Harmonic Characterisation Model Of Grid Interactive Photovoltaic Systems

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***Abstract*—This paper presents an alternative model of a grid interactive photovoltaic (PV) system which can be used for characterising the harmonics from a PV system when connected to a distorted and undistorted network respectively. The approach uses an orthogonal series function in modelling the different sections of a practical PV system thus yielding a complete harmonic domain model. The proposed model accurately handles the harmonic cross-coupling between the PV system and the network. Both single and three phase grid interactive single-stage transformerless PV systems are presented. Simulation results show the effectiveness of the proposed model.**

***Index Terms*—Photovoltaic, orthogonal series function, single-stage transformerless, modelling, grid interactive.**

I. Introduction

There is a paradigm shift in the operation of modern distribution networks (DNs) due to the increasing penetration of renewable distributed generators (RDGs) in the system. This increasing proliferation of RDGs is expected to continue in the far future as several countries are striving to reduce their carbon footprint, save fuel cost, liberalise the electricity industry, increase customer participation and enjoy national energy independence. Amidst the numerous merits of embedded generation, there are technical and operational challenges associated with their network integration. Line congestion, voltage variation and reverse power flows, power loss increase, power quality deterioration and stability concerns are just a few to mention. Nonetheless, the magnitude of the challenges that arise in a given power network with RDG depend on the level of penetration of these non-dispatchable generations and their location in the network. Of these RDGs, study has shown that photovoltaics are the fastest growing DG technology embedded into the power system [1]. Recently, the Spanish government introduced the 'sun tax' which was targeted at customers whose PV-DG installation exceeded 10kW. The decision was reached by the government on the claim that high penetration of non-dispatchable generators like PVs impacted the utility network adversely with respect to voltage quality thus increasing the financial and technical constraints in maintaining the network by the utilities. Several researchers have proposed different models of PV systems for various power system analysis studies in order to ascertain the actual impacts of these RDGs on the network. Steady-state models ranging from constant voltage and current sources at fundamental frequency to generator (P-V) or load (P-Q) buses [2] for power flow analysis (PFA) have been proposed. Such models do not consider the power electronic device switching hence harmonics generated by the PV systems are neglected. Reference [3] has proposed modelling of the different sections of a practical PV system ranging from the PV module, inverter section, filter circuit and the interconnecting transformer and thereafter, all these units are combined to produce a complete model. Again, the above proposed model neglected harmonics. There also exist other PV models that accounted for harmonics [4]; these models are often very computationally demanding. Moreover, many of these models do not include the dependence of harmonic voltages and currents produced by the PV generator on the network (background) distortion or operating conditions. In an effort to develop a steady-state harmonic model of PV, a frequency response model of PV was proposed in [5]. The proposed model applied the phasor-domain frequency analysis which involves analyzing one harmonic frequency at a time thus impeding the accurate study of the possible interactions and harmonic cross-couplings between the PV system (or several parallelled PV systems) and the distorted distribution network.

Consequently, it is pertinent to develop an improved steady state PV-DG model capable of accurately characterizing the harmonics generated by a PV system when it is connected to either a distorted or undistorted node in a power network. Reference [6] has shown that harmonics can be accurately predicted using steady-state models as compared to dynamic models. To obtain such a steady-state model would require an approach capable of handling all harmonic frequencies at the same time. [7] has proposed a powerful 'harmonic-domain' (HD) modelling approach which has the capability of taking into account the harmonic cross-couplings between nonlinear components of the power network.

The model proposed here is based on the HD concept. This model uses the real Fourier series (RFS) expansion although the complex Fourier series can also be used. RFS has been chosen for the sake of computer memory space and speed of simulation [8]. Other orthogonal series functions can also be

978-1-4673-8848-1/16/ $31.00 2016 IEEE

used. Improved harmonic power flow (HPF) analysis can be conducted using this proposed model as it naturally handles the harmonic interaction between the PV system and distorted network or any nonlinear load.

