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Flexible harmonic domain model of solar PV supply system

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Abstract. This paper presents a flexible harmonic domain (FHD) model of a grid-connected solar PV system amenable to harmonic analysis. The system consists of a 4.12 kW solar photovoltaic array that provides supply continuity and reliability for unmanned aerial vehicle (UAV) ground control station. The proposed system consists of a solar array, a boost converter, a three-phase inverter, and a three-phase filter. FHD technique is used to model the system, as it accounts only for dominant frequencies which enables obtaining of compact yet precise description of the system's harmonic interactions. Compared to complexity, extra harmonic extraction routines, and large computational resources of the time domain technique (TD), FHD needs only one matrix inversion to obtain both the voltage/current waveforms and harmonic content of each part of the system. The obtained results prove the feasibility, accuracy, and simplicity of the proposed FHD technique for modeling switched devices while maintaining the computational resources. For each part/state of the proposed system, both the waveform and its harmonic content are visualized.

1. Introduction

The increased installation of renewable energy resources in modern distribution systems, such as small grid-tied solar PV systems, has caused the distortion of voltage and current waveforms [1]. Although renewable energy resources have many advantages, power intermittency and integration of its power electronics converters (PECs) have set new challenges for power system engineers [2]. Generally, the operation of the power system is assumed as purely sinusoidal, however, PECs integration in the power distribution system produces individual frequencies to be imposed into the fundamental power frequency, which affects the voltage as well as current waveforms [3]. The need for accurate and low computational cost modeling techniques for those switched devices constructs a serious problem in recent years. The modeling technique should also have an adequate representation method of the ripple information of the waveforms without increasing the computational capabilities [4].

In fact, detailed modeling of grid-tied solar PV systems has been extensively reported in the literature. Time domain (TD) modeling and simulation are the main methods for studying power system harmonics [5]. PSCAD/EMTDC is considered the reliable simulation package for TD simulation which provides accurate waveform for both voltage and current at each part of the system [6]. Nevertheless, TD simulation requires large computational resources and also depends on the simulation time step to provide detailed ripple information. Besides the small time-step, TD simulation requires a large observation time until the transient state vanishes. Moreover, extracting the harmonics from time domain waveforms needs extra processing algorithms. Therefore, a considerably large computational cost is accounted for TD modeling and simulation. Compared to TD, harmonic domain modeling (HD) provides accurate instantaneous harmonic information of switched devices [7]. Basically, HD converts linear time-periodic system (LTP) into linear time-invariant (LTI) by representing the state space of the switched devices into complex-valued vectors corresponding to its TD counterpart [8]. However, including sequentially ordered harmonics in HD modeling may cause an explosion of the system dimensions. Therefore, the authors in [9] have introduced a reduced-order FHD model to work for steady-state analysis of an isolated PV system with non-linear loads [9].

In this paper, FHD modeling of a grid-tied PV system is introduced for the sake of harmonic analysis. As the usage of unmanned ariel vehicles (UAV) in both military and civilian applications is gaining more and more feasibility, a reliable electric power system is needed to supply its ground control station (GCS) [10]. These GCSs often have several electronic loads such as control work station, weather station, radio, illumination, and air conditioning systems. Some of the GCSs are located near urban areas. Therefore, the energy supply of GCSs is mainly done through the power distribution grid and is also supported by renewable energy resources such as solar or wind energy as a backup supply for assurance of system reliability. In this case, a three-phase PV system is considered as a backup energy supplying source for the UAV GCS for modeling and simulation purposes.

In general, the power supply system design, modeling, and analysis are considered to be of great importance to assure power quality and reliability. The GCS power supply system, shown in figure 1, consists of the utility grid as the main power source as well as a grid-connected solar PV system. In [11], [12], the aforementioned configuration is proved to be the optimum power system to supply this type of load. In this paper, the PV array is modeled as a Thévenin equivalent voltage source and Thévenin resistance [9]. The voltage-sourced inverter and the Boost converter, which is commonly used for the maximum power point tracking MPPT [13], are considered to work at a certain operating point.

