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A Proposed Single-Tuned Filter for Harmonic Reduction in Grid-Tied PV Systems

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ABSTRACT
The increasing of the Photovoltaic (PV) systems penetration requires study of their effects on the grid's power quality. Therefore, in this paper the grid-tied PV system is studied. This needs an appropriate simulation of the PV system. Therefore, PSCAD/EMTDC is used in this study. The paper starts with investigation of the effect of PV on the harmonic distortion of the system. Finally, a proposed low-cost series connected single tuned-filter is designed for harmonic reduction in grid-tied PV systems. The results confirm the validity of the proposed filter for wide rating of PV systems.

Keywords: PV Systems, Harmonic Reduction, Series single tuned filter, PSCAD/EMTDC.

1. INTRODUCTION

Power quality becomes an important issue due to the use of electronic devices [1]. The grid voltage is assumed pure sinusoid at a fundamental frequency [2]. The development of the smart grid and the distributed generation based microgrid makes the photovoltaic (PV) systems more effective at sunny region [3].

Rapidly increasing of power electronics applications and utilization makes both grid operators and customers and knowing about the harmonic distortion and the utility power quality. Connecting PV to the grid introduces more harmonic problems. Therefore, all previously literatures conclude that more studies are needed on the effects of high PV penetration on the grid's power quality [3]. In this paper, PSCAD/EMTDC is used for simulating the grid–tied PV system [4].

Passive filters, active filters, and/or hybrid filters are used for mitigating the harmonic distortion. However, passive filters are widely used for harmonic reduction and reactive power compensation, due to its simple design and cost acceptable. Passive filters are designed from non-active component such as resistors, inductors, and/or capacitors. It provides low impedance path for non-sinusoidal components flow [5].

Single-tuned filter is low cost and simple in configuration. Therefore, it is commonly used as compared to the other methods of harmonic mitigation. These filters are connected in the shunt with the system and provide low impedance path to the harmonics [6].

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Therefore, in this paper a simple single–tuned passive filter is proposed for harmonic reduction in grid–tied PV systems. nI section II, the grid–tied PV system is simulated in PSCAD/EMCDT and the noitalumis is verified. The harmonics generated in the test system are briefly analyzed, in section III, via individuals and total harmonics at all system regions. Also, a proposed filter is designed in selection IV and the result are discussed and analyzed in section V. Finally, the overall calculation is summarized in section VI.

2. GRID-TIED PV SYSTEM SIMULATION

A. MODEL DESCRIPTION AND SIMULATION

The solar cell module is a semiconductor device that converts the solar radiation directly to electrical energy. The modules are connected in series and in parallel to form a PV array with the required rated power. Fig. 1a illustrates a schematic diagram for grid-tied PV system [7]. The system contains PV source, a dc-link capacitor, a dc-dc converter, a dc-dc controller with Maximum Power Point Tracking (MPPT), a grid interface inverter with a filter and a step-up transformer. The PSCAD/EMTDC model for the grid-tied PV system is illustrated in Fig. 1b.

The converter transfers maximum power from the PV module to the load by changing the duty cycle [8]. It is used for MPPT by control by achieving a reference voltage and a PI controller.

The converter transfers maximum power from the PV module to the load by changing the duty cycle [8]. It is used for MPPT by control by achieving a reference voltage and a PI controller. Fig. 2a illustrates the simulation of the reference voltage (V_{MPPT}) generation. The PV current (Iarray) and voltage (Varray) must pass through a filter [3].

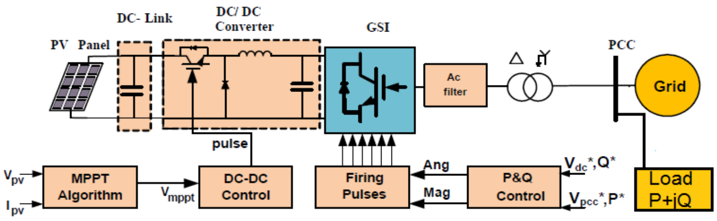
The objective of the converter control is to keep the PV voltage equals to the voltage at MPPT. The difference between Varray and Vmppt is used as an input to a PI controller. Its output and a saw tooth waveform are compared to generate a 1 kHz frequency duty cycle, as shown in Fig. 2b.

