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A Novel Technique for Harmonics Estimation in Smart Urban Utility Grid with Solar Photovoltaic

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Abstract
Revolution in the field of electrical energy system is happening worldwide and existing grids are transforming into smart grids. The vision of smart grid demands a cutting edge technology for integrating the different renewable energy sources. Integration of renewable such as solar photovoltaic (PV) pose various challenges in the system, one such challenge is harmonics generation. Harmonics are generated by the associated power electronics based interfacing devices. Moreover the load connected to the distribution system is nonlinear and harmonic is rich in nature. Therefore, a lot of harmonics is injected into the system either from the source or from the load ends and affects the performance of power system. Harmonic distortions create excessive power loss and abnormal temperature rise, results the overheating of transformer, overheating of neutral conductor and malfunction of protective devices, which endangers the stability and reliability of the system. The smart distribution grid must absorb such concerns through critical technological solutions. In this paper, harmonics are analyzed for a solar PV integrated smart urban utility distribution feeder. In order to obtain the exact nature of harmonics and its contribution, a fast decoupled harmonic load flow algorithm is formulated and implemented on the designed smart utility grid. Results show that a lot of voltage/current harmonics are injected at various buses, lines and transformers by the solar PV and associated interfacing devices which even violates the harmonic limit of IEEE standards 519-1992. The authors feel that in order to achieve the smart distribution grid objectives of clean power supply to the customers, there is a serious necessity to study the issues related to harmonic generation, and further to develop control strategies to mitigate them.
Keywords: Harmonics (THD), fast decoupled load flow, grid integration, solar PV, smart distribution system.

1. Introduction

Harmonics are non-sinusoidal current and voltage waveforms which occur in power systems due to nonlinear characteristics of equipment and connected loads. The solar PV system introduces harmonics in the distribution network. The harmonics are generated in the conversion of DC to AC power by the inverters. The order of harmonics and its magnitude will depend on the power inverter technology, modulation technique, method of commutation and the existence of high or low frequency coupling transformer and interconnection configuration [1-4]. Moreover, the number of solar PV units connected to the grid system and the interaction between grid components and PV units further intensify the harmonic distortions. Such harmonic distortion affects the operation of distribution systems in variety of ways. Oliva and Balda [5] presented the study of two PV system connected to the distribution grid through a PWM inverter and reported the malfunction of harmonic-sensitive equipment due to excessive injection of harmonic current in in the system. In a weak power system where the operation is not perfectly symmetrical, these harmonics can be represented by positive, negative, and zero sequence harmonic components. The unbalance components produce adverse effects on the transformers and connecting cables. The neutral of transformer carries zero sequence and the residual unbalance of positive and negative sequence currents [6-8], which affects the performance of protection system. The objective of this paper is to investigate the harmonics contribution for a solar PV integrated smart utility distribution grid which feed power to the consumers of varying nature. In order to obtain the exact nature of harmonics and its contribution, a fast decoupled harmonic load flow algorithm is formulated and implemented on the designed smart utility grid. Results show a lot of harmonics are injected by the solar PV and associated interfacing devices which even violates the harmonic limit of IEEE standards 519-1992 [18].

This paper is organized as follows; Modeling of solar PV is discussed in Section 2. The harmonic analysis and simulation algorithm is presented in Section 3. Modeling of smart distribution grid system is presented in Section 4 using a practical distribution system. Section 5 presents the results and discussions. Section 6 concludes the paper by summarizing the work carried and investigations made.

2. Modeling of Solar PV System

This section presents the modeling of solar PV module and the interfacing inverter system.

2.1 Solar PV Modules

A PV system exhibits the nonlinear I-V characteristics and introduces harmonics in the system by itself. PV panels are typically made from the modules which contains PV cells. Many PV panels are combined together to build a PV array. For large electric utility or industrial applications, hundreds of PV arrays are interconnected to form a large utility-scale PV system. Accurate model of the PV system is required for analyzing the behavior of entire systems. To model the arrays of solar PV, other effects also need to be considered which influence the external behavior of the system. An ideal PV cell is modeled as a current source which represents the generated current due to incident light and a parallel diode for p-n junction of PV cell. The equivalent model of real PV cell is shown in Figs.1-2. It contains the representation of leakage current proportional to the terminal voltage of a solar cell, a parallel resistance Rp, represents the current leakage through the cell and a series resistance Rs, accounts for an extra voltage drop between the junction and the terminal voltage of the solar cell for the same flow of current. In an ideal situation, to determine upper limit of open circuit voltage and the efficiency of solar cell, it is assumed that only radiative recombination takes place. But In actual solar cell, the recombination via impurities predominates [9-12]. This effect is shown in Fig.3 . The effect of solar array capacitance on the operation of the system [13-14], has been presented in Fig. 2. This capacitance increases the voltage ripple and has the dominant effect on the performance of the switching regulators at higher switching frequencies.

The equation for current and voltage relationship of PV array is expressed in (1).

$$I = I_{ph} - I_0\left[\exp\left(\frac{q\left(V+R_sI\right)}{N_sKT}\right)-1\right]-\left(\frac{V+R_sI}{R_p}\right) \qquad (1)$$

Where, I_{ph} : Photo generated current (A) i.e. current generated by the incident light (it is directly proportional to the sun irradiation), I_d : Diode current (A), I_0 : Reverse saturation or leakage current of the diode (A), q : Charge of electron (1.160217646 $\times 10^{-19}$C), K : Boltzmann constant (1.3806503 $\times 10^{-23}$J/K) , T : Temperature of the p-n junction (°Kelvin), N_s : Number of cells, R_s : Series resistance (Ω), R_p : Parallel resistance (Ω), I_{d1} : Recombination current.

