common coupling (PCC) with the power grid contain a degree of harmonic distortion which, in some instances, may surpass the level recommended by existing standards



The Photo-Voltaic Generator

- It is stated that the current total harmonic distortion in photovoltaic systems should be less than 5%. Individual current harmonic limits are presented in the table below

Odd Harmonics	**Distortion Limit**
3rd-9th	<4.0%
11th-15th	<2.0%
17th-21st	<1.5%
23rd-33rd	<0.6%
Above the 33rd	<0.3%

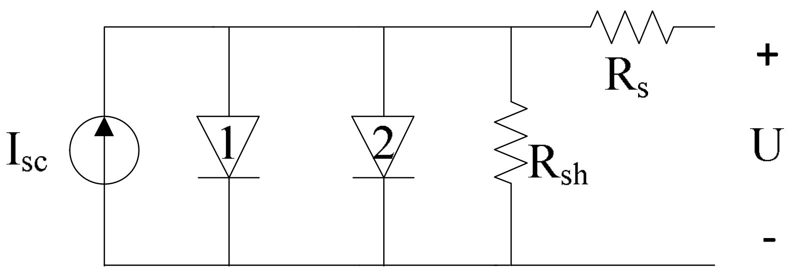
- Research has been carried out by some researchers on the impact of environmental factors and pulse width modulation (PWM) control methods, on the current harmonic injection at the PCC produced by one and two photovoltaic units
- Further to the harmonic issue, there is one key performance-related issue which remains unresolved and requires an in-depth investigation. It relates to the control performance under conditions of partial shading

The Research's Aims

- To assesses further the impact of environmental and operational conditions on PV generators, more realistic equipment and operational conditions are incorporated in the analysis
- Further to the impact of irradiance; imperfect conditions of the filtering system, loading imbalances, selection of inverter switching frequency, the presence of resonance conditions and the choice of maximum power point tracking (MPPT) controller; were all comprehensibly investigated
- The research casts additional light into the here-to-fore, little researched problem of the inter-harmonics produced by PV generators. It pinpoints at what are the main environmental and operational factors responsible for the amplification of inter-harmonics
- The research demonstrates that the use of a well-designed filtering system is of paramount importance to maintaining the operational integrity of the PV plant under a wide range of non-ideal but credible operating and environmental conditions, except in cases when the AC equivalent circuit at the PCC exhibits an excitable resonance

The Model of the Photo-Voltaic Panel

- A basic PV cell circuit model comprises an ideal current source and two diodes; one representing the dark saturation currents due to electrons recombination in the quasi-neutral and the depletion regions, respectively
- The width of the depletion region is relatively small compared to the quasi-neutral region, and it is usually neglected when modelling the cell. In addition the actual photovoltaic cell also has parasitic elements, namely parasitic shunt and series resistance, as shown in the figure below
- The main origin of the parasitic series resistance is the metal contacts and the transverse flow of current. The reason behind the parasitic shunt resistance is the p-n junction and impurities near the junction.



The Model of the Photo-Voltaic Panel

- The I-V characteristic of the PV cell is given as:

$$I = I'_{SC} - I_{O1}\left(e^{\frac{q(U+IRs)}{kT}} - 1\right) - I_{O2}\left(e^{\frac{q(U+IRs)}{2kT}} - 1\right) - \frac{U+IRs}{Rsh}$$

  where I'_{SC} is the short-circuit current in case of no parasitic resistances, I_{O1} is the dark saturation current due to recombination in the quasi neutral regions, I_{O2} is the dark saturation current due to recombination in the depletion region, T is the temperature, k is the Boltzmann constant, q is the electron charge, U is the output voltage of the PV cell, R_{sh} is the parasitic shunt resistance and R_s is the parasitic series resistance

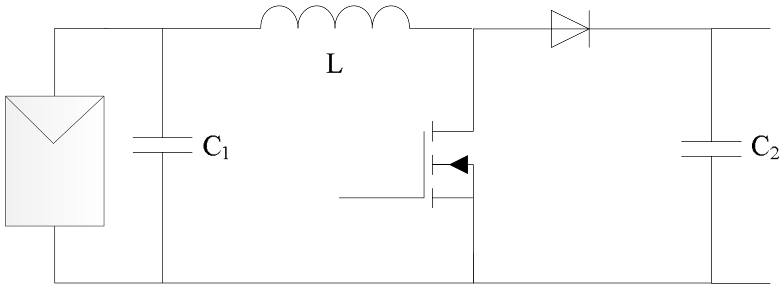
- For most simulation purposes, the PV cell model above reduces to the one-diode model:

$$I = I_{ph} - I_o\left(e^{\frac{(U+IRs)}{AU_t}} - 1\right) - \frac{U+IRs}{Rsh}$$

  where I_{ph} is the photocurrent, U_t is the thermal voltage and I_O is the diode saturation current.