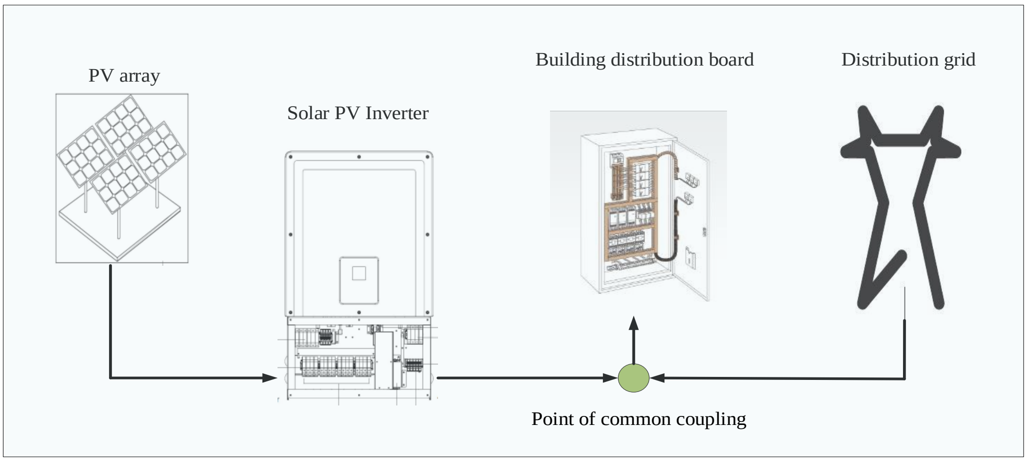


Figure 1. Schematic diagram of the proposed power supply system

2. Harmonic domain modeling

As mentioned in the introduction section, TD modeling and simulation is used to be the most useful tool for modeling LTP systems. On the contrary, the proposed HD modeling technique provides a steady-state solution for switched devices without the need for complex partial derivatives. HD simply converts time-varying differential equations into a set of algebraic equations [14]. In general, any *kth* order LTP system in TD, such as power electronic devices in PV systems, is represented as:

$$\begin{aligned} \dot{x}(t) &= a(t)x(t) + b(t)u(t) \\ y(t) &= c(t)x(t) + d(t)u(t) \end{aligned} \tag{1}$$

where, *a, b, c*, and *d* are the system's state, input, output, and feedthrough matrices, respectively. *x, y,* and *u* represent the state variables, output, and input column vectors, respectively. The Fourier series expansion of the elements of *a, b, c*, and *d* can be represented as:

$$a^{i}(t) = \sum_{k=-h}^{h} a_m(t)e^{jk\omega_o t} \tag{2}$$

In (2), h refers to the highest considered harmonic order and $\omega_o$is the fundamental power frequency. The proposed HD modeling technique transforms the system from (1) into:

$$\begin{aligned} NX &= AX + BU \\ Y &= CX + DU \end{aligned} \tag{3}$$

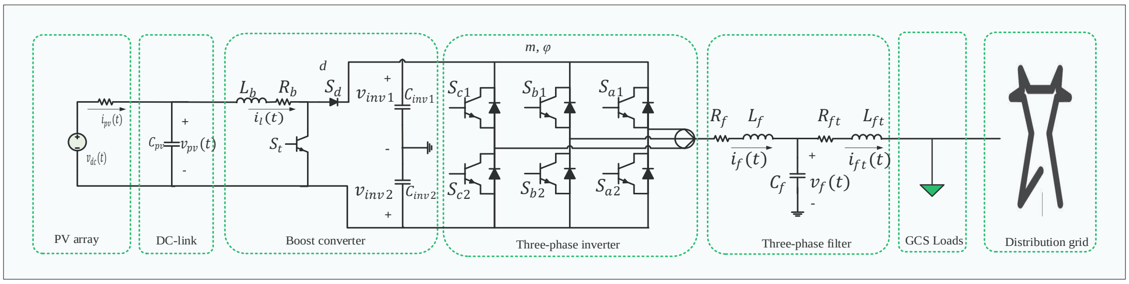


Figure 2. PV system detailed circuit diagram

Matrix N is a block diagonal matrix that consists of m repeated times of a certain differentiation matrix (where m is the number of the system state variables). This matrix can be represented as a diagonal matrix with its diagonal containing the harmonic vector [-h:h] multiplied by the fundamental frequency [15]. Matrices A, B, C, and D are enlarged matrices of the original state matrices a, b, c, and d where all elements of $a(t)$ are presented as a Toeplitz-type sub-matrix of A (similarly b, c, and d). these sub-matrices are considered to contain the corresponding harmonics. In fact, matrices A, B, C, and D of the PV system under study depicted in figure 2 can be represented in the state space below. From (4) through (6), X, U, and Y are considered the state variable vector, the input and output vectors respectively.