The three-phase inverter is constructed by three pairs of IGBT switches and the snubber circuits are used to to protect them from damage. The sine wave generators and the triangular waveform generators are used to determine the switches on-off states [9], as shown in Fig. 2c.

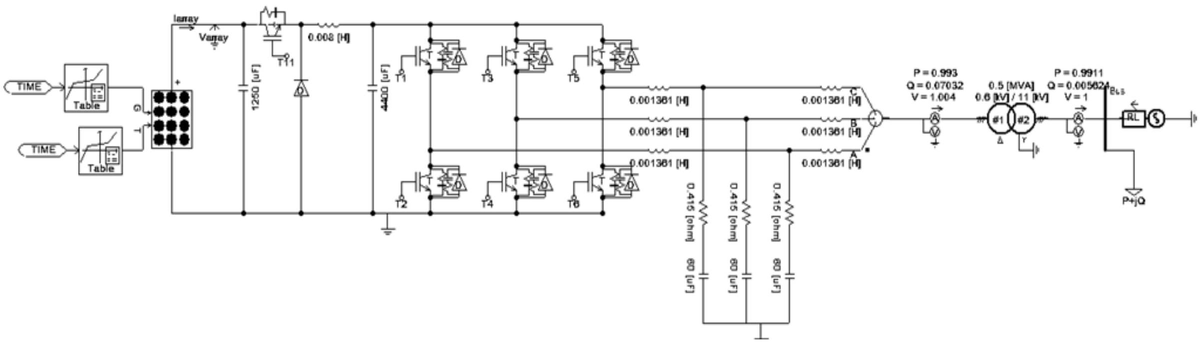
The PV active and reactive power is controlled by power flow equations. The difference between the voltage of the inverter and the dc voltage is fed into a PI controller. The controller output is the phase angle of firing pulse which is used as an input to the firing pulse generator as shown in Fig. 2d. The difference between the inverter's output voltage and the grid voltage is used as an input to another PI controller. The output is used as an input to the pulse generator, as shown in Fig. 2e.

The LCL filter is used to remove the high order harmonics and to confine the variation of maximum power within 5%. The filter capacitance is 60 μF. The inverter's and grid's inductance are 1.361 mH and 0.1 mH, respectively, as shown in Fig. 1b [9].

A 0.5 MVA, 0.6/11 kV, Δ/Y transformer is used. The copper losses and no-load losses of the transformer are 0.2 pu and 0.01 pu, respectively. The PV array operates at 1.5 kV and 0.27 MW due to the MPPT effect [10].



(a) Schematic diagram of Grid-tied PV system



(b) The PSCAD/EMTDC simulation

Fig. 1: The Grid-tied PV system

B. VALIDATION OF THE SIMULATION

The grid-tied PV simulation is validated via a comparison between the outputs and previously published results in [9]. It is noted that the irradiation and temperature are changed as Table 1 and, therefore, the voltage, current, and power are affected.

Fig. 3 shows the closeness between the results of the simulation and the published, that confirming the validity of the simulation results and readiness to make any modification to it.

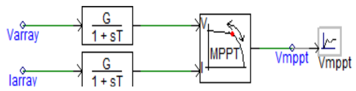
Table 1: Input of the test conditions of PV array [9]

Seconds	*Irradiance (Wm^{-2})*	*Temperature (°C)*
0 < t <3.	1000.0	25.0
0 < t < 6.	800.0	30.0
3. < t < 9.	600.0	50.0
6. < t < 11.	400.0	40.0
9. < t < 13.	200.0	50.0
11. < t <16.	1000.0	40.0

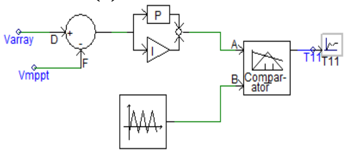
3. HARMONIC ANALYSIS OF GRID-TIED PV SYSTEM

Harmonics are periodic waves with multiples of original system frequency. Connecting of PV systems to the grid generates harmonics. Therefore, power quality standards regulate the effects of such grid-tied PV system. One of the standards is IEEE Std 929-2000 "IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems" [11] which ensures accepted operation of grid-tied PV systems. It is recommended by this standard, that the harmonic distortion at the connection point between the PV system and the grid, should satisfy the IEEE Standers [11].

