Single Phase Power Quality Analysis of Solar Cell Power System in Harmonics Measurement

Mohammad Taufik, Emilliano, Septian Ari Kurniawan, Darmawan Hidayat, Agus Trisanto, Dessy Novita, and Taufik

Abstract— **This paper analyzes single-phase power quality in solar cell power systems, focusing on harmonic measurement issues when comparing nonlinear loads to configurations with both linear and nonlinear loads (RC Load). As photovoltaics increasingly dominate renewable energy generation, they offer a clean source of energy with significantly reduced carbon dioxide (CO2) emissions compared to conventional sources. The output waveforms of voltage and current generated by photovoltaic systems produce harmonics due to power electronics in inverters and nonlinear loads. We present experimental results from an interactive standalone photovoltaic system connected to various linear and nonlinear load configurations, conducted using MATLAB/Simulink with both serial and parallel methods of RC load. Key findings show that the Total Harmonic Distortion for Current (THDI) of nonlinear loads exceeds 62%, while combining linear and nonlinear loads reduces THDI to as low as 0.25%. Similarly, Total Harmonic Distortion for Voltage (THDV) improves from 11.28% for nonlinear loads to 0.09% in combined configurations. These results demonstrate that integrating linear loads effectively enhances power quality by minimizing harmonic distortion, ensuring compliance with IEEE 519-1992 standard norms. This study provides valuable insights for optimizing solar power systems and improving performance.**

Index Terms—**Power quality analysis, PV harmonic analysis, Total harmonic distortion.**

I. Introduction

DUE to the intensive use of power converters and other non-linear loads, the number and the severity of power quality problems in the electric systems are increasing. Problems like harmonics, inter-harmonics, flicker, notches, sags, swells, and others can cause malfunction of various equipment based in microelectronic circuits that are very sensible to disturbances in the power supply. In order to minimize the impact of these power quality problems, in 1976 Gyugi and Strycula introduced the concepts of active filters [1]. Active filters, different from the passive ones, have the capability to dynamically adjust to the conditions of the system in terms of harmonics and reactive power compensation. In other words, the shunt active filter drains from the network the distorted components of the load currents, such that the system currents present a waveform with small harmonic distortion, and in phase with the system voltages.

Photovoltaic (PV) electricity generation is one of the promising and friendly renewable energy that is free from environmental emission. Presently, PV cells are one of the fastest means of electricity generation in at least over 100 countries in the world [1]. Almost half of 16,000MW of PV arrays are installed and utilized in 2010 in Germany alone [2]. Moreover, the deregulation of power system generation in the world has given an autonomous freedom to generate and sale the produced renewable power to the commercial and individual consumers in the energy market in the world [3][4].

Some of the major drawbacks of this Photovoltaic power generation are disturbances caused by irradiance and temperature variations due to the surrounding weather condition within the installed PVs array. Similarly, the harmonics injected by the power electronics devices like rectifiers, inverters, and mostly the non-linear connected loads associated with the PVs, adversely affect the system generated output Voltage/Current wave forms. Harmonics injected by these devices as a standalone PVs generation resulted in serious severe problems cause over heating in the supply cables, interference in the nearby neighboring communication facilities, equipment failure, loads unbalanced, power losses, and pre matured ageing failure of equipment [5][6].

The problems of harmonics in power system are the most devastating factors that are seriously affect the power system performances which lead to the power quality issues, but due to these, serious attention of utilities system, power engineers and individual consumers were drawn in order to remedy the situation [7]. The result of these power quality issues problems leads to a unique solution of the harmonics distortion, with an appropriate device like filters to mitigate the unwanted harmonics within the system to it minimal percentage of Total Harmonic Distortion (THD) level, and within the IEEE 519-1992 standard norms. In this paper, we present an experimental results analysis for a 2.16KW standalone PV generation connected by different linear and non-linear loads in order to study the behavior of the THD percentage of Voltage (THDV) and Current (THDI) wave forms. The result presented shows the percentage of THD of the various linear and nonlinear loads and was compared with the IEEE 519-

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ISSN: 1942-9703 / CC BY-NC-ND

1992 standard norms.