$$X = [\, v_{pv} \quad i_l \quad v_{inv1} \quad v_{inv2} \quad i_f^{abc} \quad v_f^{abc} \quad i_{ft}^{abc} \,]^T \tag{4}$$

$$U = [\; u_{dc} \quad v_{pcc}^{a}]^T \tag{5}$$

$$Y = [\; i_{pv} \quad - i_{ft}^{a}]^T \tag{6}$$

$$A = \begin{bmatrix} -I/(R_{pv}C_{pv}) & -I/C_{pv} & 0 & 0 & 0 & 0 & 0 \\ I/L_b & -R_b/L_b & -S_d/L_b & S_d/L_b & 0 & 0 & 0 \\ 0 & S_d/C_{inv} & 0 & 0 & S_{x1} & 0 & 0 \\ 0 & -S_d/C_{inv} & 0 & 0 & S_{x2} & 0 & 0 \\ 0 & 0 & S_{y1} & S_{y2} & -R_f I/L_f & -I/L_f & 0 \\ 0 & 0 & 0 & 0 & I/C_f & 0 & -I/C_f \\ 0 & 0 & 0 & 0 & 0 & I/L_{ft} & -I/L_{ft} \end{bmatrix}, \tag{7}$$

$$B = \begin{bmatrix} I/(R_{pv}C_{pv}) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -I/L_{ft} \end{bmatrix}^T, \tag{8}$$

$$C = \begin{bmatrix} -I/R_{pv} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -I \end{bmatrix}, \qquad D = \begin{bmatrix} I/R_{pv} & 0 \\ 0 & 0 \end{bmatrix} \tag{9}$$

Where all HD switching matrices in A can be considered as in (10). T stands for transpose and I is the identity matrix. Then all state variables of the system are readily available involving their harmonic content in the steady state solution in (11).

$$\begin{bmatrix} S_{x1} \\ S_{x2} \end{bmatrix} = -1/C_{inv} \begin{bmatrix} S_{a1} & S_{b1} & S_{c1} \\ S_{a2} & S_{b2} & S_{c2} \end{bmatrix}, \qquad \begin{bmatrix} S_{y1} \\ S_{y2} \end{bmatrix} = \; 1/L_{ft} \begin{bmatrix} S_{a1} & S_{b1} & S_{c1} \\ S_{a2} & S_{b2} & S_{c2} \end{bmatrix}^T \tag{10}$$

$$X = (N - A)^{-1}BU$$
$$Y = CX + DU \tag{11}$$

3. FHD and harmonic order selection

Generally, HD modeling involves all harmonic spectrum of the switched devices under study which may cause the system to explode. FHD modeling allows to involve only important harmonic with the largest energy density, e.g., the harmonics around the switching frequency of the involved power electronic devices besides the fundamental power frequency [16,17]. For each part of the system, the dominant frequency content may differ from other parts. Indeed, the considered harmonics of each state of the system will depend on the information provided by its topology, e.g., control scheme and converter frequencies. Thus, restructured Toeplitz-type matrix shall be derived to account only for the harmonic interaction of the selected order. Further details about the restructured matrix/vector operation can illustrated in [9].

