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Assessment of the Effect of Harmonics from Renewable Energy Sources on the 110 kV Regional Grid

H. V. P. Nguyen*[1], D. T. Ha[1]
*[*1]Faculty of Electrical Engineering, University of Science and Technology – The University of Danang*

Abstract
Renewable energy sources have been developing rapidly in the world as well as in Vietnam. Currently, the total capacity of solar power sources connected to the national and regional grid accounts for a large proportion of the power generation structure. In addition to generating capacity to meet the requirements of the load, these power plants also generate a significant amount of harmonics into the power grid, affecting the power quality in the area. Harmonic sources come mainly from power electronic converters, the heart of the plant, used to connect photovoltaic panels to the local grid. This report simulates a 110 kV regional power grid in Quang Nam province with a high percentage of solar power plants currently in commercial operation. Indicators of power quality, harmonic distortion are simulated and evaluated specifically according to international and domestic standards. Since then, the study has proposed methods to reduce the influence of harmonics from solar power plants to the grid in the connected area. The simulation results show the effectiveness of the proposed methods, which can be applied in practice to meet the harmonic standards.

Keywords: *renewable energy; solar power; harmonic; Quang Nam; DIgSILENT; inverter; filter.*

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I. INTRODUCTION

Along with the development of the world, the demand for electricity is increasing, along with the problem of energy security in each country and the impact on the environment from the energy industry. Therefore, renewable energy sources are used more and more widely, in which solar power using photovoltaic (PV) batteries has developed extremely rapidly in recent years [1]. The fast and efficient introduction of solar power has important implications for energy security, climate change mitigation, and economic benefits [2]-[3]. That makes the issues related to PV systems to be focused on research.

Solar energy systems use inverters to convert direct current (DC) from solar energy into alternating current (AC) to optimize system operation. However, using an inverter will cause negative effects on the electrical system by causing waveform distortion (high harmonics) [4]. Therefore, in order to minimize harmonics, countries around the world have set forth requirements for limiting harmonics. Until now, there are many methods to reduce harmonics on the system such as using active filter, passive filter, using inverter with active rectifier... Which type of filter to use depends on the source of the harmonic, its position in the grid.

To clarify the influence of harmonics from solar power plants on the 110 kV power grid in Quang Nam province, Vietnam, the research presents a study on the influence of harmonics from solar power plants connected to feeder 373 of the station of 110 kV Dai Loc, Quang Nam province. The paper consists of 4 parts, part 1 presents the problem, part 2 presents the research fundementals, part 3 evaluates the influence of harmonics on the simulation diagram using the DIgSILENT PowerFactory tool and the conclusion of the article in part 4.

II. THE RESEARCH FUNDEMENTALS

2.1. Harmonics

Harmonics are periodic, sine waves and are integer multiples of the fundamental frequency (50 or 60 Hz). These components when added to the original sine wave (50 Hz) will cause distortion, distortion of the sine wave. Figure 1 shows an ideal three-phase sine waveform and the sine waveform is distorted under the influence of harmonics.

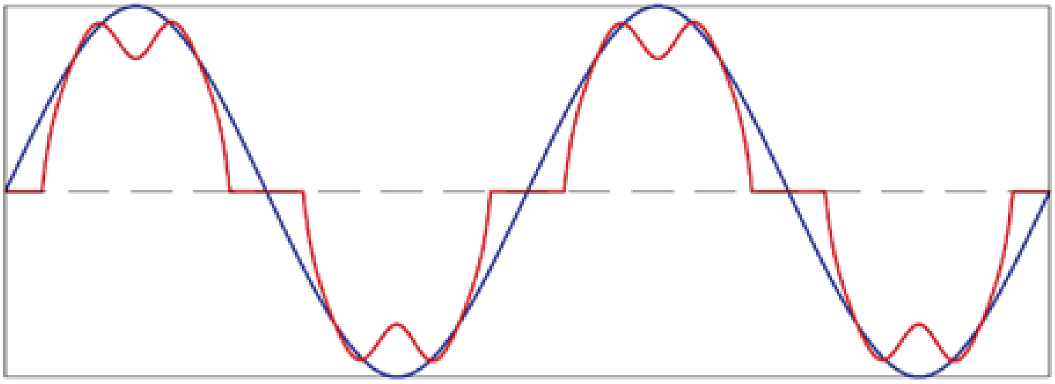

Figure 1. Ideal sinusoidal three-phase waveform and harmonic waveform [5]

The effects of harmonics caused in the power system are: causing power loss, side effects, resonance causing damage to electrical equipment, causing overvoltage, overloading current and causing errors in the system. measuring and control devices. The amount of losses on transmission, distribution and transformer lines is enormous [6].