II. Modelling

In this paper, grid interactive PV systems are considered. The illustration in Fig. 1 summarises the approach used for the development of the model for different sections of the PV system. Each unit is modelled and thereafter all sections are combined to form the complete model. Both single and

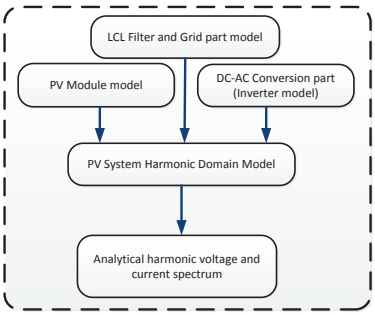


Fig. 1. Illustration of modelling approach

three phase utility-scale single-stage transformerless PV systems are presented in this work. Although, the models considered are single-stage transformerless PV systems, the approach can also be extended to PV systems with two stages and interconnecting transformer. Fig. 2 shows a generic PV

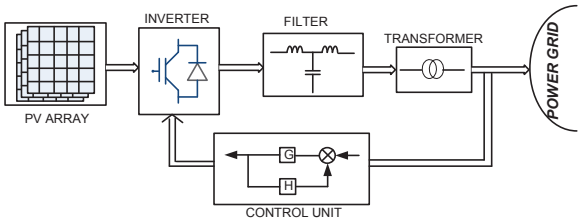


Fig. 2. Generic PV system

system. The circuit equations are first presented in time domain for the purpose of completeness and to enhance readability. These equations are transformed into their HD equivalence in Section III.

1) PV module model: The output of a PV module is by nature stochastic since its voltage and current are dependent on meteorological data such as solar irradiance and temperature which are unpredictable. It therefore becomes difficult to obtain with high accuracy the output voltage, current and power of a PV module without measurements. Nonetheless, several mathematical models that can be used to estimate PV module outputs exist. Such models are developed using the PV module current-voltage or power-voltage (I-V and P-V) characteristic curve(s) and the data provided in the manufacturer's data sheet at specific operating conditions such as open circuit, short circuit and maximum power point. The equations are generated depending on the choice of model of PV module used namely: ideal, single, modified single and double diode models [1]. Parameter dependence on weather data are often embedded in the equations for improved results (estimates) [9]. Models of PV modules proposed in [10], [11] have been adopted in this research owing to its simplicity and relatively better estimates of results.

2) Inverter model: Numerous methods abound for analytical model of inverter [12], [13] in the power electronic literature. Such models can be circuit-element-based or operational-based. The latter is usually applied using the programmed pulse width modulation (PWM) technique [14] which is useful for digital implementation unlike the former which is suitable for analogue circuit implementation. The switching function law [15], [16] has been used in modelling the three-level full-bridge inverter (both single and three phase respectively). The switching function derived for single phase case is given below.

$$G(\theta) = \frac{8}{\pi} \sum_{k=1}^{\infty} \sum_{m=1}^{\frac{P}{4}} \frac{1}{k} \sin(k\alpha_m) \sin\left(\frac{k}{2}\delta_m\right) \sin(k\omega t) \quad (1)$$

For a three phase PV system, the following per phase switching functions were obtained.

$$G_x(\omega t) = \frac{8}{\pi} \sum_{k=1}^{\infty} \left({g_x}^s(k) \sin(k\omega t) + {g_x}^c(k) \cos(k\omega t)\right) \quad (2)$$

where: $x \in \{a, b, c\}$

Fig. 3 shows a zoomed view of a portion of the switching

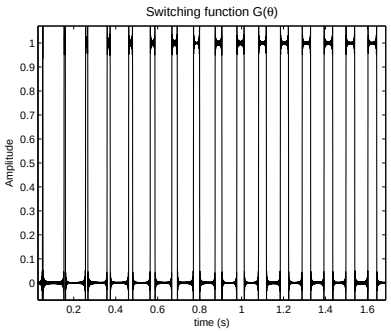


Fig. 3. Switching function pulse train

function pulse train plotted in MATLAB. The output voltage of the PV module and the output voltage of the inverter can be related by the equation:

$$V_{inv}(t) = G(\omega t) V_{dc} \quad (3)$$

Equation (3) clearly reveals that the output voltage of the inverter contains a theoretically infinite number of harmonic frequency components. However, a closer assessment of the performance of a typical 3-level PWM-based converter reveals that not all harmonic frequencies will be present in equation (1). Actually, only odd harmonics are present.