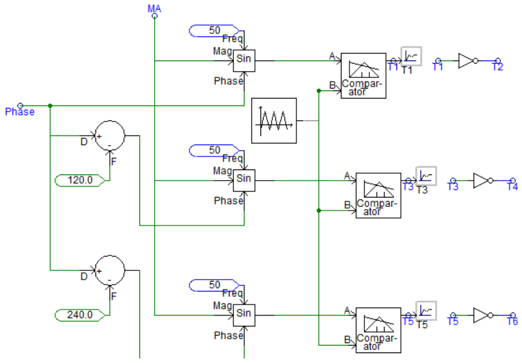
For safe operation of the grid-tied PV system IEEE Std recommended total harmonic current distortion less than 5% [11]. Table 2 gives the limits of individual harmonic.



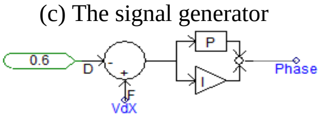
(a) MPPT control



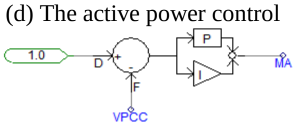
(b) The converter control



(c) The signal generator

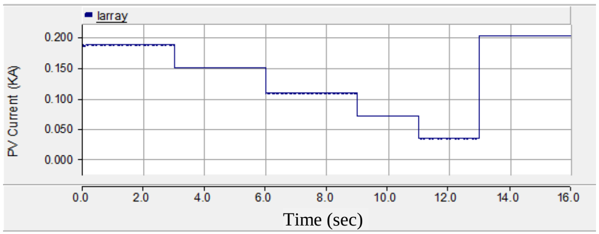


(d) The active power control

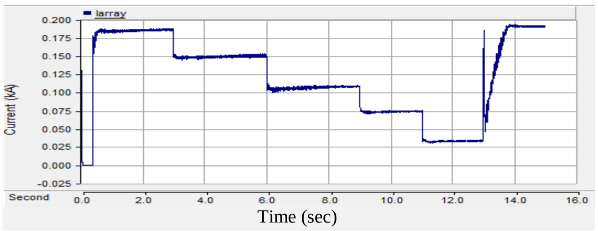


(e) The reactive power control

Fig. 2: PV Grid-tied Controllers simulation in PSCAD/EMTDC



(a) Simulated current



(b) Published current

Fig. 3: A comparison between the simulated and the published current in [9]

In order to teg the Total Harmonic Distortion (THD) for both voltage and current, the PSCAD/EMTDC is used as illustrated in Fig. 4. Fast Fourier Transform (FFT) is used for determining the harmonics as a function of time. Furthermore, it is used for determining both the total and individual harmonic distortion (HD) in percentage (%). The FFT block is configured to output the magnitude of 15 harmonics with the fundamental frequency. The inputs to this block are the three RMS values of the three-line currents at measuring point or voltage of the three-phases

Table 2: IEEE Std. for Distortion Limits of the Current

Harmonic	Distortion Limit
3^{rd} – 9^{th}	< 4.0%
11^{th} – 15^{th}	< 2.0%
17^{th} – 21^{st}	< 1.5%
23^{rd} – 33^{rd}	< 0.6%
Above the 33^{rd}	< 0.3%