All electrical energy converters used in different forms in the power system can increase harmonic noise by injecting harmonic currents directly into the grid. Inverters used in power systems are one of the most common sources of harmonics.

2.2. Harmonics standards

Harmonic standards specify the voltage limits of the individual harmonic components and the total harmonic distortion in each different voltage class.

Total Harmonic Distortion (THD) of a signal is the current harmonic distortion. It is defined as the ratio of the square root of the sum of all harmonic components of the current waveform to its fundamental component times the square of the voltage at the point of connection (PCC - Point of Common Coupling). on the base voltage value [7].

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_{PCC}^2}}{V_1} \qquad (1)$$

In which: V_{PCC} is the connection point voltage (kV);
V_1 is the base voltage value (kV);
THD_V is the value of total harmonic distortion (%).

The value of total harmonic distortion is specified differently in each specific standard.

According to international standard IEC 61000-3-6 second edition [8]: THD at high and super high voltage should not exceed 3%. The voltage classes in this standard are specified as follows:

- Low voltage is rated voltage up to 1 kV;
- Medium voltage (MV) is the rated voltage above 1 kV to 35 kV;
- High voltage (HV) is the rated voltage above 35 kV to 230 kV;
- Extra high voltage (EHV) is the rated voltage above 230 kV [9].

Limit values for harmonic voltage levels expressed as a percentage of base voltage at high voltage and ultra high voltage classes are described in table 1.

Besides, for IEEE 519-2014 [10] standard, THD ≤ 5% is required, individual strain ≤ 3% at medium voltage level. This standard is applicable in the case of power systems consisting of linear and nonlinear loads only under steady system operating conditions and under worst-case conditions [7]. The voltage limit value of harmonics is presented in Table 2.

Table 1. Limits of individual harmonic voltage distortion for each voltage level

Harmonic order (h)	Harmonic Voltage (%)		Harmonic order (h)	Harmonic Voltage (%)		Harmonic order (h)	Harmonic Voltage (%)	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1.8	1.4
7	4	2	9	1.2	1	4	1	0.8

11	3	1.5	15	0.3	0.3	6	0.5	0.4
13	2.5	1.5	21	0.2	0.2	8	0.5	0.4
$17 \leq h \leq 49$	$1.9*\frac{17}{h}$ - 0.2	$1.2*\frac{17}{h}$	$21 \leq h \leq 45$	0.2	0.2	$10 \leq h \leq$ 50	$0.25*\frac{10}{h}$ + 0.22	$0.19*\frac{10}{h}$ + 0.16

Table 2. Individual harmonic distortion and THD for different voltage levels [7]

Voltage at PCC	Individula harmonic distortion (%)	THD (%)
$V \leq 1$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5

In Vietnam, the harmonic standard mentioned in Circular 39/2015/TT-BCT [11] stipulates: the total voltage harmonic distortion at all medium and low voltage connection points must not exceed the limit such as THD ≤ 6.5%, individual strain ≤ 3%.

2.3. Harmonic filter models

2.3.1 Harmonic filtering method using active filter

The active harmonic filter acts as a current source. It will analyze harmonics in the system to determine harmonic strength, harmonic order. From there, the active harmonic filter will emit harmonic current with the opposite number of orders and magnitude and then cancel. The structure of an active harmonic filter is shown in Figure 2.

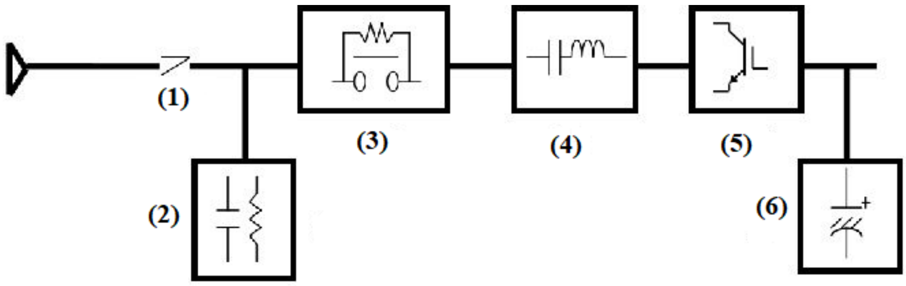

Figure 2. Components of an active harmonic filter

An active filter consists of components in the following order:
• (1) Fuse;
• (2) Mass flow filter;
• (3) Massive soft starters;
• (4) High frequency response capacitor combination;
• (5) AC voltage rectifier bridge;
• (6) Combination of DC capacity capacitors.