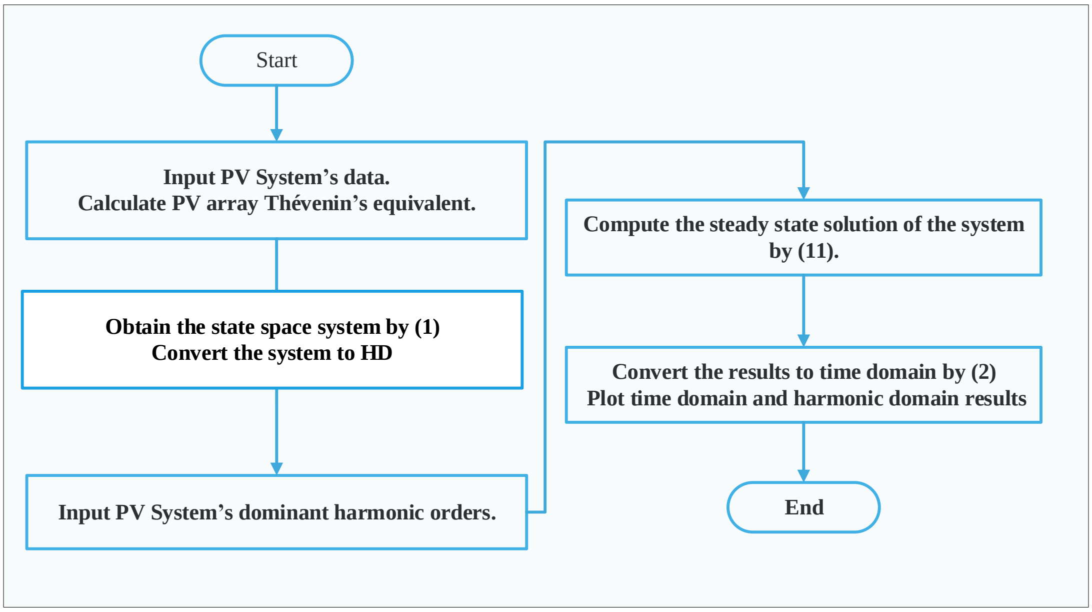
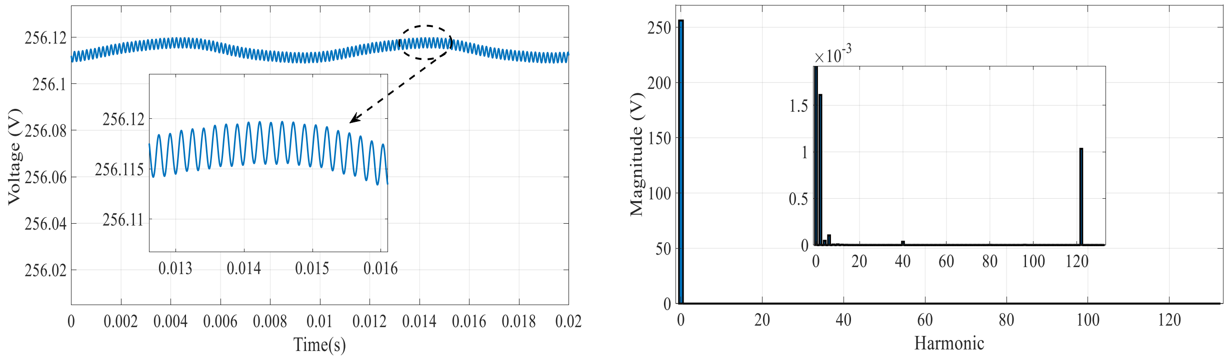