The Model of the DC-DC Converter

- The electrical circuit of the Boost converter shown below is used in this research



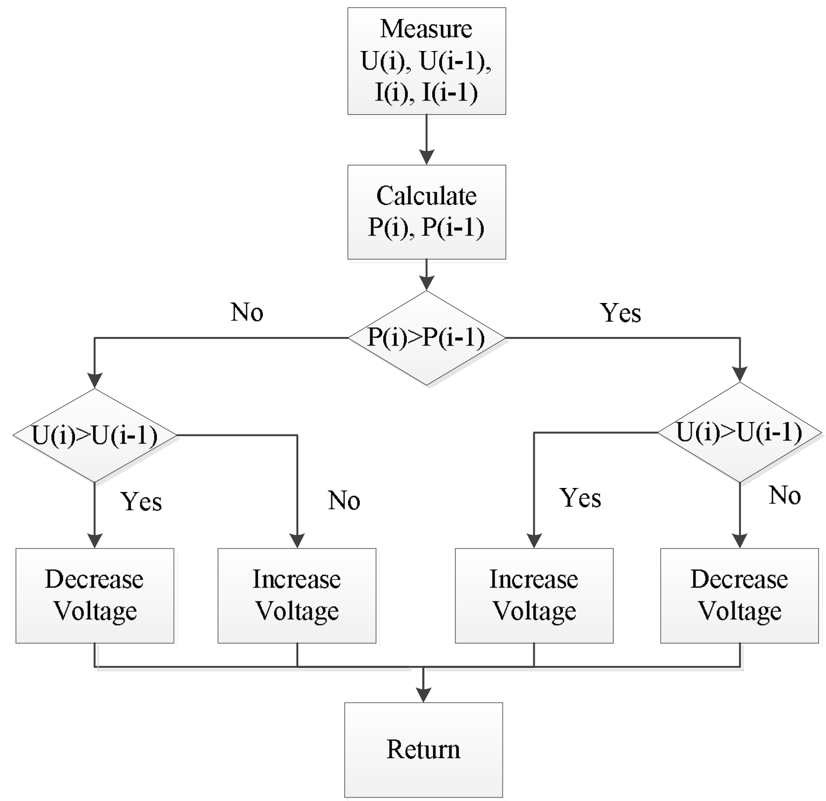
- The capacitor C_1 is added to the input in order to achieve a current fed topology. The main reason for using a current fed boost converter is that the control system regulates the voltage
- The current produced by the PV system is very sensitive to irradiance variations, which means that the PV current's fluctuations are large in scale and fast. Therefore control for such currents would require fast dynamics and it might lead to the controller saturation. It is said that changes in irradiance have relatively little effect on the output voltage

The Model of the DC-DC Converter

- The DC to DC converter is fitted with the Perturb and Observe (P&O) controller in order to achieve MPPT. The flowchart of the P&O method is shown below

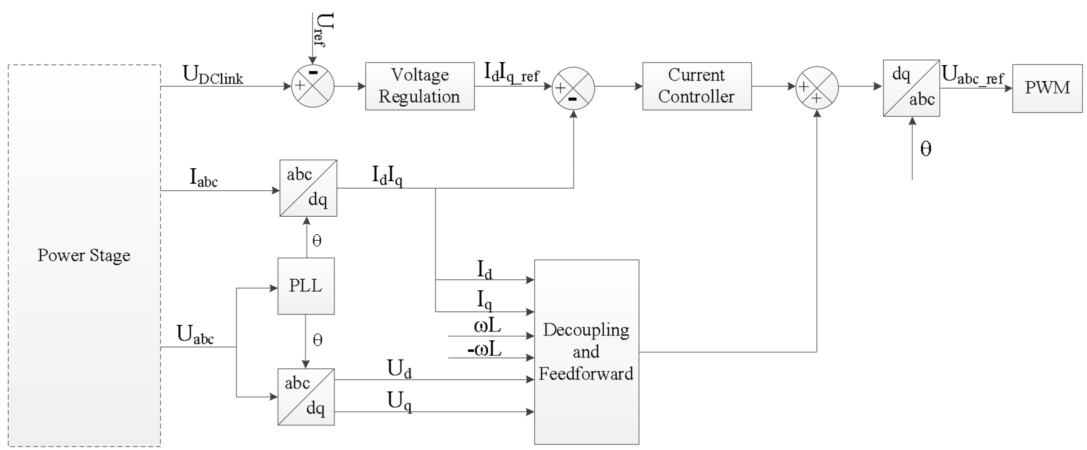
- The control system operates by periodically incrementing or decrementing (perturbing) the PV voltage and current and by comparing the new and the old powers to increase or decrease the duty cycle