2.3.2 Harmonic filtering method using passive filter

Passive harmonic filter devices have a wider range of applications than active devices due to their simple structure and small loss, there are 3 main types of this device: single filter device, 2nd order high pass filter and condenser filter. Figure 3 describes the structure of passive harmonic filtering devices.

The most common passive filter device is the single filter. Because its structure consists of only capacitors in series with inductors, simple operation should be commonly used. The single form filter is tuned to a low impedance corresponding to a particular harmonic current. So the harmonic current is diverted off the line through the filter. However, it is only effective with a single harmonic type at the resonant frequency. In addition, there is almost no impact with other harmonic components [12].

The second-order high-pass filter is also a device that is used a lot in practice because in addition to good effect on harmonics at the resonant frequency, it also works with harmonics at high frequencies (above 20). . However, because the component has a resistance R, the effective power loss is much higher than that of a single filter device.

The condenser filter is similar to the 2nd order high-pass filter in that it can filter out harmonics at the resonant frequency and other higher harmonics. However, unlike conventional high-pass filter devices, at the fundamental frequency (50 Hz) this device causes no loss.

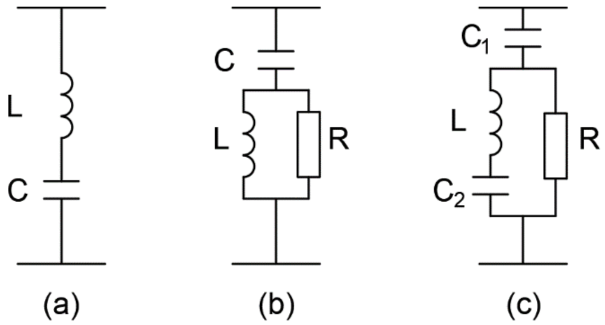

Figure 3. Single (a), 2nd order high pass (b) and condenser filters (c) [13]

III. EVALUATE THE INFLUENCE OF HARMONICS ON THE SIMULATION DIAGRAM

3.1. Introduction of the diagram

Harmonic analysis diagram includes: The system is powered from 110 kV Dai Loc substation (E155) with capacity S=100 MVA, using voltages of 22 kV and 35 kV, frequency of 50 Hz, capacity of Solar energy sources include: Thao Kien Solar Power 1250 kVA; Tuan Phong Solar Power 1250 kVA; Solar power UCD 1000 kVA, power electronic converters in solar power plants use 6-pulse bridge rectifiers. The schematic details are shown in Figure 4.

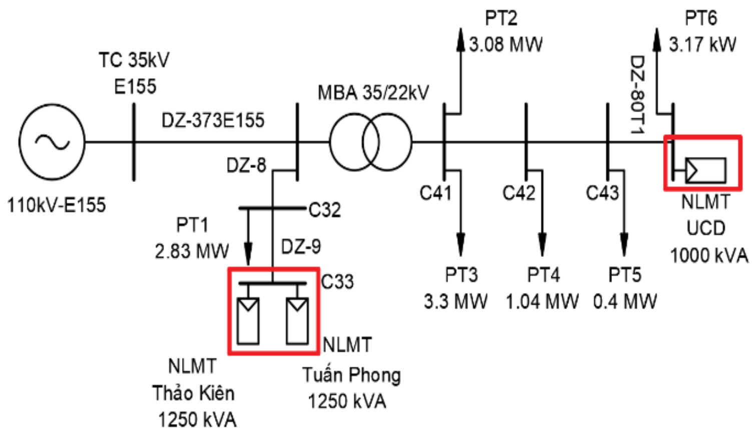

Figure 4. Simulated diagram of power system

3.2. Harmonic analysis in the simulated diagram

In the normal operating state, the total harmonic distortion at the surveyed locations has the value as shown in Table 3. In which, the current and voltage at the surveyed locations and the individual harmonic components. as shown in Figures 5, 6 and 7.