II. General Block Diagram of Standalone PV

The proposed system comprises of the following components, with their respective rating capacity. Twelve number of PV modules rated 2160W, Lead-acid battery of capacity 325Ah at 48V, Charge controller rated at 48A, and a sine wave inverter of capacity 3000W. The overall system depicted in Fig. 1. Various harmonics measurement has been conducted with linear and nonlinear loads at the point of common coupling (PCC) i.e. between the inverter and the loads.

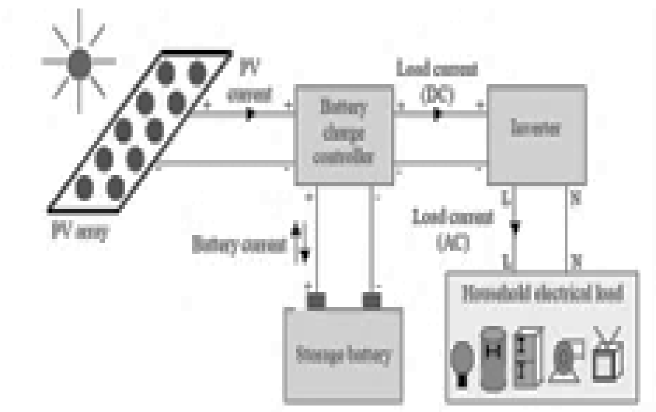

Fig. 1 General block diagram of the complete standalone photovoltaic system

In line with these problems, IEEE 519- 1992 standard were first imposed in 1981 and revised in 1992, that aimed at providing a standard limit for the THD of the system voltage and current caused by the modern electronics converters and the nonlinear loads within the PV System [8]. Table I below depicts the IEEE 519 imposed standard.

TABLE I
HARMONIC VOLTAGE DISTRIBUTION LIMITS IN PERCENT OF NOMINAL FUNDAMENTAL FREQUENCY

Bus voltage at PCC, V_n (KV)	Individual harmonic voltage distortion (%)	Total voltage distortion, THD_{Vn} (%)
$Vn \leq 69$	3.0	5.0
$69 < Vn \leq 161$	1.5	2.5
$Vn > 161$	1.0	1.5

III. Single Phase Power Quality Analysis in THD using MATLAB/Simulink

Fig. 2 shows the experiment for single phase Power Quality Analysis in THD using Non-Linear load only. Fig. 3 shows the experiment for single phase Power Quality Analysis in THD using Linear and Non-Linear load in series. Fig. 4 shows the experiment for single phase Power Quality Analysis in THD using Linear and Non-Linear load in parallel. All of the experiment was done by using MATLAB/ Simulink.

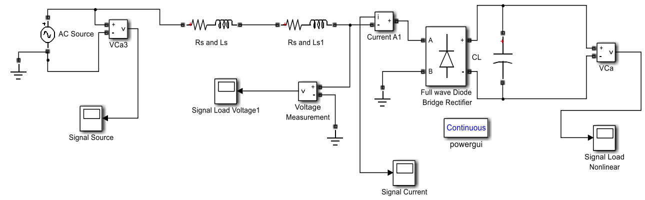

Fig. 2 Single phase power quality analysis using non-linear load only

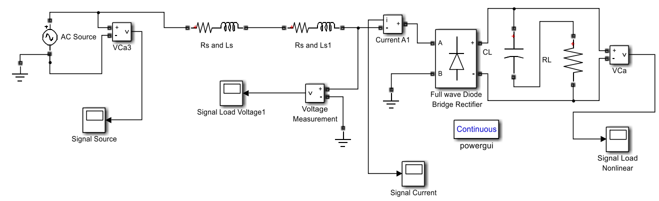

Fig. 3 Single phase power quality analysis using linear and non-linear load (series)

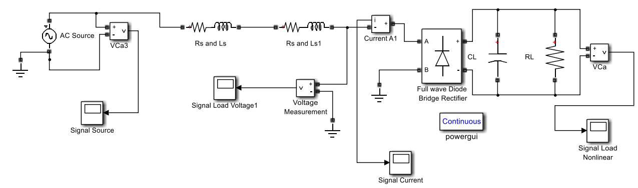

Fig. 4 Single phase power quality analysis using linear and non-linear load (parallel)

IV. Power Quality Analysis Simulation Methods

The experiment has been done in 4 methods in below.