- If the perturbation results in an increase of power then the direction of the perturbation pattern remains unchanged. In case of power decreases the sign of the perturbation reverses



The Model of Inverter

- The inverter model used in this work is a three-level neutral-point-diode-clamped. The inverter incorporates at its output an *LCL* filter, which yields good harmonic and ripple cancellation using small size components
- The DC-AC inverter is designed to operate in a grid-parallel mode, thus enabling maximum power injection and synchronization to the power grid operating voltage and frequency, where the grid-current is the inner loop and the DC-link voltage provides the feedback for the grid-current loop
- The controlling is done using the synchronous reference frame shown below



Simulation Results – One PV generator

- The PV system feeding into an infinite bus-bar via a connecting transformer. An *RL* shunt load sits between the infinite bus-bar and the transformer
- The main motivation behind this experiment is to gain fundamental insight into the main factors responsible for distorting the waveform in grid-connected PV systems. The environmental, design and operational factors considered are the following: solar irradiance, converter switching frequency, load unbalances, resonances in *RLC*-type loads, single-phase open-circuit faults in *LCL* filters and *LCL* filter deterioration
- The FFT algorithm is used to extract the harmonic content from the PV voltage and current waveforms. It is set to calculate the frequencies at every 2 Hz – notice that the ensuing frequency spectrums will show not only the harmonic terms but also all the inter-harmonic terms. Hence, the following expression is useful:

$$THD = \frac{\sqrt{I_{RMS}^2 - I_{RMS(1)}^2}}{I_{RMS(1)}} \cdot 100\%$$

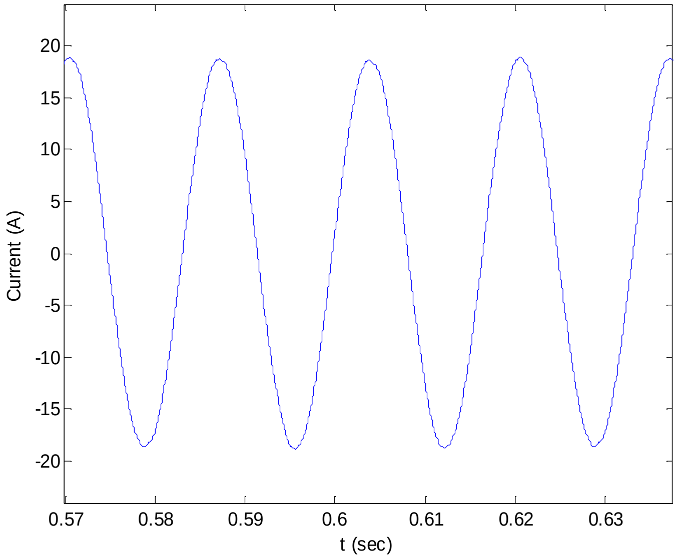
Simulation Results – One PV generator

where I_{RMS} is the sum of all harmonic components of current, including the fundamental and $I_{RMS(1)}$ is the fundamental component of current waveform

- Another common term used to assess harmonics is total demand distortion (TDD) which is calculated against the maximum load current or the rated/nominal current $I_{RMS(L)}$:

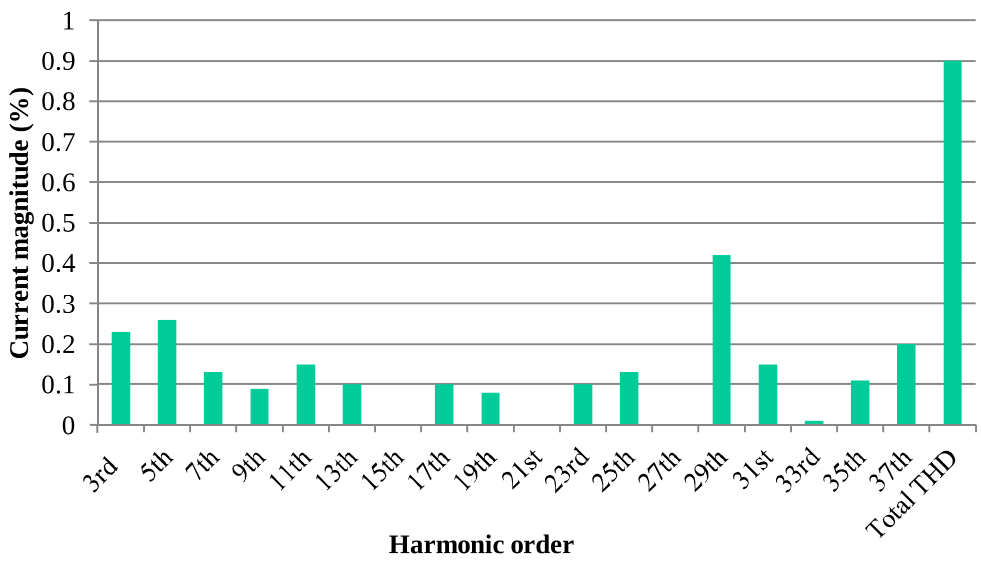
$$TDD = \frac{\sqrt{I_{RMS}^2 - I_{RMS(1)}^2}}{I_{RMS(L)}} \cdot 100\%$$

- The simulation results under normal operating conditions, i.e. irradiance of 1000 W/m^2, temperature of 25^{o}C, DC to DC converters switching at 5 kHz, DC to AC inverter switching at the 33rd harmonic (1980 Hz) and the associated filters in good working order, show quite a low level of THD



Simulation Results – One PV generator

- The data presented below shows that the harmonic emissions produced by a single PV array are much lower than the limits set by the IEEE 929 standard, i.e., the THD carries a value of 0.9%
- However, some individual harmonics cause some concern, especially the 29th, 31st, 35th and 37th. Further experiments are carried out in order to investigate potential problems



Simulation Results – One PV generator

The impact of switching frequencies on harmonic emissions

- Table I presents evidence that selection of the switching frequency is an important factor in designing PV inverters, since higher switching frequencies result in smaller THD values

Inverter switching frequency	Current THD (%)	Highest harmonics (%)			
2700 Hz	0.83	41st	43rd	47th	49th
		0.15	0.05	0.04	0.09
2340 Hz	1.37	35th	37th	41st	43rd
		0.24	0.09	0.06	0.13
1980 Hz	0.91	29th	31st	35th	37th
		0.42	0.15	0.11	0.20
1620 Hz	1.29	23rd	25th	29th	31st
		0.82	0.27	0.17	0.34
1260 Hz	2.53	17th	19th	23rd	25th
		1.84	0.52	0.32	0.62
900 Hz	4.61	11th	13th	17th	19th
		3.65	0.81	0.51	1.29

Simulation Results – One PV generator

The impact of switching frequencies on inter-harmonic emissions

- Moreover, unsuitable selection of the switching frequency may yield inter-harmonic generation close to the fundamental frequency, which will result in THD increases
- Data on the inter-harmonic generation is shown in the table below

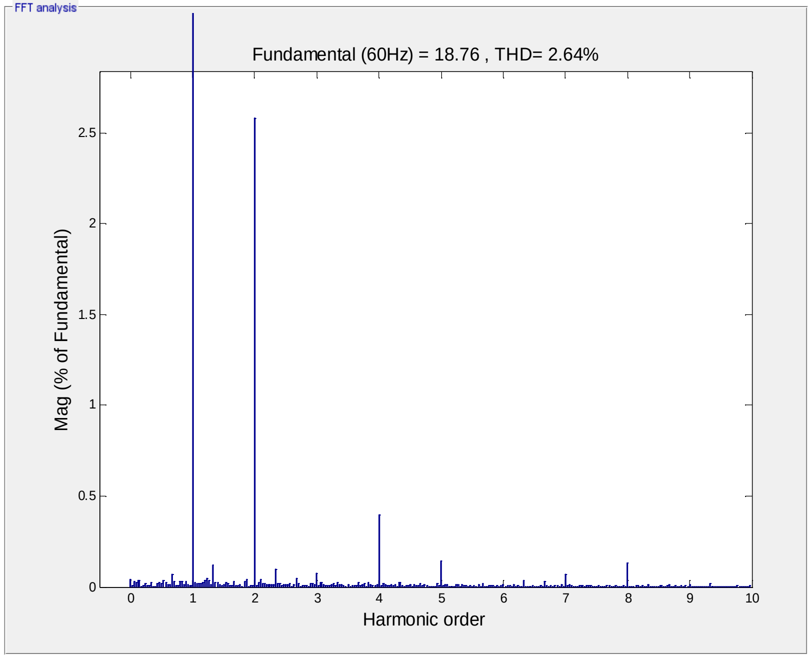
Harmonic content	*Inverter switching frequency (Hz)*					
	5000	2700	2340	1980	1620	900
20 Hz	0.00	0.15	0.07	0.03	0.06	0.24
100 Hz	0.01	0.08	0.18	0.03	0.04	0.11
140 Hz	0.02	0.08	0.09	0.05	0.06	0.13
220 Hz	0.01	0.03	0.08	0.04	0.01	0.05
260 Hz	0.01	0.04	0.08	0.04	0.05	0.08
340 Hz	0.00	0.04	0.03	0.03	0.03	0.07
380 Hz	0.01	0.04	0.05	0.03	0.06	0.12
Total inter-harmonic value	0.22	0.54	0.67	0.41	0.52	1.13
Note: Values are provided in amperes (A)						