Table 3. THD values at multiple locations

Location	THD (%)
Transmission line no. 8 (DZ-8)	16.3
Transmission line no. 9 (DZ-9)	10.2
Transmission line DZ-373E155	9.3
Transmission line 80T1 (DZ-80T1)	10.2
Busbar C32	0.7
Busbar C44	1.0

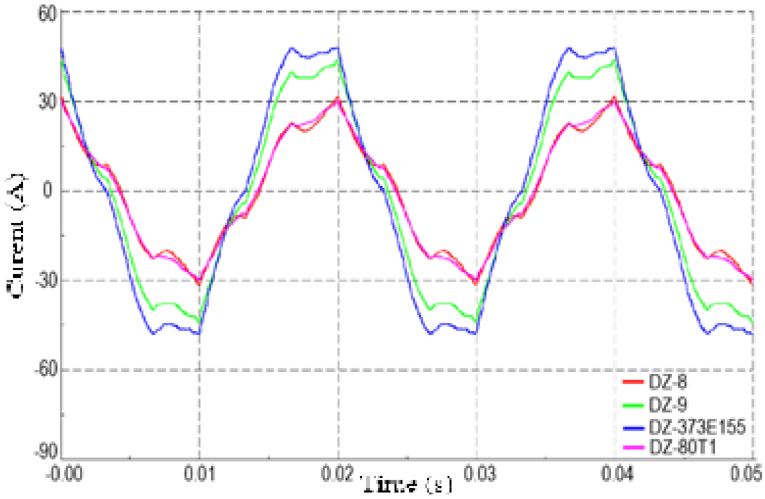

Figure 5. Current waveforms under normal operation

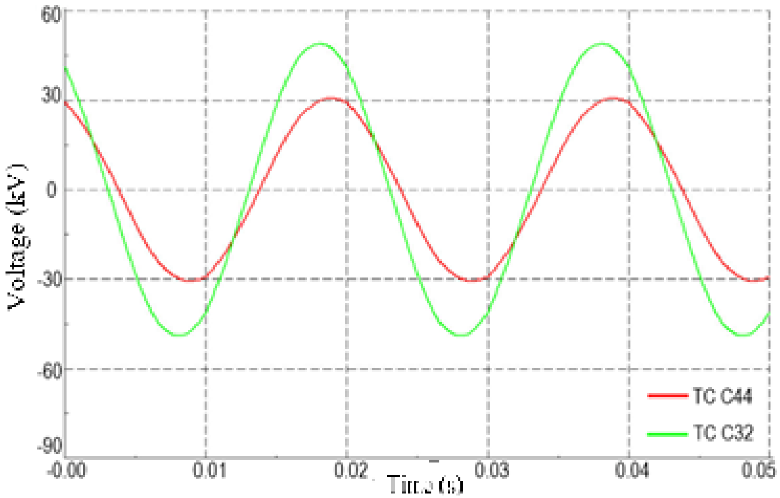

Figure 6. Voltage waveforms under normal operation

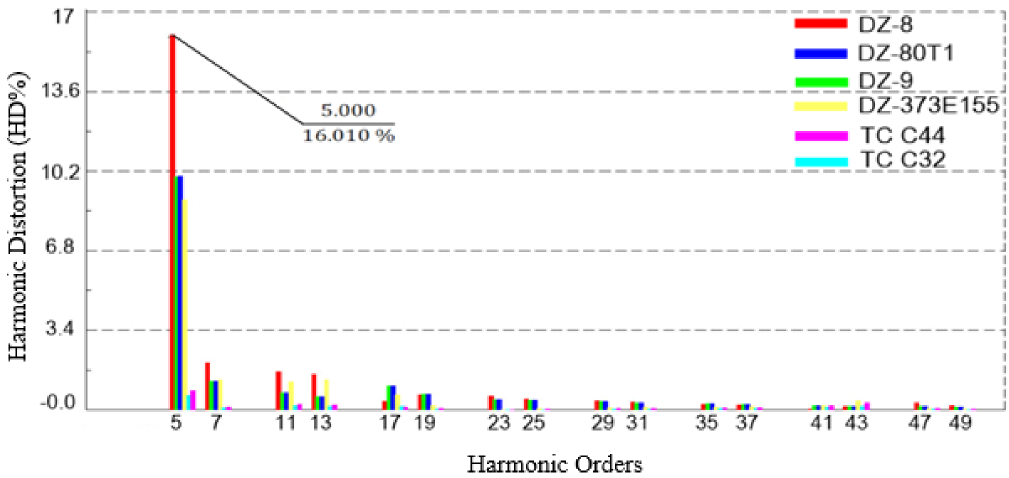

Figure 7. Individual harmonics under normal operation

Table 3 shows a large THD value, up to 16.3% at line No. 8, exceeding the standards for the maximum permissible value of total harmonic distortion.