1. Harmonic measurement analysis for Linear with Non-Linear Load Parallel (R increase and C constant).
2. Harmonic measurement analysis for Linear with Non-Linear Load Parallel (R constant and C increase).
3. Harmonic measurement analysis for Linear with Non-Linear Load Series (R increase and C constant).
4. Harmonic measurement analysis for Linear with Non-Linear Load Series (R constant and C increase).

V. Comparison between Non-Linear Load Load and Linear with Non-Linear Load Methods

The comparison between Non-Linear Loads and a combination of Non-Linear and Linear Loads was conducted using four different methods. First, harmonic measurement analysis was performed for the parallel configuration of Linear and Non-Linear Loads, where the resistance (R) was increased while the capacitance (C) remained constant, and the results were compared with those of the Non-Linear Load alone. The second method involved a similar parallel setup, but with the capacitance (C) increased while keeping the resistance (R) constant, followed by a comparison with the Non-Linear Load by itself. In the third method, harmonic measurements were taken for a series configuration of Linear and Non-Linear Loads, with resistance (R) increased and capacitance (C) constant, and the outcomes were compared to the Non-Linear Load operating independently. Lastly, the fourth method analyzed the harmonic measurements in a series configuration, increasing the capacitance (C) while maintaining constant resistance (R), and comparing the results with the Non-Linear Load alone. These methods provided a comprehensive assessment of harmonic behavior under varying electrical conditions.

VI. The Simulation Result

Test Non-Linear with Linear load using RC load parallel when the R load = 20 Ohm and C load = 160 uF. The results of THD are 41.05% for load current and 16.58% for load voltage. Waveform of load current and voltage are shown in Fig. 5 and 6.

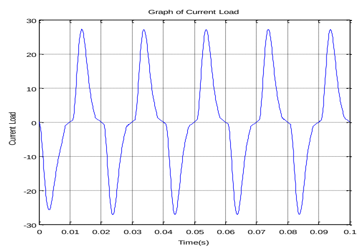

Fig. 5 Waveform of load current

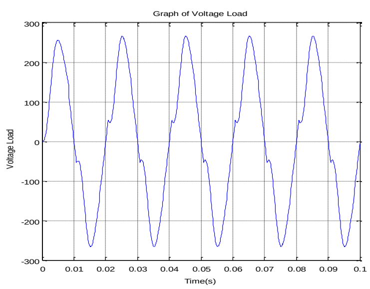

Fig. 6 Waveform of load voltage

Table II shows the THD current increase when the R load increases. The table shows that as the resistance (R) increases while capacitance (C) remains constant at 160 μF, there is a noticeable rise in THDI, peaking at 63.74% when the resistance reaches 80 Ω. Beyond this point, THDI begins to slightly decrease. This pattern indicates that lower resistance values result in less harmonic current distortion, but once the resistance surpasses 80 Ω, THDI stabilizes or declines. In contrast, the THDV fluctuates as the resistance increases. It rises initially, reaching 18.01% at 40 Ω, but then decreases at higher resistance levels, stabilizing at 11.77% for 1500 Ω. Overall, increasing resistance has a stabilizing effect on THDI after a certain point, while reducing THDV at higher resistances.