Figure 3. Flexible harmonic domain solution flow chart

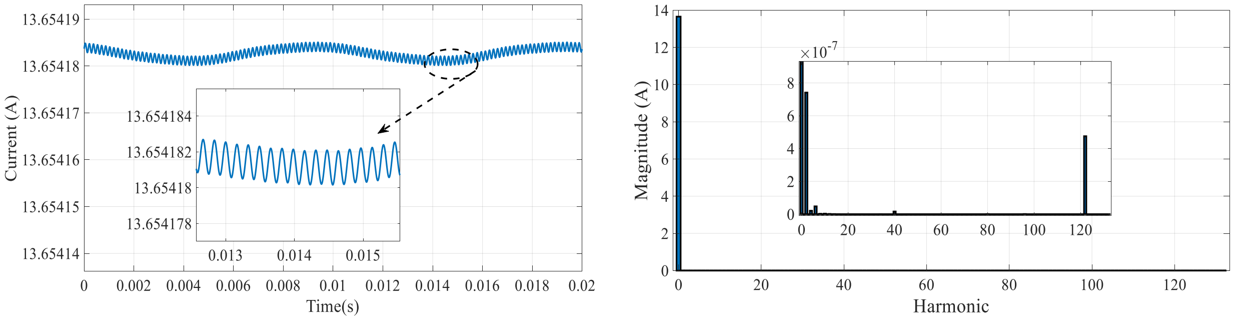
4. Simulation results and discussion

As mentioned in the previous section, FHD modeling technique will provide a periodic steady state solution with no simplification in the PV system harmonic content. the simulation flow chart depicted in figure 3 illustrates the proposed FHD procedures. First, the system data is inserted to the program. The Thévenin's equivalent of the solar PV array is calculated. Second, the state space representation of the proposed system is obtained. Then the important harmonic orders of the system, according to the system topology, is supplied to the program. The harmonic steady state solution is finally obtained and visualized in both TD and HD. The model is implemented on Matlab R2020b package and by the use of an 8th generation core i7 model (i7-8550u), 1.8 GHz computer. figure 4 shows the simulation results of the proposed FHD. For each state of the system, the voltage/current waveform and the harmonic content in time domain is easily provided from the steady state solution. In figure 4.a.1, the voltage waveform at the DC link capacitor is obtained mainly dc voltage and other frequencies imposed on it. These frequencies are readily available in the obtained harmonic domain with the magnitude of each harmonic order as shown in figure 4.a.2. Similarly, figure 4.b.1 through figure 4.g.1 show the voltage/current waveform for each state of the system represented as time domain waveform while figure 4.b.2 through figure 4.g.2 show their harmonic content. These obtained results prove the capability of the proposed FHD to provide accurate ripple information. Thus, FHD represents the switched devices without the need of involving sequentially ordered harmonics of its full order HD counterpart. Moreover, there is no need for using excessive processing routines to obtain the harmonic content like its TD counterpart as ripple information is readily available in the obtained solution.



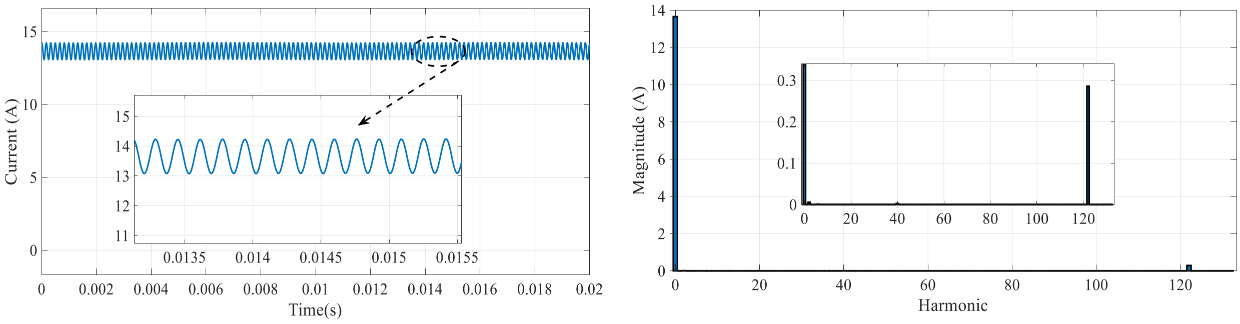
(a.1) DC link capacitor voltage waveform, $v_{PV}(t)$

(a.2) DC link capacitor voltage harmonics, V_{PV}



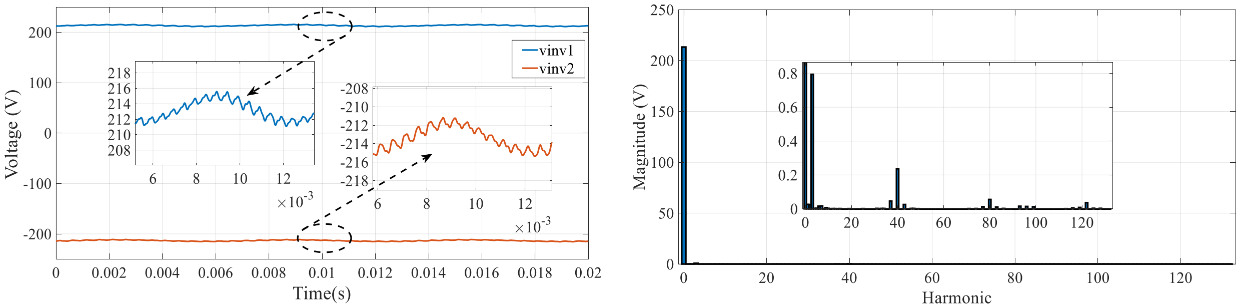
(b.1) PV array current waveform, $i_{PV}(t)$