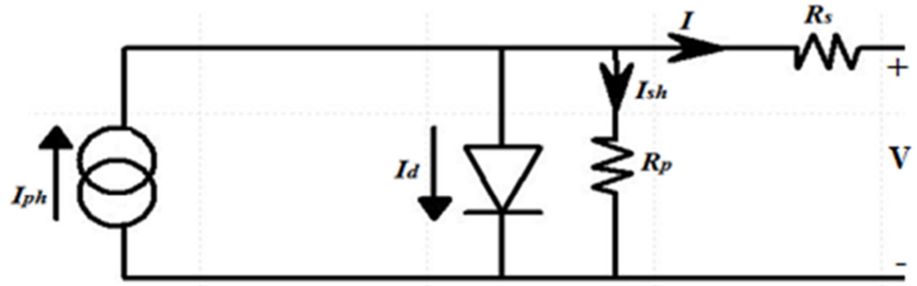

Figure 1 Single diode model of photovoltaic cell

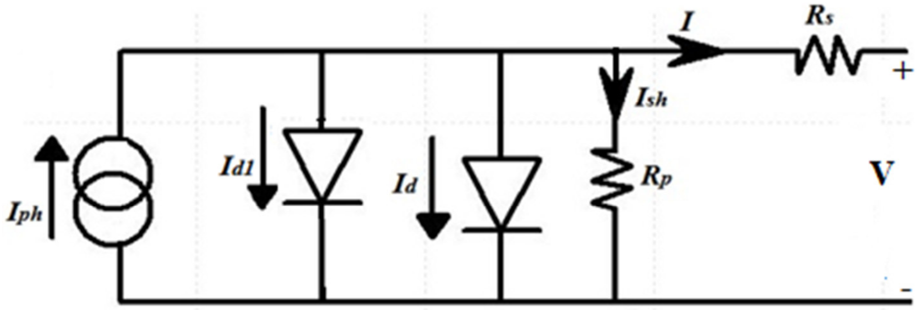

Figure 2 Double diode model of photovoltaic cell

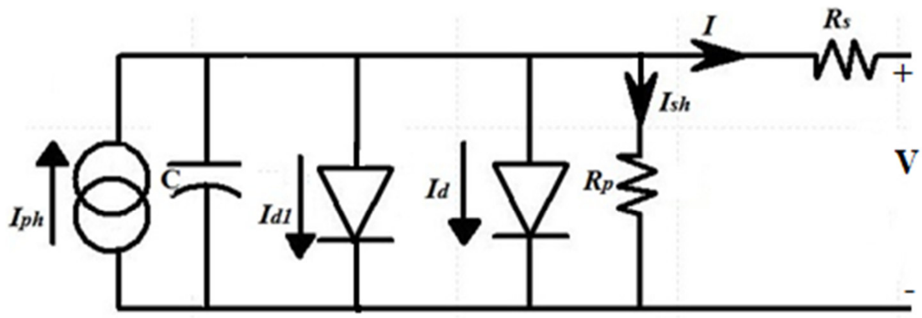

Figure 3 Equivalent circuit with solar array capacitance

2.2 Grid Inverter Modeling

The small signal model [15-16] of the inverter for harmonic studies can be developed as shown in Fig. 4. Where, Ip is the inverter current and Zp is the impedance. If the grid has low fault level, the integration of solar PV inverters may form harmonic resonance with the grid impedance [17]. Such resonance may occur at any frequency depending on inverter and grid impedance characteristics.

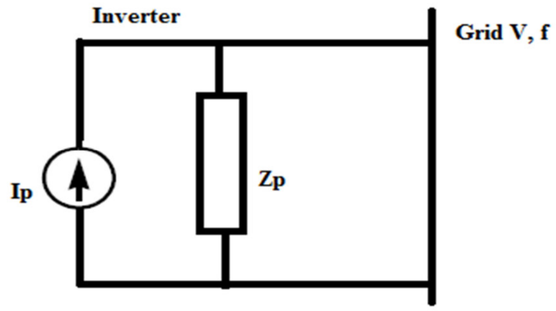

Figure 4 Grid inverter model

3. Modeling of Smart Utility Distribution Grid

The model of a generic utility distribution grid is presented in Fig.5, which supplies power in a residential area, a shopping complex and a small industry. Two transformers, each of capacity 15 MVA, 33/11 KV are operating in parallel to cater the power demand. The loads are variety of nature particularly the industry has mixed lighting and motor loads, variable speed drives are used to control the speed of induction motors, the capacity of load connected at various buses is presented in Table 1. The rating details of the solar PVs installed at various buses are given in Table 2.