TABLE II
THD_V AND THD_I FOR RC PARALLEL – R INCREASE AND C CONSTANT

R Load (Ω)	C Load (μF)	THD_I Load (%)	THD_V Load (%)
20	160	41.05	16.58
30	160	53.49	17.80
40	160	58.51	18.01
50	160	60.99	17.81
60	160	62.37	17.43
70	160	63.21	17.05
80	160	63.74	16.72
550	160	63.43	12.48
1500	160	62.65	11.77

Table III presents the relationship between Total Harmonic Distortion for Voltage (THDV) and Current (THDI) in an RC parallel configuration, where the resistance (R) is held constant at 20 Ω, and the capacitance (C) increases. As capacitance rises, the THDV initially increases, peaking at 27.60% when the capacitance reaches 400 μF. After this point, THDV begins to decline, with a gradual reduction to 25.76% at 950 μF. This pattern indicates that increasing capacitance initially amplifies voltage harmonic distortion, but once it exceeds 400 μF, the voltage distortion starts to decrease. On the other hand, the THDI fluctuates as the capacitance increases. Starting at 41.05% for 160 μF, THDI climbs to 52.30% at 950 μF, but with varying degrees of change along the way. While there is a general upward trend, the fluctuations in THDI suggest that the relationship between capacitance and current distortion is less predictable compared to voltage distortion.

TABLE III
THD_V AND THD_I FOR RC PARALLEL – R CONSTANT AND C INCREASE

R Load (Ω)	C Load (μF)	THD_I Load (%)	THD_V Load (%)
20	160	41.05	16.58
20	200	47.88	20.58
20	300	50.74	26.01
20	400	50.43	27.60
20	560	49.78	27.54
20	600	49.78	27.22
20	700	50.14	26.82
20	800	50.91	26.41
20	950	52.30	25.76

Table IV illustrates the effect of increasing resistance (R) while keeping the capacitance (C) constant at 160 μF in an RC series configuration, with a focus on THDI and THDV. The data shows a clear trend: both THDI and THDV consistently decrease as the resistance increases. Starting at 29.53% for THDI and 3.72% for THDV when the resistance is 20 Ω, the harmonic distortions steadily decline as the resistance rises. At higher resistance values, such as 550 Ω and 1500 Ω, THDI and THDV are almost negligible, with THDI dropping to 0.25% and THDV reaching a minimal 0.09%. This indicates that higher resistance leads to significant improvements in both current and voltage harmonic distortions, bringing them closer to zero. The table suggests that increasing the resistance in an RC series circuit effectively reduces both voltage and current harmonic distortions. This behavior demonstrates the strong influence of resistance in improving the overall power quality of the system, making it a key factor in minimizing THD in RC series configurations.

TABLE IV
THD_V AND THD_I FOR RC SERIES – R INCREASE AND C CONSTANT

R Load (Ω)	C Load (μF)	THD_I Load (%)	THD_V Load (%)
20	160	29.53	3.72
30	160	24.16	2.97
40	160	20.59	2.52
50	160	17.99	2.22
60	160	15.97	1.98
70	160	14.35	1.81

80	160	13.01	1.66
550	160	1.42	0.32
1500	160	0.25	0.09

Table V illustrates the relationship between THDI and THDV in an RC series configuration as the resistance (R) increases while maintaining a constant capacitance (C) of 160 µF. The data clearly shows a downward trend in both THDI and THDV as resistance increases, indicating significant improvements in harmonic distortion levels. Initially, with a resistance of 20 Ω, THDI is recorded at 29.53% and THDV at 3.72%. However, as resistance increases to 30 Ω, THDI drops dramatically to 5.59%, and THDV decreases to 0.87%. This trend continues as resistance increases, with THDI declining to 0.57% and THDV reaching 0.16% at 1500 Ω. These results highlight that higher resistance values effectively minimize both current and voltage harmonic distortions, bringing them close to zero.