Since the solar inverter switching frequency is usually within $2-20kHz$ [17], the inverter output voltage is expected to contain high frequency harmonic components which can be filtered out using a low-pass filter. The harmonic spectrum is shown in Fig. 4. It is important to note however, that

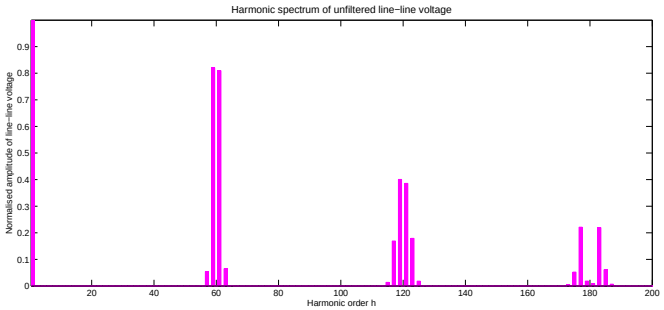


Fig. 4. Harmonic spectrum of unfiltered inverter normalised output voltage

low order harmonic frequency components in voltages and currents sometimes appear at the grid side of the PV system owing to the effect of the current controller and network operating conditions.

3) Model of filter circuit and grid section: Both passive and active filters can be used to eliminate harmonics generated from the inverter switching operation. Passive filters such as L, LC and LCL types are the most common in PV systems [18]. An LCL filter is used in this model.The equations for all sections of the PV system (shown in figures 5 and 6 respectively) can be summarised as written in the subsections below.

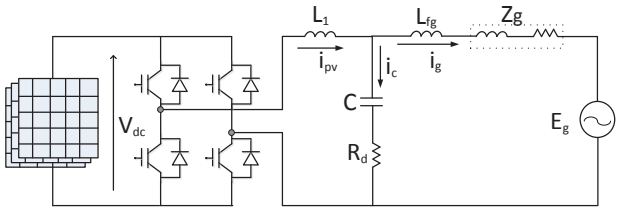


Fig. 5. Single-phase single stage transformerless PV system

Single-Phase circuit equations in time-domain (TD)

The circuit equations can be written as shown below.

$$\frac{di_g(t)}{dt} = \frac{1}{L_2}\left[V_c(t) - E_g(t) - R_2 i_g(t)\right] \tag{4}$$

$$\frac{dV_c(t)}{dt} = \frac{1}{C} i_c(t) + \frac{di_c(t)}{dt} R_d \tag{5}$$

$$\frac{di_g(t)}{dt} = \frac{1}{L_1} G(\omega t) V_{dc} - \frac{1}{L_1} V_c(t) - \frac{di_c(t)}{dt} \tag{6}$$

Terms with subscript 'c' are variables associated with the filter capacitor, for instance, i_c is the capacitor current. Similarly, terms with subscript 'g' represent the grid bus parameters such as E_g which denotes the grid voltage.

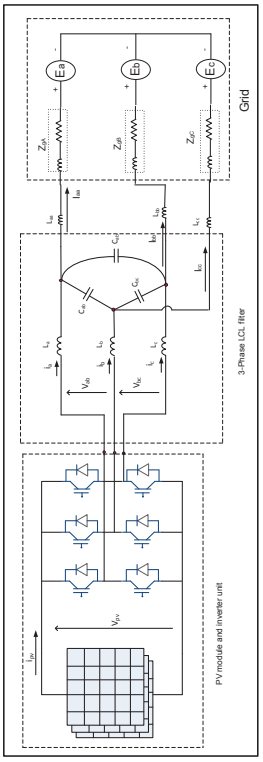


Fig. 6. 3-phase single stage transformerless PV system

Three-phase equations in TD

By applying traditional circuit theorems to Fig. 6, the following equations are derived.