(b.2) PV array current harmonics, I_{PV}



(c.1) Boost current waveform, $i_l(t)$

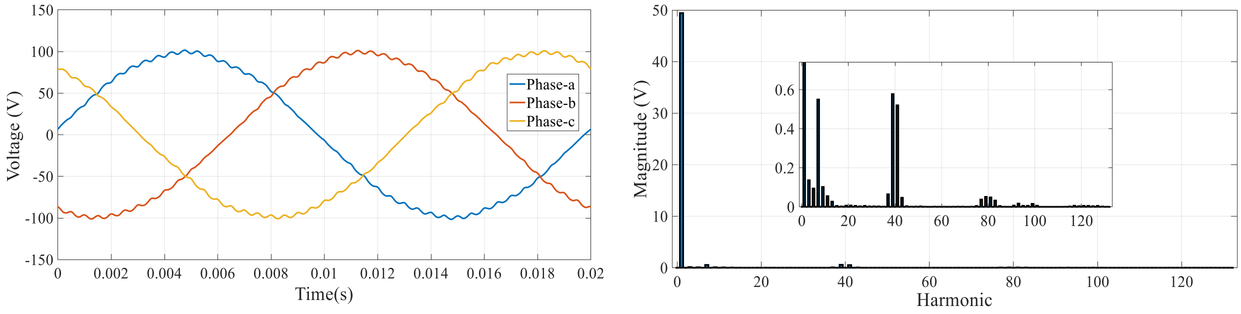
(c.2) Boost current harmonics, I_l



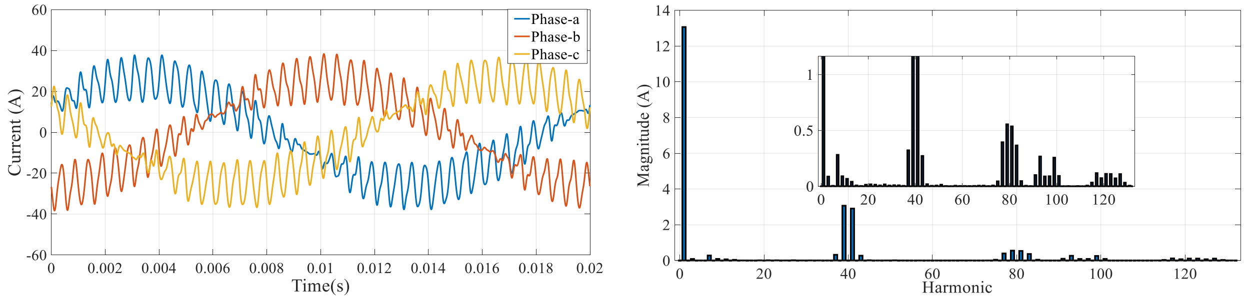
(d.1) Inverter capacitor voltage waveform, $v_{inv}(t)$

(d.2) Inverter capacitor voltage harmonics, V_{inv}

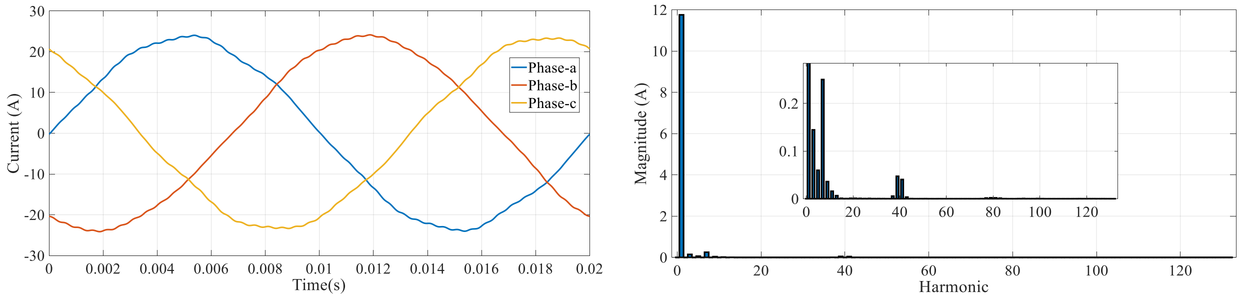
Figure 4. Simulation results time domain and harmonic domain.



(e.1) Filter voltage waveform, $v_f(t)$ (e.2) Filter voltage harmonics, $\mathrm{V_f}$



(f.1) Filter current waveform, $i_f(t)$ (f.2) Filter current harmonics, $\mathrm{I_f}$



(g.1) PCC current waveform, $i_{ft}(t)$ (g.2) PCC current harmonics, $\mathrm{I_{ft}}$

Figure 4. Continue simulation results time domain and harmonic domain.

5. Conclusion

This paper has introduced FHD model of PV grid connected system. The state space of the system is obtained and converted into HD. This HD is then transformed into reduced order FHD that contains only important frequencies. The stationary state computation of the system is calculated. The obtained results successfully represent the harmonic content of the proposed system without the need of full-sized HD. For each state of the system, FHD solution provides the waveforms using single matrix operation. This requires less computational resources for modeling switches devices. The results also provide detailed ripple information at each state of the system. These results assure the feasibility of the proposed FHD technique.

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