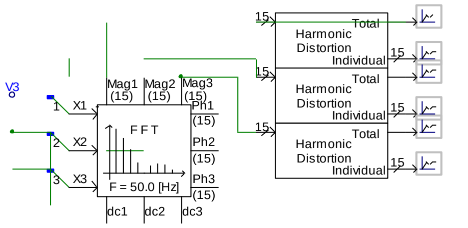
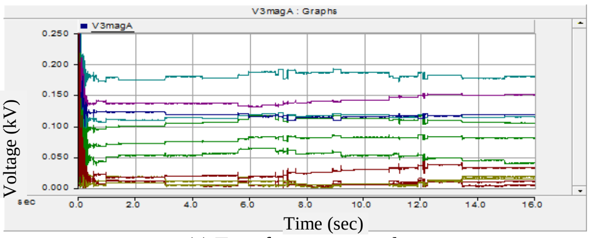
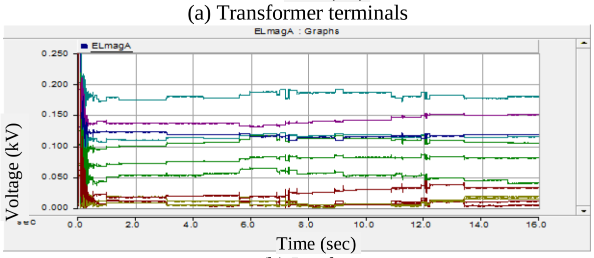


Fig. 4. PSCAD/EMTDC simulation for calculating the individual harmonics and THD

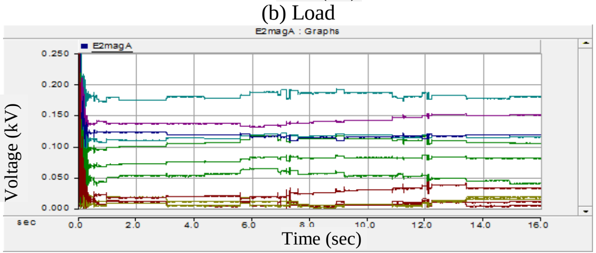
Fig. 5 shows the individual voltage harmonic distortion without using filters at the transformer terminal, the load and the grid. Also, the total harmonic distortion of the voltage is presented in Fig. 6 at radiation of 1000 w/m^2 and temperature of 25 ^{0}C. It can be seen the equality of the individual voltage harmonics at the three coupled points. The individual and the total harmonics are more than the international standards' limits as given in Table 3.



(a) Transformer terminals

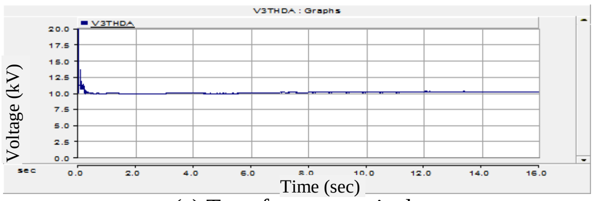


(b) Load

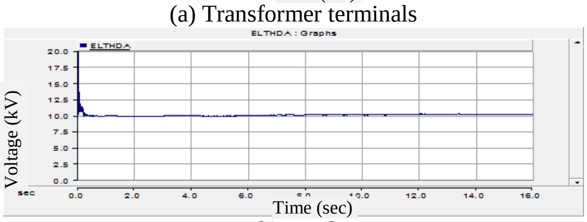


(c) Grid

Fig. 5: The voltage harmonic distortion for phase A for grid-tied PV system without filtering



(a) Transformer terminals



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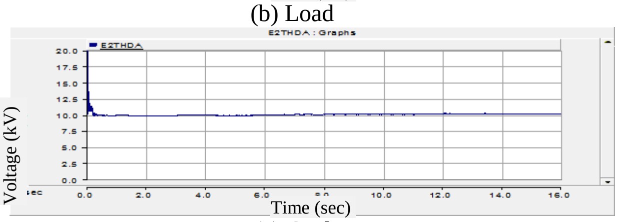


(c) Grid

Fig. 6: The voltage THD for grid-tied PV system without filtering

Table 3: Harmonics of Grid-tied PV system without filtering

Harmonic	Filter less HDi %	HDi Limits %	Filter less HDv %	HDv Limits %
5^{th}	6.166	4.0	6.122	3.0
7^{th}	5.333	4.0	6.236	3.0
11^{th}	1.833	2.0	2.450	3.0
13^{th}	1.500	2.0	1.930	3.0
THD	9.576	5.0	10.201	5.0