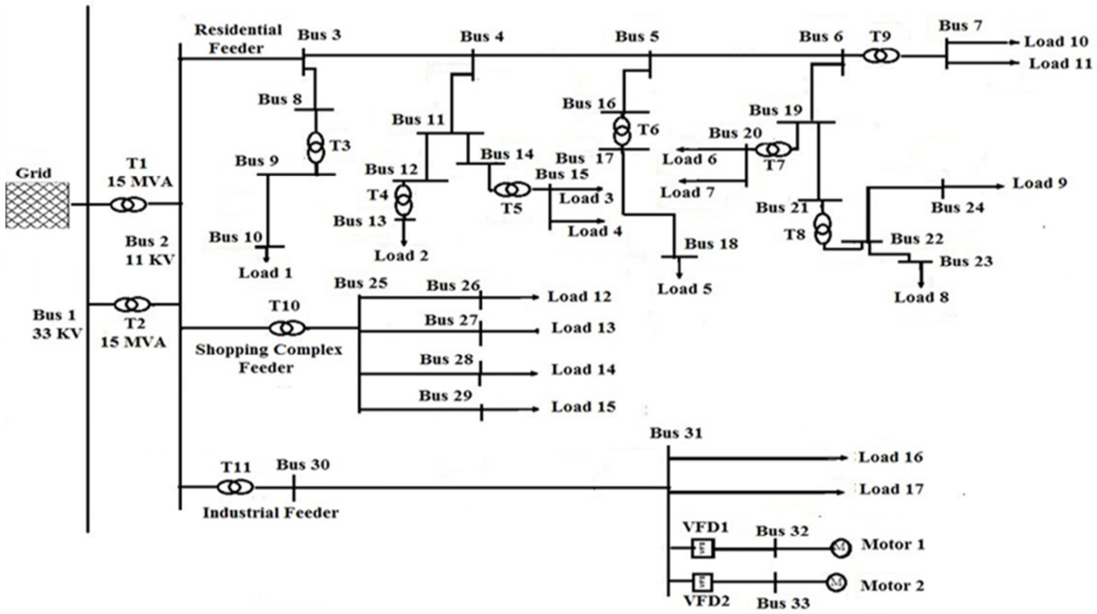

Figure 5 Model of a smart urban utility distribution feeder

Table1 Load on the various buses of utility distribution feeder

Load Id.	Bus Id.	Capacity (MW)
1	10	1
2	13	1
3	15	0.6
4	15	0.5
5	18	0.8
6	20	0.8
7	20	0.6
8	23	0.6
9	24	0.8
10	7	0.8
11	7	0.8
12	26	0.6
13	27	0.6
14	28	0.8
15	29	0.6
16	31	0.6
17	31	0.6
Motor 1	32	0.5
Motor 2	33	0.5

Table2 Rating of solar PV connected at various buses

Bus Id.	PV panel (Watt/panel)	Rating of solar PV (MW)
7	280	0.5
9	280	1
13	280	0.5
15	280	1
23	280	0.5

4. Formulation of Harmonic Power Flow Algorithm

This section presents the decoupled harmonic power flow algorithm to assess the individual harmonic contribution of voltage and total harmonic distortion. The conventional Newton-Raphson power flow algorithm is used to obtain the fundamental component of voltage. At harmonic frequency the harmonic admittance matrix is formulated for the solar PV integrated nonlinear distribution system. The PVs system injects harmonic current into the utility distribution grid. The h^{th} harmonic admittance of various components can be expressed by equations (2-5).

$$y_k^{(h)} = \frac{P_{lk}}{\left|V_k^{(1)}\right|^2} - j\frac{Q_{lk}}{h\left|V_k^{(1)}\right|^2} \tag{2}$$

$$y_{cap,k}^{(h)} = h y_{cap,k}^{(1)} \tag{3}$$

$$y_{k,k+1}^{(h)} = \frac{1}{R_{k,k+1} + jhX_{k,k+1}} \tag{4}$$

$$y_p^{(h)} = \frac{1}{z_p^{(h)}} \tag{5}$$

The current injected by solar PV inverter is given by equations (6-7)

$$I_{sPV,k}^{(1)} = \left[\frac{P_{sPV,k} + jQ_{sPV,k}}{\left|V_k^{(1)}\right|^2}\right]^* \tag{6}$$

$$I_{sPV,k}{}^{(h)} = R(h) I_{sPV,k}{}^{(1)} \quad (7)$$

Where

$y_k{}^{(h)}$	h^{th} harmonic load admittance at bus *k*
$y_{cap,k}{}^{(h)}$	shunt capacitor admittance at bus *k*
$y_{k,k+1}{}^{(h)}$	feeder admittance between bus *k* and *k+1*
$y_p{}^{(h)}$	admittance of filter p at h^{th} order harmonics
P_{lk} , Q_{lk}	Load active and reactive power at bus *k*
$y_{cap,k}{}^{(1)}$	Fundamental frequency admittance of the capacitor connected at bus *k*
$R_{k,k+1}$, $X_{k,k+1}$	Resistance and reactance of the branch connected between bus *k* and *k+1*
$R(h)$	Ratio of h^{th} order harmonic current to its fundamental value
$I_{sPV,k}{}^{(1)}$	Fundamental current of solar PV connected at bus *k*
$P_{sPV,k}$, $Q_{sPV,k}$	Real and reactive power generated by solar PV at bus *k*
$I_{sPV,k}{}^{(h)}$	Harmonic current of solar PV connected at bus *k*

Finally, a set of nodal equations are solved for assessing the harmonic voltage profile values using (8)

$$Y^{(h)} V^{(h)} = I^{(h)} \quad (8)$$

The steps to implement decoupled harmonic power flow analysis are given below:

step 1) Perform the conventional power flow analysis to obtain the results at fundamental frequency.
step 2) Calculate the admittance of various components as given in equations (2-5) at h^{th} order harmonic.
step 3) Calculate the current injection from solar PV using equations (6-7).
step 4) Solve the set of nodal equations using equation (8) and obtain harmonic distortions.