$$[V_{123}] = [M]^{-1}[H][V_{abc}] \tag{7}$$

where:

$$[M] = \begin{bmatrix} [M_{11}] & [M_{12}] & [M_{13}] \\ [M_{21}] & [M_{22}] & [M_{23}] \\ [M_{31}] & [M_{32}] & [M_{33}] \end{bmatrix} \tag{8}$$

$$[M_{11}] = \left(\frac{1}{L_a} + \frac{1}{L_{aa}} + (C_{ca} + C_{ca})P^2\right) \tag{9}$$

$$[M_{13}] = -(C_{ab} + C_{ca})P^2; [M_{21}] = -C_{ab}P^2$$

$$[M_{22}] = \left(\frac{1}{L_b} + \frac{1}{L_{bb}} + (C_{ab} + C_{bc})P^2\right) \tag{10}$$

$$P = \frac{d}{dt}; [M_{12}] = 0; [M_{23}] = -\left(C_{bc}P^2\right) \tag{11}$$

$$[M_{32}] = -C_{bc}P^2; [M_{31}] = -\left(C_{ca}P^2 + \frac{1}{L_{cc}}\right)$$

$$[M_{33}] = \left(\frac{1}{L_c} + \frac{1}{L_{cc}} + (C_{bc} + C_{ca})P^2\right) \tag{12}$$

$$[H] = \begin{bmatrix} \frac{1}{L_a} & 0 & 0 & \frac{1}{L_{aa}} & 0 & 0 \\ 0 & \frac{1}{L_b} & 0 & 0 & \frac{1}{L_{bb}} & 0 \\ 0 & 0 & \frac{1}{L_c} & 0 & 0 & \frac{1}{L_{cc}} \end{bmatrix} \tag{13}$$

$$V_{123}^T = \begin{bmatrix} V_1 & V_2 & V_3 \end{bmatrix} \tag{14}$$

$$V_{abc}^T = \begin{bmatrix} V_a & V_b & V_c & V_{aa} & V_{bb} & V_{cc} \end{bmatrix} \tag{15}$$

III. Orthogonal series function analysis

The use of orthogonal series functions in solving integro-differential equations that arise from electric circuits is well known [19].
Consider a truncated Fourier series function f,

$$f = \langle \Psi, F \rangle$$

where $\langle\rangle :=$ inner product
$\Psi^T = \begin{bmatrix} \sin(wt) & \cdots & \sin(Hwt) & 1 & \cos(wt) & \cdots & \cos(Hwt) \end{bmatrix}$
and $F^T = \begin{bmatrix} F_1^* & \cdots & F_H^* & F_0^{**} & F_1^{**} & \cdots & F_H^{**} \end{bmatrix}$
It is trivial to see that

$$\dot{\Psi}^T = \Psi^T \Phi \tag{16}$$

where $\Phi = \begin{bmatrix} 0 & \cdots & 0 & \cdots & -\omega & \cdots & 0 \\ \vdots & \cdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & -H\omega \\ 0 & \cdots & 0 & \cdots & \vdots & \cdots & 0 \\ \omega & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & \cdots & H\omega & \cdots & 0 & \cdots & 0 \end{bmatrix}$

By induction $\left(\Psi^T\right)^m = \Psi^T \Phi^m$ where m on left hand side of the equation denotes the mth derivative whereas it stands for power on the right hand side. Applying this concept of orthogonal series expansion, the time domain equations above are converted into their HD equivalents as presented next.

Single-phase equations in HD

The equations (4), (5), and (6) transformed into HD produce the following expressions:

$$\mathbf{I_c} = \mathbf{Q^{-1}} \left[\frac{\mathbf{1}}{\mathbf{L_1}} \mathbf{\Phi^{-1}} \mathbf{G V_{dc}} + \mathbf{B}(\mathbf{E_g} - \mathbf{V_c}) \right] \tag{17}$$

$$\mathbf{V_c} = \mathbf{\Phi^{-1}} \left(\frac{\mathbf{1}}{\mathbf{C}} \mathbf{U} + \mathbf{R_d \Phi} \right) \mathbf{I_c} \tag{18}$$

$$\mathbf{I_g} = \mathbf{\Phi^{-1}} \left[- \left(\mathbf{\Phi} + \frac{\mathbf{1}}{\mathbf{L_1}} \mathbf{\Phi^{-1}} \left(\frac{\mathbf{1}}{\mathbf{C}} \mathbf{U} + \mathbf{R_d \Phi} \right) \right) \mathbf{I_c} + \frac{\mathbf{1}}{\mathbf{L_1}} \mathbf{G V_{dc}} \right] \tag{19}$$