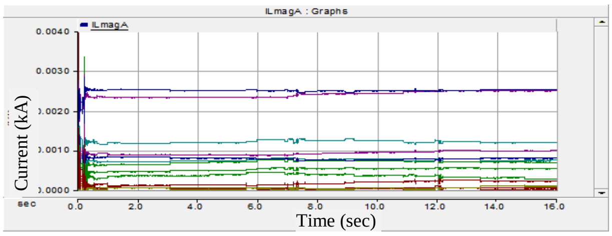
Furthermore, Figs. 7 and 8 illustrate the individual current harmonic distortion without using filters at the load and the transformer terminals, respectively. Both the time domain waveforms and the polymeter diagrams are given at radiation of 1000 w/m^2 and temperature of 25 ^{0}C. Also, Table 3 gives the current harmonic values at radiation of 1000 w/m^2 and temperature of 25 ^{0}C.

Besides, Fig. 9 illustrates THD of the current of phase A at the transformer terminals and the load. It can be seen that, there are inequality of the individual current harmonics. The individual and the total harmonics are more than the international standards' limits as given in Table 3.

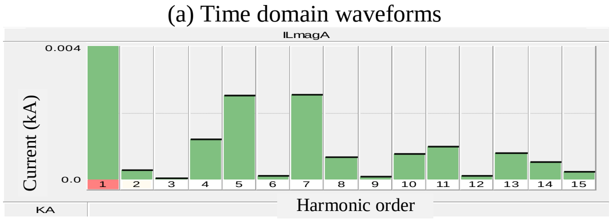
4. THE PROPOSED DESIGN

The proposed filter is based on simplicity of design aiming for reducing the passive components for lowering the total filter cost. Therefore, a simple RLC filter is proposed, as seen in Fig. 10. Then, two three-phase inductors are eliminated.

The calculation of the required reactive power of the filter (Q_C) is used to reduce the current harmonics disturbance (HDi) in this study. The 5th and 7th order of harmonics will be reduced. The three-phase system is considered in a balanced state.

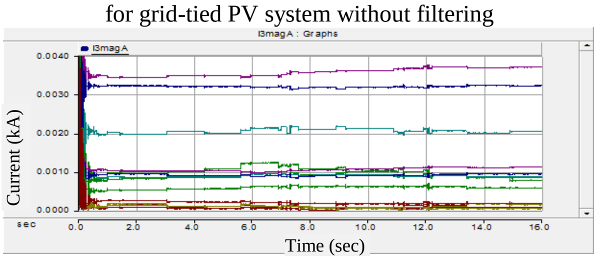


(a) Time domain waveforms

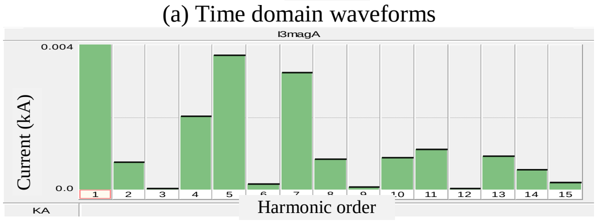


(b) Polymeter

Fig. 7. Individual harmonics of the currents of phase A at load for grid-tied PV system without filtering

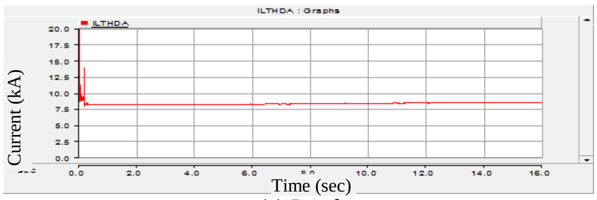


(a) Time domain waveforms

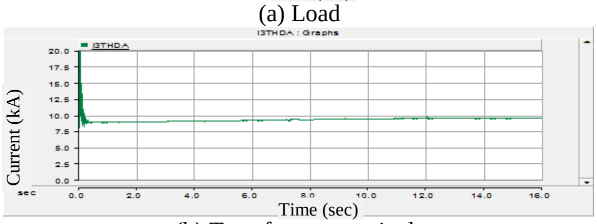


(b) Polymeter

Fig. 8: Individual harmonics of the currents of ph-A at transformer terminals for grid-tied PV system without filter