TABLE V
THD_V AND THD_I FOR RC SERIES – R INCREASE AND C CONSTANT

R Load (Ω)	C Load (µF)	THD_I Load (%)	THD_V Load (%)
20	160	29.53	3.72
30	160	5.59	0.87
40	160	3.42	0.61
50	160	2.30	0.46
60	160	1.65	0.36
70	160	1.24	0.29
80	160	0.96	0.23
550	160	0.77	0.20
1500	160	0.57	0.16

VII. THE COMPARISON BETWEEN NON-LINEAR LOAD AND LINEAR WITH NON-LINEAR LOAD USING MATLAB/SIMULINK

Table VI compares the THDI of a nonlinear load versus a combination of nonlinear and linear loads in an RC parallel configuration, with capacitance (C) held constant at 160 µF. The results show that when the resistance (R) is 60 Ω or lower, the THDI for the nonlinear load alone (62.07%) is significantly higher than that of the combined load (41.05% at 20 Ω), indicating that the linear load effectively reduces harmonic distortion in this range. As resistance increases to 60 Ω, the THDI for the nonlinear load remains high (up to 62.37%), while the combined load's THDI increases gradually. Beyond 60 Ω, the THDI values for both configurations converge, suggesting that higher resistance diminishes the linear load's mitigating effect on harmonic distortion. For resistance values up to 60 Ω, the nonlinear load exhibits greater THDI compared to the combination with the linear load, highlighting the latter's role in reducing harmonic distortion. However, this effect diminishes as resistance increases.

TABLE VI
COMPARISON FOR C LOAD VS RC PARALLEL – R INCREASE AND C CONSTANT

R Load (Ω)	C Load (µF)	THD_I Load (%) C Load	THD_I Load (%) RC Load	THD_V Load (%) C Load	THD_V Load (%) RC Load
20	160	62.07	41.05	11.28	16.58
30	160	62.07	53.49	11.28	17.80
40	160	62.07	58.51	11.28	18.01
50	160	62.07	60.99	11.28	17.81
60	160	62.07	62.37	11.28	17.43
70	160	62.07	63.21	11.28	17.05
80	160	62.07	63.74	11.28	16.72
550	160	62.07	63.43	11.28	12.48
1500	160	62.07	62.65	11.28	11.77

Table VII compares THDI and THDV between a nonlinear load and a combination of nonlinear and linear loads in an RC parallel configuration, with resistance (R) constant and capacitance (C) increasing. The results indicate two significant trends: THDI for the nonlinear load is consistently higher than that of the combined load, while THDV for the nonlinear load is always lower. For example, at 20 µF, THDI for the nonlinear load is 62.07%, compared to 41.05% for the combined load. This pattern continues across all capacitance values, demonstrating the linear load's effectiveness in reducing current harmonic distortion, which reaches a maximum of 65.42% at 800 µF for the nonlinear load. In contrast, THDV for the nonlinear load decreases as capacitance increases, starting at 11.28% at 20 µF and dropping to 6.33% at 950 µF, while the combined load's THDV fluctuates around 26%. This indicates that the nonlinear load is more effective in minimizing voltage harmonic distortion.

TABLE VII
COMPARISON FOR C LOAD VS RC PARALLEL – R CONSTANT AND C INCREASE

R Load (Ω)	C Load (µF)	THD_I Load (%) C Load	THD_I Load (%) RC Load	THD_V Load (%) C Load	THD_V Load (%) RC Load
20	160	62.07	41.05	11.28	16.58
20	200	60.85	47.88	10.83	20.58
20	300	62.42	50.74	10.10	26.01
20	400	63.45	50.43	9.28	27.60
20	560	62.91	49.78	8.58	27.54
20	600	65.09	49.78	8.06	27.22
20	700	64.49	50.14	7.53	26.82
20	800	65.42	50.91	7.05	26.41
20	950	64.77	52.30	6.33	25.76