Simulation Results – One PV generator

The impact of switching frequencies on inter-harmonic emissions

- The appearance of inter-harmonics is an intriguing problem and aiming at gaining some insight, the switching frequency of the inverter is set to be equal to the switching frequency of the switched-mode DC-DC converter (i.e. 5 kHz)

- It is noticed from the figure opposite that this action reduces the presence of the inter-harmonic terms very considerably. Even though these frequency terms are not completely eliminated, it can be appreciated that the inter-modulation of the two different switching frequencies employed in the DC-DC and DC-AC converters seems to be the main culprit



Simulation Results – One PV generator

<u>The impact of solar irradiance on harmonic emissions</u>

- The table below gives values of harmonics for different irradiances reaching the surface of the PV panel
- It can be appreciated that changes in irradiance can dramatically increase harmonic current production. In particular, harmonics emissions seem to be very susceptible to low levels of solar irradiance
- Low irradiance levels result in highly distorted current waveforms, pushing the THD levels above the accepted IEEE limits.

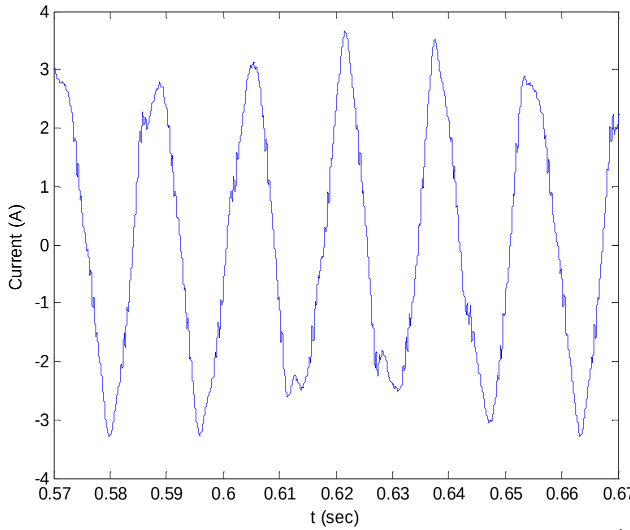
Irradiance levels	Current THD (%)	29^{th} (%)	31^{st} (%)	35^{th} (%)	37^{th} (%)
1000 W/m^2	0.91	0.42	0.15	0.11	0.20
500 W/m^2	1.56	0.77	0.47	0.33	0.37
200 W/m^2	14.48	2.37	2.04	1.42	1.14

Simulation Results – One PV generator

The impact of solar irradiance on harmonic emissions

- Such anomalous power quality indexes may be explained partly because of the definition available for the calculation of current THD and partly because of the larger values of inter-harmonics at low irradiance levels (here calculated as summation of peak values)
- Alternatively, the TDD is given in the table below for different irradiance levels
- The current waveform for the case of 200 W/m^2 is shown in the figure opposite

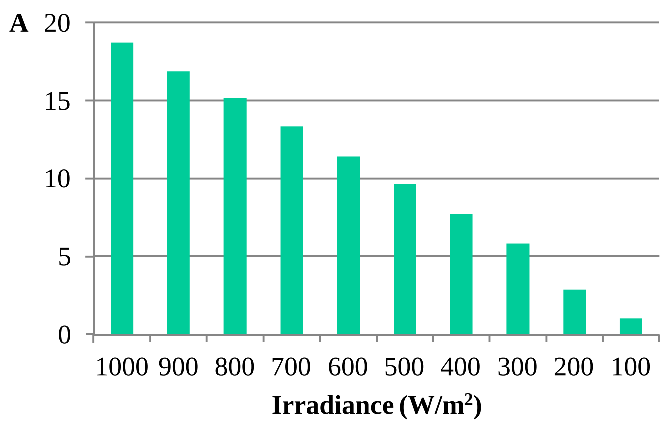
Irradiance levels	Current TDD (%)
1000 W/m^2	0.977
500 W/m^2	0.862
200 W/m^2	2.40