where

$$\mathbf{Q} = \mathbf{\Phi^{-1}} \left(\frac{\mathbf{1}}{\mathbf{L_1}} \mathbf{\Phi^{-1}} \left(\frac{\mathbf{1}}{\mathbf{C}} \mathbf{U} + \mathbf{R_d \Phi} \right) + \mathbf{\Phi} \right) \tag{20}$$

$$\mathbf{B} = \left(\mathbf{L_2 \Phi} + \mathbf{R_2 U} \right)^{-1} \tag{21}$$

and $\mathbf{U}$ is an identity matrix in HD. Rearranging equations (17) through (19) and applying KCL results in the PV current I_{pv} been written as a function of the PCC voltage. This can be considered as HD Norton equivalent model.

Three-phase equations in HD

For the 3-phase system, we have in HD the following expressions

$$\mathbf{V_{123}} = [\triangle]^{-1} [\beta] \mathbf{V_{abc}} \tag{22}$$

where

$$[\mathbf{\Delta}] = \begin{bmatrix} [\triangle_{11}] & [\triangle_{12}] & [\triangle_{13}] \\ [\triangle_{21}] & [\triangle_{22}] & [\triangle_{23}] \\ [\triangle_{31}] & [\triangle_{32}] & [\triangle_{33}] \end{bmatrix} \tag{23}$$

$$[\triangle_{11}] = \left(\mathbf{J_1} + \mathbf{e_1} \left[\mathbf{\Phi^2} \right] \right); [\triangle_{12}] = - \left(\mathbf{C_{ab}} \left[\mathbf{\Phi^2} \right] + \mathbf{e_2} \right)$$

$$[\triangle_{13}] = - \mathbf{C_{ca}} \left[\mathbf{\Phi^2} \right]; [\triangle_{21}] = - \mathbf{C_{ab}} \left[\mathbf{\Phi^2} \right]$$

$$[\triangle_{22}] = \left(\mathbf{J_2} + \mathbf{e_3} \left[\mathbf{\Phi^2} \right] \right)$$

$$[\triangle_{23}] = - \left(\mathbf{C_{bc}} \left[\mathbf{\Phi^2} \right] + \mathbf{e_4} \right); [\triangle_{31}] = - \left(\mathbf{C_{ca}} \left[\mathbf{\Phi^2} \right] + \mathbf{e_5} \right)$$

$$[\triangle_{32}] = - \mathbf{C_{bc}} \left[\mathbf{\Phi^2} \right]; [\triangle_{32}] = \left(\mathbf{J_3} + \mathbf{e_6} \left[\mathbf{\Phi^2} \right] \right)$$

where

$$\mathbf{V_{123}^T} = \begin{bmatrix} \mathbf{V_1} & \mathbf{V_2} & \mathbf{V_3} \end{bmatrix} \tag{24}$$

$$\mathbf{V_{abc}^T} = \begin{bmatrix} \mathbf{V_a} & \mathbf{V_b} & \mathbf{V_c} & \mathbf{V_{aa}} & \mathbf{V_{bb}} & \mathbf{V_{cc}} \end{bmatrix} \tag{25}$$

The current injected into the grid is expressed in HD as follows:

$$[\mathbf{I_{abc}}] = [\mathbf{MM}] [\mathbf{FF}] [\mathbf{V_{abc}}] \tag{26}$$

where

$$[\mathbf{MM}] = \begin{bmatrix} \mathbf{\Phi} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{\Phi} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{\Phi} \end{bmatrix} \tag{27}$$

$$[\mathbf{FF}] = \begin{bmatrix} \mathbf{f_1} & \mathbf{f_2} & \mathbf{0} & \mathbf{f_3} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{f_4} & \mathbf{f_5} & \mathbf{0} & \mathbf{f_6} & \mathbf{0} \\ \mathbf{f_7} & \mathbf{0} & \mathbf{f_8} & \mathbf{0} & \mathbf{0} & \mathbf{f_9} \end{bmatrix} \tag{28}$$

Equation (26) relates the current flowing into the grid from the 3-phase PV system and the PCC voltages. The terms in the HD equivalent equations for both single and 3-phase PV systems are written in bold letters because they are matrices and vectors of appropriate dimensions. Consider for example the term E_g, it is a vector of $(2H + 1)$ elements where H denotes the Hth harmonic order. Similarly, Φ is a matrix of dimension $(2H + 1)$x$(2H + 1)$.