Table VIII compares the THDI and THDV between a nonlinear load and a combination of nonlinear and linear loads in an RC series configuration, with resistance (R) increasing while capacitance (C) remains constant at 160 µF. The results clearly indicate that the THDI of the nonlinear load is consistently higher than that of the combined load, while the THDV of the nonlinear load is also higher than that of the combined load. For instance, at 20 Ω, the THDI for the nonlinear load is 62.07%, significantly exceeding the 29.53% observed for the nonlinear load with the linear load. This trend continues across all resistance values, demonstrating that the presence of the linear load effectively reduces current harmonic distortion. Additionally, the THDV for the nonlinear load is recorded at 11.28% at 20 Ω, which is much higher than the 3.72% for the combined load, indicating that the linear load also improves voltage harmonic distortion. As the resistance increases, both THDI and THDV for the combined load decrease substantially, highlighting the benefits of the linear load in improving overall power quality. For example, at 1500 Ω, the THDI for the nonlinear load drops to 0.25%, while THDV reaches 0.09%, showing a significant reduction in both current and voltage distortions.

TABLE VIII
COMPARISON FOR C LOAD VS RC SERIES – R INCREASE AND C CONSTANT

R Load (Ω)	C Load (μF)	THD_I Load (%)		THD_V Load (%)	
		C Load	RC Load	C Load	RC Load
20	160	62.07	29.53	11.28	3.72
30	160	62.07	24.16	11.28	2.97
40	160	62.07	20.59	11.28	2.52
50	160	62.07	17.99	11.28	2.22
60	160	62.07	15.97	11.28	1.98
70	160	62.07	14.35	11.28	1.81
80	160	62.07	13.01	11.28	1.66
550	160	62.07	1.42	11.28	0.32
1500	160	62.07	0.25	11.28	0.09

Table IX compares the THDI and THDV between a nonlinear load and a combination of nonlinear and linear loads in an RC series configuration, with constant resistance (R) and increasing capacitance (C). The results consistently show that the THDI of the nonlinear load is higher than that of the combined load, while the THDV of the nonlinear load is also greater. For instance, at 20 μF, the THDI for the nonlinear load is 62.07%, significantly higher than the combined load's 29.53%. This trend continues across all capacitance values, with the nonlinear load's THDI peaking at 65.42% at 800 μF, while the combined load remains considerably lower at 7.05%. Similarly, the THDV for the nonlinear load decreases from 11.28% at 160 μF to 6.33% at 950 μF, whereas the combined load’s THDV drops sharply from 3.72% to 0.16%. The data in Table IX highlights that adding a linear load to a nonlinear load improves both THDI and THDV, demonstrating the linear load's effectiveness in enhancing power quality and reducing harmonic distortion in the system.

TABLE IX
COMPARISON FOR C LOAD VS RC SERIES – R CONSTANT AND C INCREASE

R Load (Ω)	C Load (μF)	THD_I Load (%)		THD_V Load (%)	
		C Load	RC Load	C Load	RC Load
20	160	62.07	29.53	11.28	3.72
20	200	60.85	5.59	10.83	0.87
20	300	62.42	3.42	10.10	0.61
20	400	63.45	2.30	9.28	0.46
20	560	62.91	1.65	8.58	0.36
20	600	65.09	1.24	8.06	0.29
20	700	64.49	0.96	7.53	0.23
20	800	65.42	0.77	7.05	0.20
20	950	64.77	0.57	6.33	0.16

VIII. CONCLUSION

The analyses of harmonic presented distortion reveal significant insights into the effects of linear and nonlinear loads on THDI and THDV in RC configurations. The data consistently indicates that the THDI of nonlinear loads is higher than that of combined linear and nonlinear loads, while the THDV for nonlinear loads remains higher as well. This trend emphasizes the effectiveness of incorporating a linear load, which substantially reduces both current and voltage harmonic distortions across various configurations, including parallel and series arrangements. Specifically, as resistance increases or capacitance changes, the presence of a linear load improves overall power quality by lowering THDI and THDV. In both the RC parallel and series configurations, the linear load effectively mitigates the adverse effects of nonlinear loads, achieving significantly lower distortion values.

ACKNOWLEDGMENT

This research was funded by the “*Hibah Riset Kompetensi Dosen*” from Universitas Padjadjaran, Indonesia, contract 1427/UN6.3.1/LT/2020 and 1959/UN6.3.1/PT.00/2021.

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