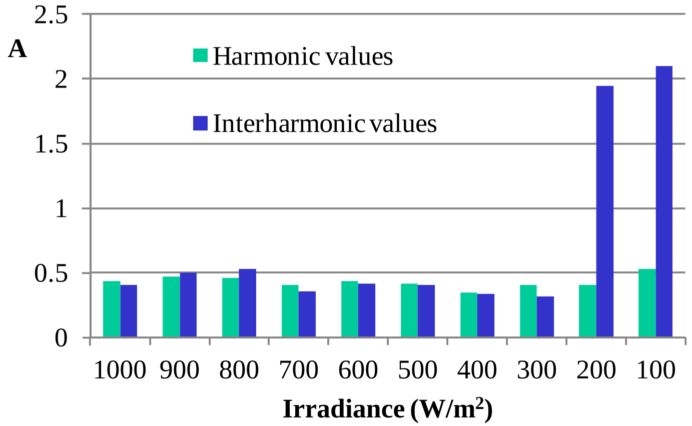


Simulation Results – One PV generator

The impact of solar irradiance on harmonic emissions

- As shown in the figures below, the harmonic values remains fairly constant but the fundamental component decreases significantly with decreasing irradiance
- There is at present no specific guidelines given by IEEE on inter-harmonics but it may be seen from the analysis that their levels increase significantly at low irradiance levels.





Simulation Results – One PV generator

The impact of imperfect filtering on harmonic emissions

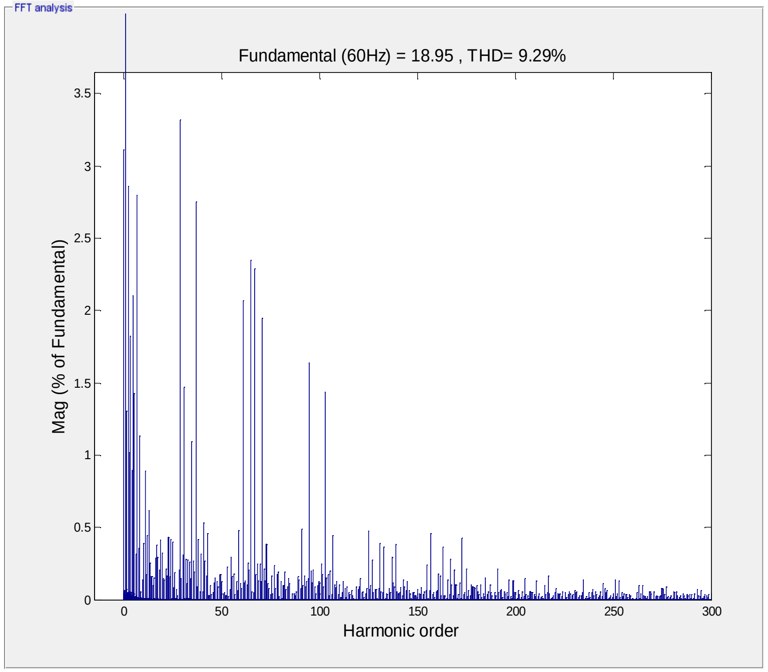
- In real-life situations, it is quite often the case that filters do not operate exactly as intended due to incipient faults of various degrees of severity, may be due to aging of filter components and ambient conditions
- Hence, simulations are carried out assuming some deterioration in the *LCL* filters

Detuning of LCL filter	Current THD (%)	29th (%)	31st (%)	35th (%)	37th (%)
10% detuning in converter side inductance L_1	1.03	0.47	0.17	0.12	0.23
10% detuning in *C* filter	0.96	0.48	0.17	0.12	0.23
Overall 10% detuning of filter components	1.10	0.54	0.20	0.14	0.26

Simulation Results – One PV generator

<u>The impact of imperfect filtering on harmonic emissions</u>

- It may be said that when a suitable filter design is in place, filter component deterioration, of the kinds investigated in this paper, do not seem to play a significant adverse role on harmonic emissions
- To put these results in context, the figure below shows the harmonic spectrum of the PV generator at PCC, with no filtering system. It is clear that the absence of the output filter yields an exceedingly high THD, where inter-harmonics and harmonic terms are clearly visible