IV. Simulations and Results

Simulations have been carried out using MATLAB software. Two simulation cases have been considered viz distorted and undistorted network. The distortion of the PCC voltage was achieved by considering that an asynchronous speed drive is connected to the same bus as the PV system. That is, harmonic orders of 5th, 7th, 11th and 13th harmonics are present in the bus voltage. In the undistorted scenario, all loads (both linear and nonlinear) are modelled as constant power (PQ) spot loads. However, the second scenario models passive loads as linear RL elements whereas the nonlinear loads are represented by an adjusted harmonic current spectrum. Practical PV system data obtained from [17] are used in the simulations. To perform the simulation, the flowchart of the algorithm used is presented in

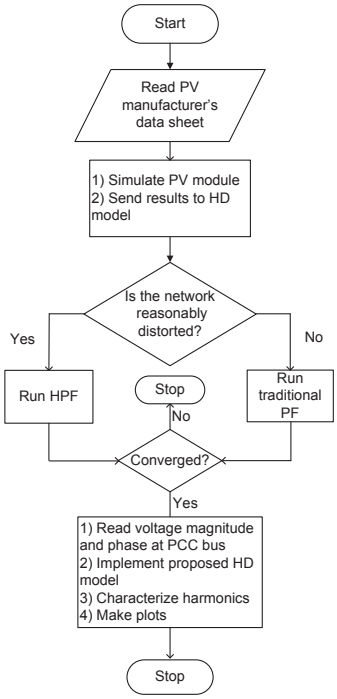


Fig. 7. Flowchart of algorithm

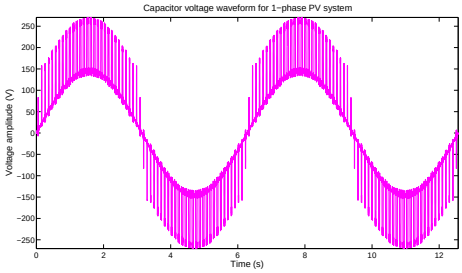


Fig. 8. Single-phase capacitor voltage for undistorted case

Fig. 7. Fig. 8 and Fig. 9 show the plots for the single phase transformerless PV system's capacitor voltage and its current injection into the grid respectively for the undistorted case.

The 3-phase PV system filter capacitor line-to-line (AB) voltage for undistorted and distorted scenarios are shown in Fig. 10 and Fig. 11 respectively. Both waveforms appear