5. Results and Discussion

This section presents the analysis of harmonics generation due to solar PV inverters at the various buses, branches and transformers of the modeled smart rural distribution grid. Figs. 6-8 show the distorted voltage waveform and corresponding harmonic spectrum at various buses such as bus7, 9 and 23. It is observed that dominant order is the fifth then other higher order harmonics are also present with more or less degree. In spectrum it is clear that the IEEE limit of individual voltage harmonic dissertation exceeds which increases the total harmonic distortion level as well. Fig. 9-10 presents the current waveform in the line 2, 9 and corresponding harmonic spectrum. In current spectrum it is clear that seventh order harmonics is the dominant harmonics here also the current limit exceed the prescribed IEEE standard limits. Figs 11-12 show the harmonic current waveform and spectrum in the transformer T3 and T8. The harmonic current and voltage contributions are very high with solar PV system even exceeds the IEEE519-1992 limits as presented in table 3 and 4. Such distorted power quality situation is harmful to the system equipment such as transformer in which the heating of neutral conductor occurs. Notwithstanding the other connected equipment also affected by the harmonics in the supply.

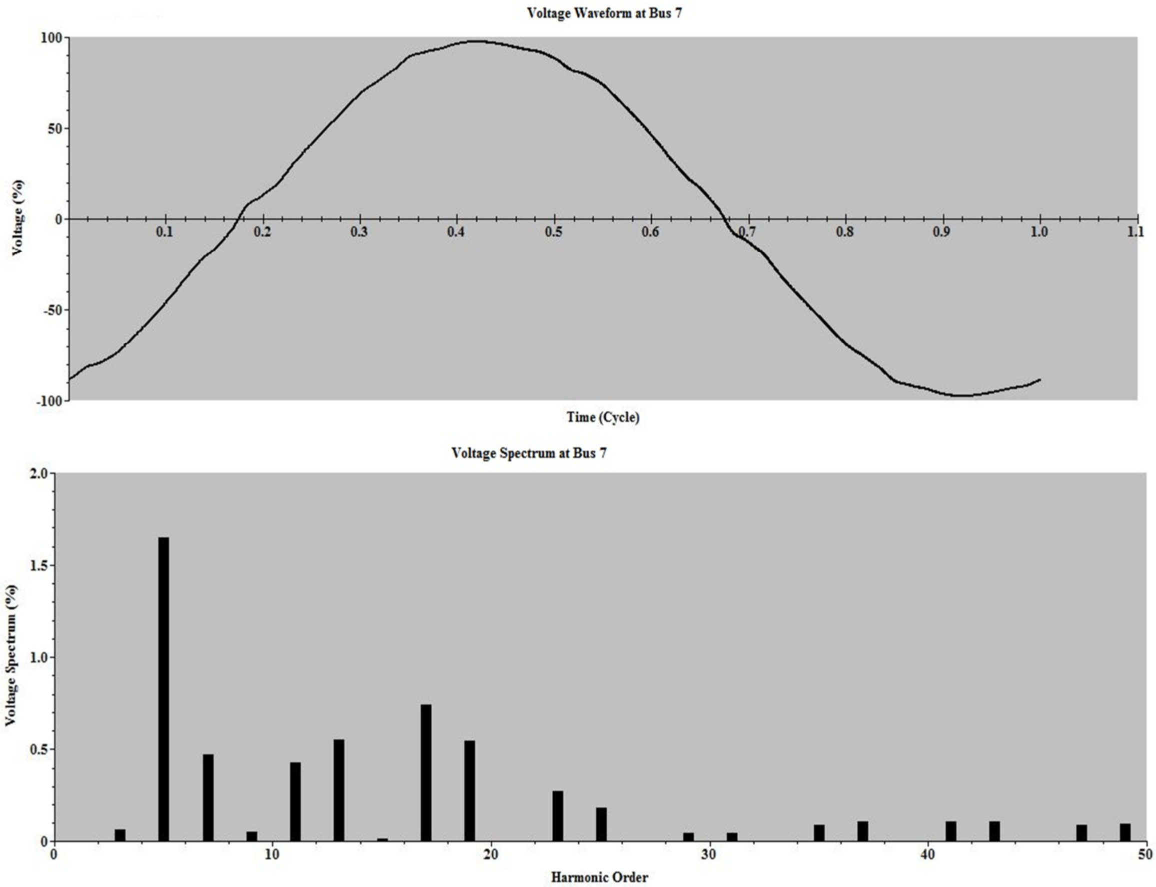