(a) Load



(b) Transformer terminals

Fig. 9: The current THD at the load and the transformer terminals of grid-tied PV system without filtering

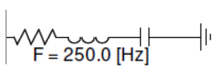


Fig. 10: The proposed single-tuned filter model in PSCAD/EMTDC

The power factor is proposed to be improved from pf$_1$ to pf$_2$. Equations (1) and (2) illustrate the design of the propose filter ratings.

$$Q_c = P_L\,[\tan\varphi_1 - \tan\varphi_2] \qquad (1)$$

$$\tan\varphi_1 = \frac{Q_L}{P_L} \qquad (2)$$

where P_L and Q_L are the load active and reactive powers, respectively. Cos φ_1 and Cos φ_2 are the power factor before compensation (pf_1) and the proposed power factor (pf_2). Assuming that $Cos\phi_2 = 0.99$, it is found that Q_C = 0.1424 MVAR for the studied system.

Assuming that the quality factor of the proposed filter (Q_f) is 100 [6, 12], the passive components (C, L, and R) of the proposed filter can be calculated, as given in equations (3)-(5).

$$C = {Q_c}/{2\pi f V^2} \qquad (3)$$

$$L = {X}/{2hf} \qquad (4)$$

$$R = {1}/{2\pi f C} \qquad (5)$$

where V and f are the power system voltage and frequency, X is the inductive reactance of filter, and h is the harmonic order of the filter.

5. RESULTS AND ANALYSIS

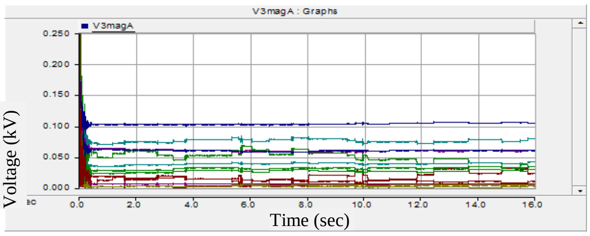
The proposed single-tuned filter reduces the current THDi, from 9.576% to 4.649%, by 51.45% from filter-less testing results and the voltage THDv from 10.201% to 2.532%, by 75.18% from filter-less testing results.

The filter reduction of the current and voltage harmonicas in each order is given in Table 4 and Table 5. Table 4 shows the change of the 5^{th} harmonic order, HDi, which is the target of harmonic to be reduced. It is noted that the proposed single-tuned RLC filter decreases the current harmonics by 99.95%, from 6.166% to 0.00286%. The decrease of 7^{th} harmonic order, HDi, is 57.03%. Also, the reduction in both 11^{th} and 13^{th} HDi is given.

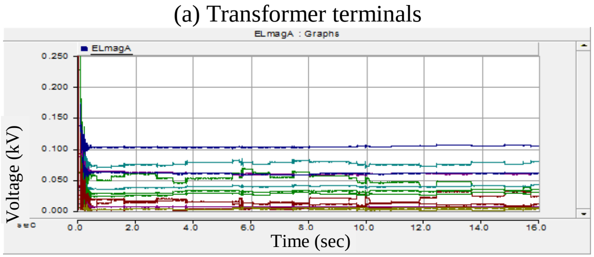
Furthermore, Table 5 gives the change of the 5^{th} harmonic order, HDv, which is the target of harmonic to be reduced. It can be seen that the proposed single-tuned filter decreases the voltage harmonics by 98.56%, from 6.122% to 0.0878%. The decrease of 7^{th} harmonic order, HDv, is 75.58%. Also, the reduction in both 11^{th} and 13^{th} HDv is given.

Fig. 11 shows the voltage harmonic distortion using the proposed filter at the transformer terminal, the load and the grid. Also, the total harmonic distortion of the voltage is presented in Fig. 12. It is seen the same equality of the individual voltage harmonics at the three coupled points in addition to the reduction in the harmonic distortion.

Furthermore, Fig. 13 illustrates the individual current harmonic distortion with using the proposed filter at the load and the transformer terminals, respectively. Besides, Fig. 14 illustrates the total harmonic distortion of the current of phase A at the transformer terminals and the load. It can be seen the reduction in the harmonic distortion.