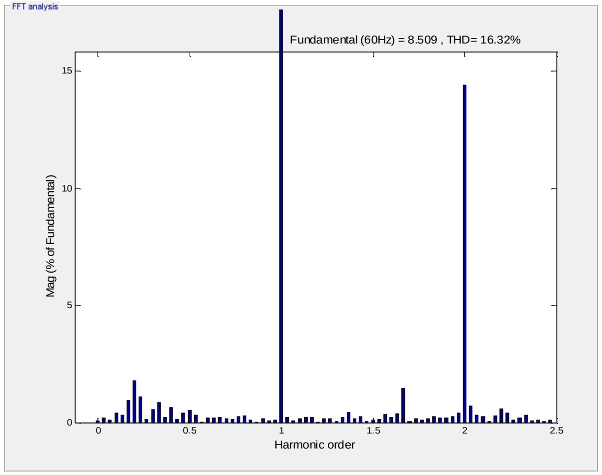


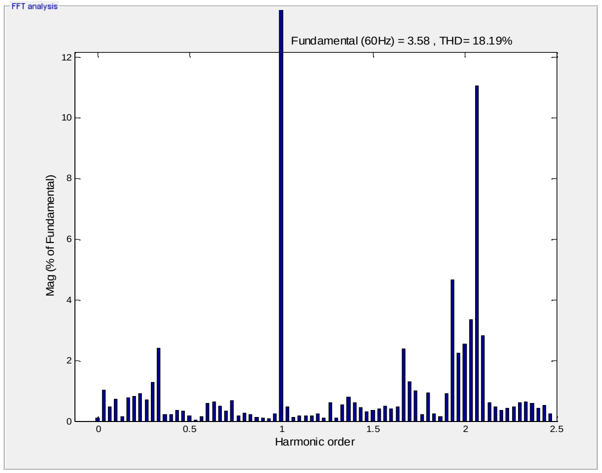
Simulation Results – One PV generator

<u>The impact of a resonance condition on harmonic emissions</u>

- As expected, when the PV system feeds into a load point that exhibits a low-order shunt resonance (e.g., second harmonic), the harmonic content of the PV system is more susceptible to inter-harmonics at lower irradiance levels
- The load is represented as an equivalent *RLC* branch and the *L* and *C* parameters happen to resonate at a given frequency

Irradiance levels	Current THD (%)
1000 W/m^2	16.32
500 W/m^2	18.19
200 W/m^2	54.64

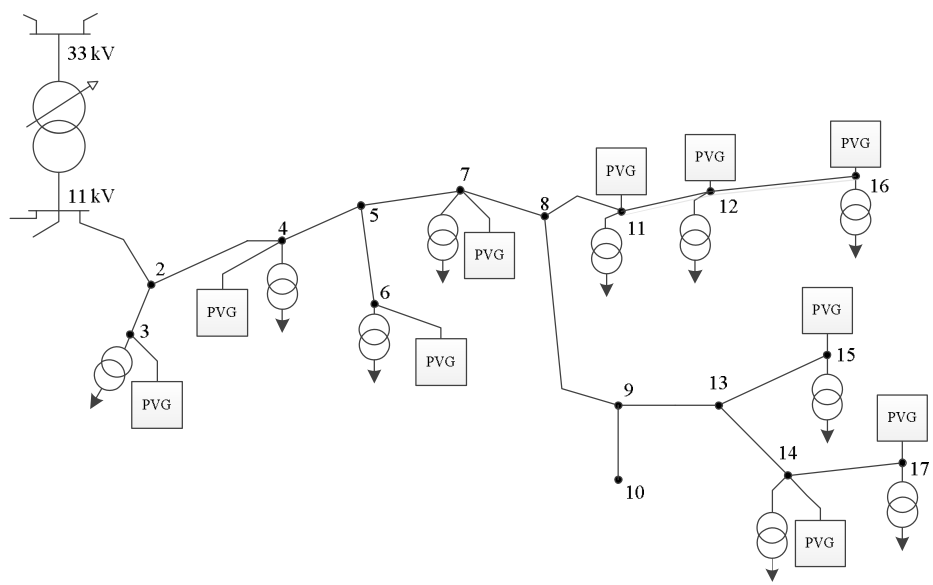




Harmonic Emissions in a Distribution System with Multiple PV generators

Simulation Results – Distribution System

- The power distribution network shown below is used to carry out the harmonic assessment
- It is a typical distribution system of the kind found in the North of England, with underground cables. The cables are modelled by means of three-phase PI section line block of SimPower toolbox. The in-feed transformer connecting to node 1 is taken to be the reference