Figure 6 Voltage waveform at bus 7 and harmonics spectrum

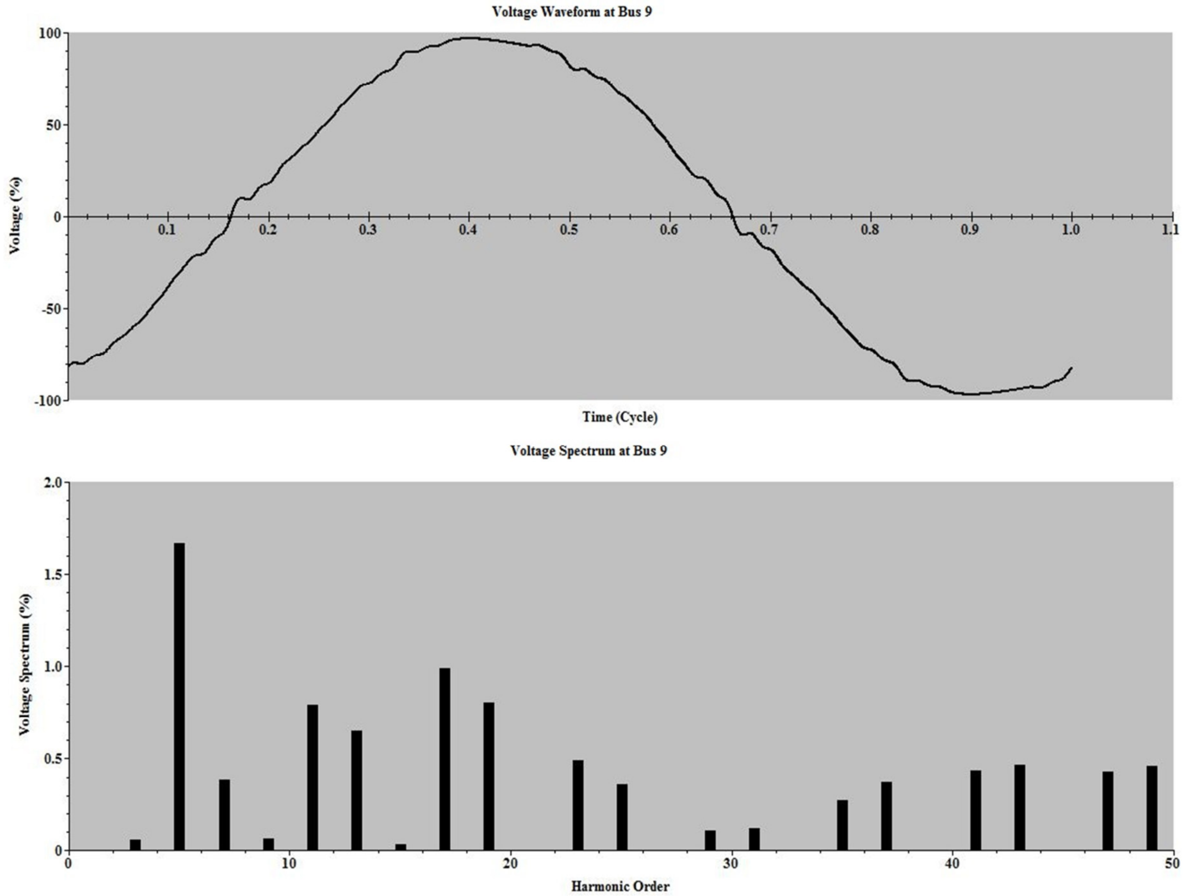

Figure 7 Voltage waveform at bus 9 and harmonics spectrum

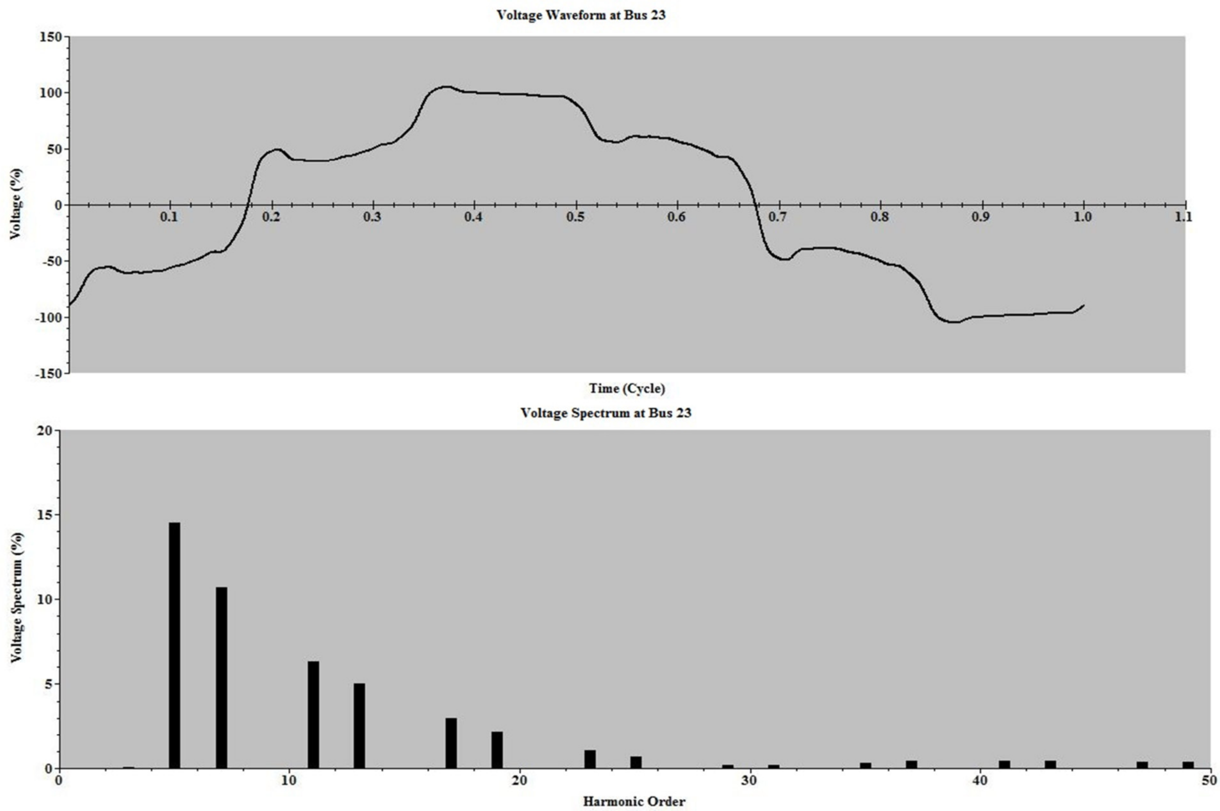

Figure 8 Voltage waveform at bus 23 and harmonics spectrum

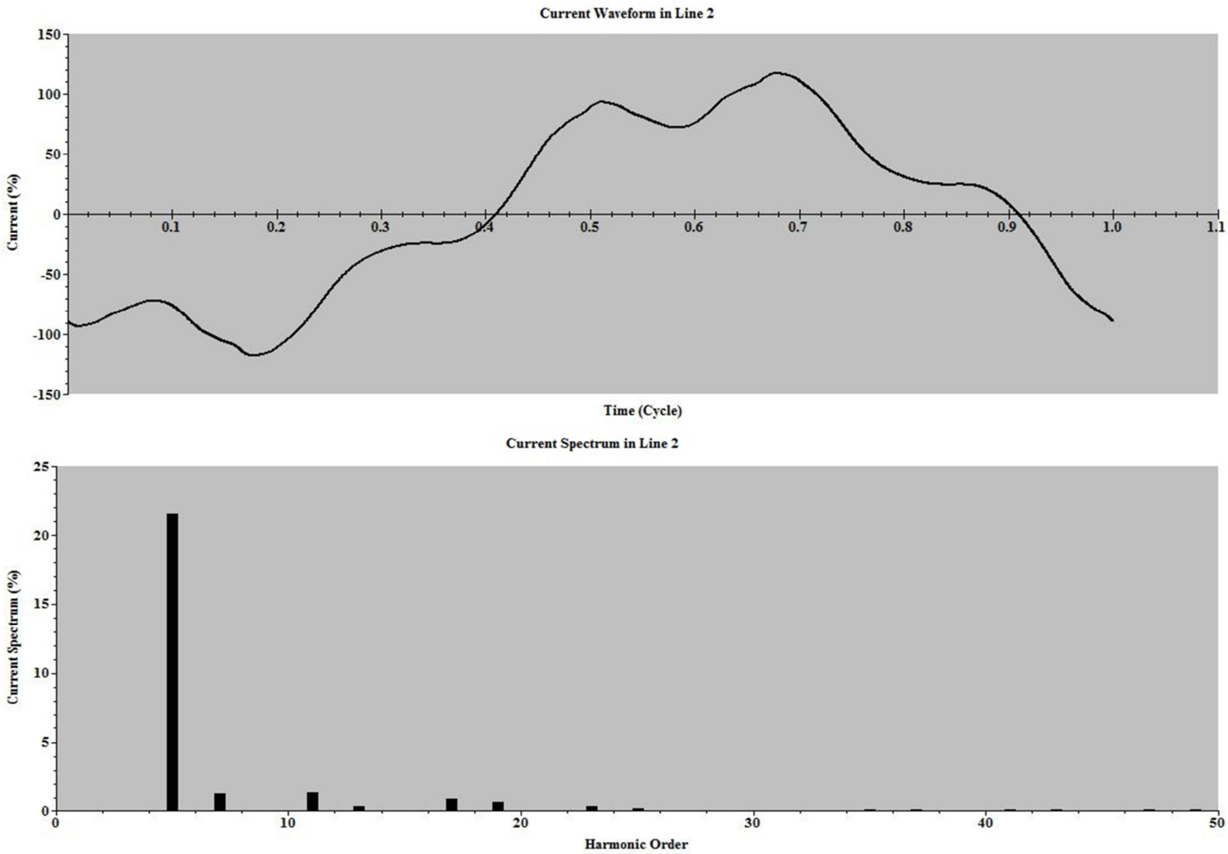

Figure 9 Current waveform in line 2 and harmonics spectrum

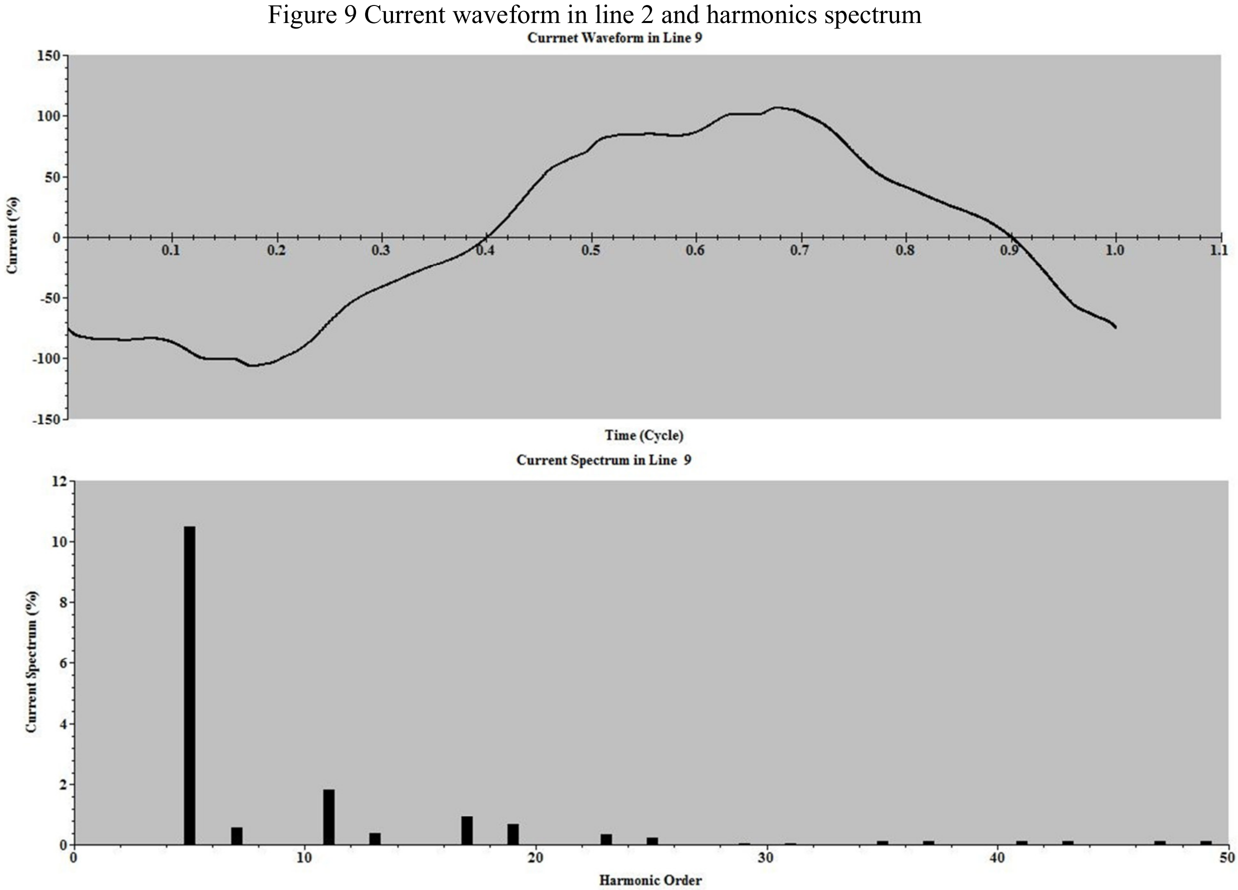

Figure 10 Current waveform in line 9 and harmonics spectrum

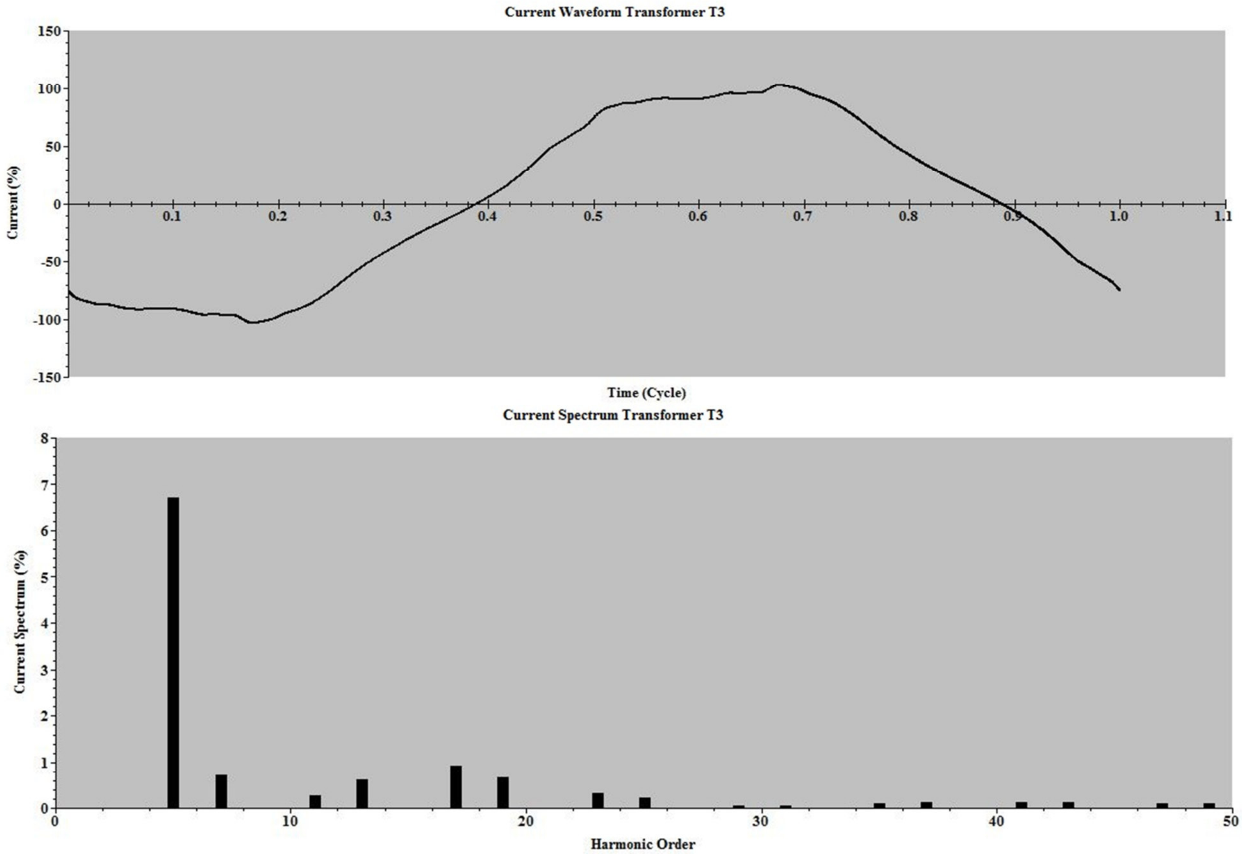

Figure 11 Current waveform in transformer T3 and harmonics spectrum

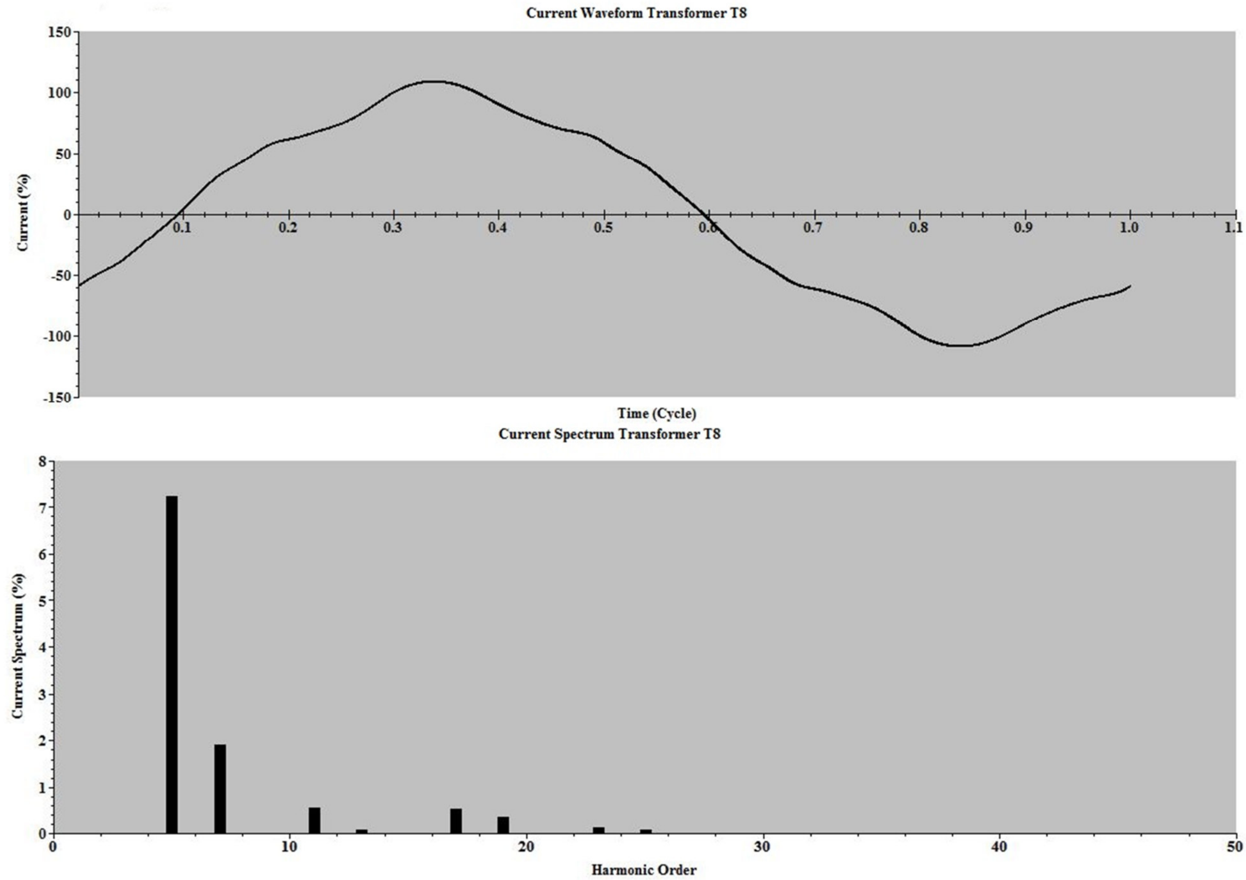

Figure 12 Current waveform in transformer T8 and harmonics spectrum