(a) Transformer terminals



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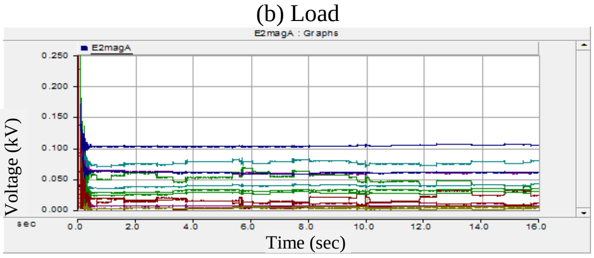
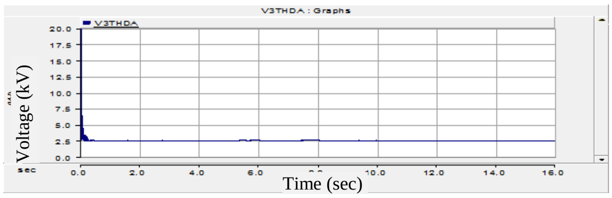
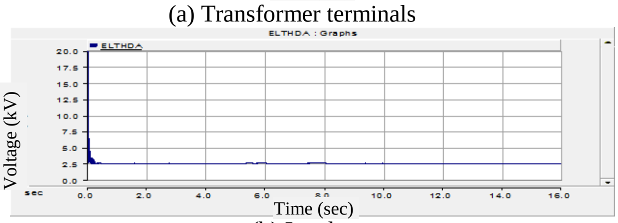


(c) Grid

Fig. 11: The voltage harmonic distortion for phase A of grid-tied PV system with the proposed filter



(a) Transformer terminals



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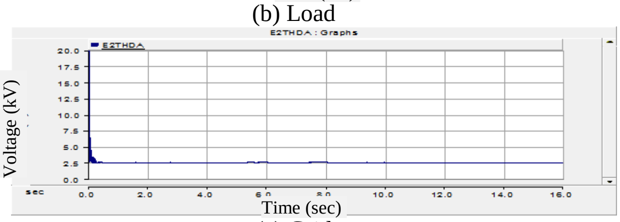
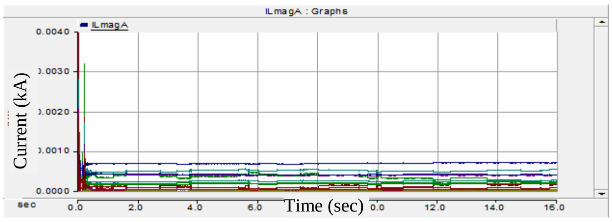


(c) Grid

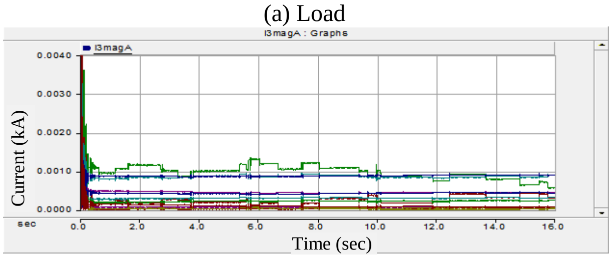
Fig. 12: The voltage THD with the proposed filter

Table 4. Current Harmonic Decreasing Rate by Using the Proposed Filter

Harmonic Order	Filter less HDi %	The proposed Filter HDi %	Decrease Rate (%)
5	6.166	0.00286	99.95
7	5.333	2.292	57.03
11	1.833	1.146	37.48
13	1.500	1.146	23.6
THDi	9.576	4.649	51.45

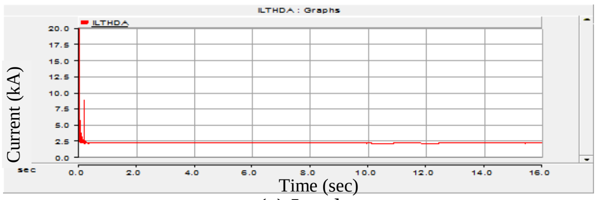


(a) Load



(b) Transformer terminals

Fig. 13: Individual current harmonics of phase A at load and transformer terminals for with the proposed filter