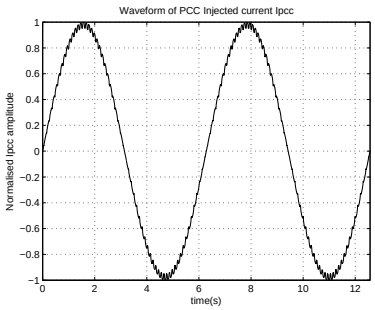


Fig. 9. Current injected by single-phase PV for undistorted case

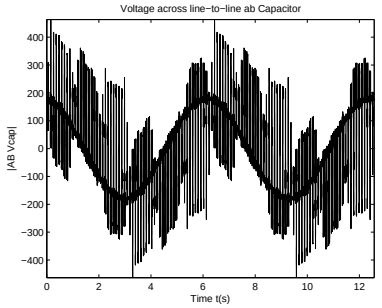


Fig. 10. 3-phase capacitor line-line ('AB') voltage for undistorted case

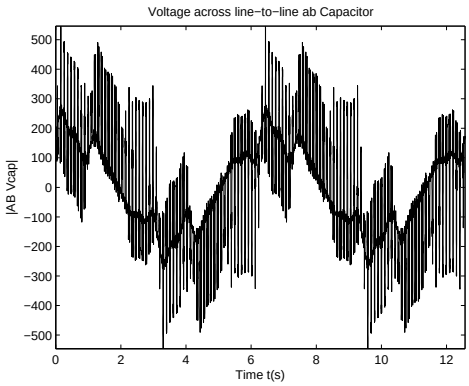


Fig. 11. 3-phase Capacitor line-line ('AB') voltage for distorted case

to be cluttered. This is because the capacitors absorb the harmonic contents of the voltages at the inverter output. Also, the waveform of the capacitor voltage for the undistorted case appears to be smooth in comparison with the waveform for the distorted scenario. The current injected into the grid for the two scenarios is shown in Fig. 12 and Fig. 13 respectively. Indeed, the current produced by the PV system for the distorted case is not purely sinusoidal due to the presence of harmonic components. Juxtaposing results of the two scenarios, it can be argued that provided the filtering circuit is working properly and a good inverter sampling technique is deployed, harmonic current generated from a PV system may not be significant if the PCC is undistorted. This is especially if there exist batteries in the PV system that ensures constant dc voltage input to the inverter unit thus curtailing the impacts of fluctuating solar irradiation on harmonic current generation.

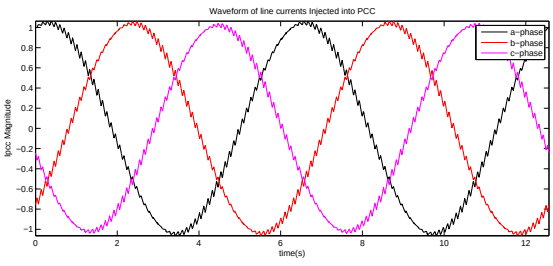


Fig. 12. Current injected by 3-phase PV for undistorted case

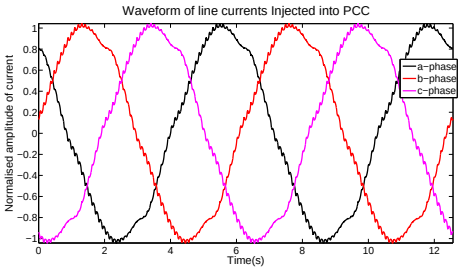


Fig. 13. Current injected by 3-phase PV for distorted case

Nonetheless, with a distorted PCC, the current produced may not be purely sinusoidal as can be observed from the above simulation results. The magnitude of this distorted current can be reduced to levels that meet the IEEE 1547 and IEC 61727 standards by using a harmonic compensator. This however was not included in the proposed model.

V. Conclusion

In this work, we have presented a harmonic characterisation model of both the single and 3-phase single-stage transformerless PV systems. The approach analyzes several harmonics simultaneously unlike the phasor-domain. This method allows for investigation of harmonic interaction and cross-couplings between the PV system and nonlinear loads or background distortion in the network. This model has all the benefits associated with the well-known HD modelling technique such as avoidance of the use of fast Fourier transform (FFT) or the discrete Fourier transforms (DFT) which may result in discretisation and aliasing errors. It can also be integrated into the harmonic power flow formulated in the HD domain. The model can be simulated using different software platforms such as C, C++ or MATLAB unlike [20] where PSCAD was used to model the PV system. In this paper, simulation results using the proposed model have confirmed that harmonic currents generated from PV systems are affected by the level of distortion (or operating conditions) at the node at which the PV system is connected. The authors therefore recommend that harmonic analysis or measurement (where possible) be carried out before the installation of a renewable energy source (RES) with power conditioning unit thereby minimising the likelihood of harmonic interaction between the converter system and the PCC voltage or current. It is important to mention that harmonic compensators were not included in the above proposed model. Although this would reduce the magnitude of the harmonic currents generated and perhaps satisfy limits stipulated in well known standards like IEEE 1547, it does not however guarantee total elimination of all possible harmonic currents generated. We will consider harmonic compensators in future work.

Acknowledgment

Mr. O.S. Nduka is grateful to the Petroleum Technology Development Fund (PTDF), and The Presidential Special Scholarship Scheme for Innovation and Development, Nigeria, for funding his PhD research at Imperial College London. He also appreciates the Management of Federal University of Technology, Owerri, Nigeria, for granting him study leave during this period.

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