Table 3 Voltage Harmonics Distortion at various Buses

Sr. No.	Bus Id.	Voltage THD (%)	IEEE std. 519-1992 Voltage THD (%)
1	7	15.57	5
2	9	19.81	5
3	13	20.58	5
4	15	21.28	5
5	23	18.19	5

Table 4 Current harmonics distortion in various branches

Sr. No.	Line Id.	From	To	Current THD (%)	IEEE std. 519-1992 Current THD (%)
1	3	Bus3	Bus8	55.07	5
2	4	Bus4	Bus11	40.18	5
3	8	Bus11	Bus14	36.22	5
4	9	Bus11	Bus12	38.92	5

6. Conclusion

In this paper a harmonic power flow approach is implemented for a utility distribution grid with solar PV integration. It is observed that solar PV increases the harmonic proportion in the distribution grid beyond the prescribed limits, which is a major challenge and needs to be addressed in integration process. The grid must be able to absorb these challenges in order to achieve the smart grid objectives. For designing a filter to eliminate the harmonics their exact nature, individual contribution and THD are required. Traditional power flow algorithms do not provide above information. Therefore, a decoupled harmonic power flow algorithm has been implemented to obtain the various harmonics indices and a comparison with and without solar PV has been presented. The analysis presented in this paper will be helpful for designing a filter and make the system harmonic free.

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