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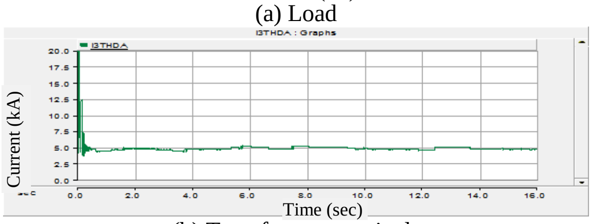

(b) Transformer terminals

Fig. 14: The current THD at the load and the transformer terminals with the proposed filter

6. CONCLUSION

In this paper a detailed simulation of the grid-tied PV system using PSCAD/EMTDC is presented. Then, investigate the effect of PV system on the power system quality. Finally, a simple single-tuned passive filter is proposed for harmonic reduction in grid–tied PV systems. The proposed filter successes in mitigating the odd harmonics in grid-tied PV system. The fifth harmonics is the main objective in this study to be filtered. The proposed filter is simple compared with other filter types.

Table 5. Voltage Harmonic Decreasing Rate by Using the Proposed Filter

Harmonic Order	Filter less HDv %	The proposed Filter HDv %	Decrease Rate (%)
5	6.122	0.0878	98.56
7	6.236	1.523	75.58
11	2.450	0.878	64.16
13	1.930	0.864	55.23
THDv	10.201	2.532	75.18

REFERENCES

[1] J. Leisse, "Electricity Meters for Coordinated Voltage Control in Medium Voltage Networks With Wind Power", Innovative Smart Grid Technologies Conference Europe IEEE ISGT Europe PES, 2010.

[2] Y. Cho and H. Cha, "Single-tuned Passive Harmonic Filter Design Considering Variances of Tuning and Quality Factor", Journal of International Council on Electrical Engineering Vol. 1, No. 1, 2011, pp. 7-13.

[3] A. Kalbat, "PSCAD Simulation of Grid-Tied Photovoltaic Systems and Total Harmonic Distortion Analysis", 3rd International Conference on Electric Power and Energy Conversion Systems, Istanbul, Turkey, 2-4 October 2013.

[4] Manitoba HVDC Research Center, "PSCAD/EMTDC Power System Simulation Software User's Manual," Version 4.5, 2012.

[5] A. Baitha and N. Gupta, "A Comparative Analysis of Passive Filters for Power Quality Improvement", 2015 International Conference on Technological Advancements in Power & Energy, 2015.

[6] R. Sachan and R. Srivastava, "Performance Analysis of Fixed Shunt Passive Filters for Harmonic Mitigation", International Conf. on Emerging Trends in Electrical and Sustainable Energy, 2016.

[7] H. Muaelou, K. M. Abo-Al-Ez, and E. A. Badran, "Control Design of Grid-Connected PV Systems for Power Factor Correction in Distribution Power Systems Using PSCAD", International Journal of Scientific & Engineering Research, Vol. 6, Iss. 8, pp. 1092-1099, August 2015.

[8] H. Muaelou, K. M. Abo-Al-Ez, and E. A. Badran, "A Proposed Control Strategy to Improve the Low Voltage Ride Through Capability of PV System with Keeping the DC-Link Voltage Constant," J. of Electrical Engineering, pp. 1-12, July 2016.

[9] K. K. Weng, W. Y. Wan, and R. K. Rajkumar, "Power Quality Analysis for PV Grid Connected System Using PSCAD/EMTDC," International Journal of Renewable Energy Research, Vol. 5, No. 1, 2015, pp. 121-132.

[10] I. Hamdeen, M. A. Saeed, and E. A. Badran, "Voltage Dip's Mitigation during PV-Grid-Connection using STATCOM", 20th International Middle East Power System Conference (MEPCON' 2018), 18-20 December, 2018, Cairo, Egypt.

[11] IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems, IEEE Std. 929, 2000.

[12] M. I. Fahmi, U. Baafai, A. Hazmi, T. H. Nasution, "Harmonic Reduction by using Single-Tuned Passive Filter in Plastic Processing Industry", 10th International Conference Numerical Analysis in Engineering, 2018.