Simulation Results – Distribution System

- A rather comprehensive set of environmental and operational scenarios were investigated using this power distribution network with distributed PV generation: (i) power grid operating under normal environmental and operating conditions; (ii) assessing the impact of varying solar radiation in the PV systems; (iii) assessing the impact of components deterioration in the *LCL* filters
- The first set of simulations the current THD levels do not exceed the levels specified by IEEE standard. It may also be concluded that there is not so much of a difference between the THD levels of different points of the distribution grid. As expected, the total harmonic emissions in a multi-PV power distribution system would increase as well as the individual high order harmonics, compared to the case of one PVG
- The second set of simulations the system is modelled in such a way that PVGs at nodes 3, 4, 6 and 7 receive an irradiance level of 200 W/m^2 and the PV systems at nodes 11, 12, 14, 15, 16 and 17 receive an irradiance of 800 W/m^2

Simulation Results – Distribution System

- It may be seen that low irradiance levels tend to impact adversely only the area where this condition applies in the network. The area where the irradiance is 800 W/m^2 does not seem to be affected by much

Node	Irradiance (W/m^2)	Current THD (%)	29th (%)	31st (%)	35th (%)	37th (%)
3	200	12.72	3.52	3.94	2.40	1.31
4	200	13.53	4.78	5.43	3.31	1.78
6	200	11.01	3.17	3.55	2.16	1.18
7	200	13.68	4.77	5.42	3.31	1.78
11	800	1.28	0.58	0.57	0.35	0.22
12	800	1.24	0.60	0.60	0.37	0.23
14	800	1.07	0.57	0.56	0.34	0.21
15	800	1.24	0.57	0.56	0.34	0.22
16	800	1.08	0.56	0.55	0.33	0.21
17	800	1.07	0.57	0.56	0.34	0.21

Simulation Results – Distribution System

- The third set of simulations corresponds to the case when 10% detuning is assumed in all the *LCL* filter components
- It is observed that detuning of filter components does impact THD negatively, mainly at the higher frequency harmonics

Node	Current THD (%)	29^{th} (%)	31^{st} (%)	35^{th} (%)	37^{th} (%)
3	1.34	0.73	0.51	0.31	0.26
4	1.35	0.73	0.52	0.31	0.26
6	1.37	0.73	0.52	0.31	0.26
7	1.34	0.73	0.52	0.31	0.26
11	1.49	0.75	0.53	0.31	0.27
12	1.47	0.77	0.56	0.34	0.27
14	1.36	0.73	0.52	0.31	0.26
15	1.46	0.74	0.52	0.31	0.26
16	1.34	0.72	0.51	0.30	0.25
17	1.37	0.73	0.52	0.31	0.26

Conclusions

- The model of a grid-connected PV generator was built in Simulink in order to gain insight into the main factors that cause waveform distortion in such installations
- Further to the PV module, the DC-DC boost converter, the DC-AC three-phase inverter, the other essential elements are the interfacing transformer, the filtering system and the power load. In line with recently published work, it is concluded that solar irradiance is the primary factor affecting THD.
- It is also concluded that a realistic degree of harmonic filter deterioration do not have a significant adverse impact on THD, provided the power electronics conversion stage and harmonic filters are well designed. The only exception found was the case when the power load exhibited a resonant point
- The so-called inter-harmonics were present to varying degrees in all the experiments. It is noted that they are quite significant at low levels of irradiance and on the other hand, the actual harmonic terms remain largely independent of irradiance level

Conclusions

- To investigate the timely issue of distributed PVGs, the full model of the PVG was placed at various locations of a power distribution network model
- On the basis of the comprehensive simulation results carried out, it may be concluded that irradiance is also in this case the primary factor that influences harmonic generation and inter-harmonic generation. However, a minor but sustained increased in the level of harmonics is noted as a result mainly, of the network of underground cables that make up the power distribution network and the increased number of PVG used in the test case
- Nevertheless, the results show that there are no resonances present in this test network and the THD is kept well within the limits set by existing standards. However, it should be noted that no capacitive effects were considered in the load points
- Research work has started on the modeling of partial shading and global MPPT control. Also, a comprehensive program of harmonic measurements has been scheduled to commence this year in our 13.1 kW_p roof-mounted PV generator at TUT