From Figures 5 and 6, it is shown that the current and voltage at the surveyed locations have large distortion due to the influence of power electronic converters in the solar system. Since the harmonics here are odd harmonics, the distorted waveforms in the positive and negative half-cycles have the same shape but different directions [14].

Figure 7 depicts the individual harmonic components in the normal operating state showing the appearance of 5th harmonics; 7; 11; 13… In which, harmonic of the 5th order accounts for the largest proportion (16.010%).

3.3. Parameters of capacitor type filter

To reduce the effect of harmonics, a condenser type harmonic filter is used. This filter consists of elements R, L, C coupled together and selected for a specified frequency. This device creates an extremely low impedance circuit at the frequency to be filtered so that harmonics at that frequency "flow" out of the system. The schematic diagram of the filter is shown in figure 3©.

The structure of this type of filter consists of 3 main parts: capacitor C_1, regulating part and a damper in parallel with the regulating part. Capacitor C_1 provides the required reactive power and fundamental frequency. Capacitor C_2 and inductor L are designed to resonate in series at rated frequency. The capacitor type filter theoretically causes no power loss at the fundamental frequency (50 Hz) because the equivalent resistance in the reactance branch and the capacitor C_2 is zero [13].

First, three important filter parameters must be determined:

- Rated voltage V_1;
- Resonant frequency f_1 of harmonics;
- The required rated reactive power Q_n.

The entire impedance of the filter can be written as:

$$Z(\omega) = \left(\frac{1}{R} + \frac{1}{j\omega L - j(\omega C)^{-1}}\right)^{-1} + \frac{1}{j\omega C} \tag{2}$$

This equation leads to:

$$Z(\omega) = \frac{R(\omega^2 LC_1 - 1) + jR^2\omega C_1(\omega^2 LC_1 - 1)}{(R^2C_1^2\omega^2) + (\omega^2 LC_1 - 1)^2} - \frac{j}{\omega C_2} \tag{3}$$

Minimize power loss at fundamental frequency:

$$\omega_F^2 LC_1 - 1 = 0 \tag{4}$$

Therefore, the impedance of the filter at the fundamental frequency is:

$$Z(\omega_1) = \frac{-j}{\omega_F C_2} = \frac{-jV_1^2}{Q_n} \tag{5}$$

At the tuned frequency, the total reactance is zero:

$$\frac{R^2\omega_F C_2(\omega_F^2 LC_2 - 1)}{(R^2C_2^2\omega_F^2) + (\omega_F^2 LC_2 - 1)^2} - \frac{j}{\omega_F C_1} = 0 \tag{6}$$

Total impedance at tuning frequency:

$$r = \frac{R(\omega_F^2 LC_2 - 1)}{(R^2C_2^2\omega_F^2) + (\omega_F^2 LC_2 - 1)^2} \tag{7}$$

Where ω_h is the adjustable angular frequency.

Therefore, the adjustment can be calculated as follows:

$$C_1 = \frac{(h_0^2 - 1)Q_n}{\omega_F V_1^2} \tag{8}$$

$$C_2 = \frac{Q_n}{V_1^2 * \omega_F} \tag{9}$$

$$L = \frac{V_1^2}{(h_0^2 - 1)Q_n\omega_F} \tag{10}$$

$$R = \frac{qV_1^2}{Q_n h_0} \tag{11}$$

With h_0 is defined:

$$h_0 = \frac{\omega_1}{\omega_F} \tag{12}$$

And q is the quality factor [15].

From there, we can calculate the filter parameters in Table 4.

Table 4. Filter parameter values

Name	Filter 1	Filter 2
V_1 (kV)	35	22
f_1 (Hz)	250	250
Q_n (Mvar)	0.94	0.20
h_0	50	50
C_1 (μF)	58.62	31.57
C_2 (μF)	2.44	1.32
L (mH)	172.84	320.96
R (Ω)	0.05	0.10

The placement of the filtering devices is located at the busbars connected to the solar sources. The details of the location of the devices are shown in Figure 8. The current and voltage waveforms after filter installation are shown in Figure 9 and Figure 10, respectively.

The results after using the filter showed that the current and voltage were "pure sine", the distortion was significantly reduced. However, the maximum current value in the lines near the filter also increased, and the lines far from the filter decreased compared to before. Specifically, the maximum current value from 43.80 A in normal operation mode increases to 59.49 A in line No. 9 (DZ-9), and for line DZ-373E155 decreases from 59.49 A down to 26.48 A. Meanwhile, the voltage value remains unchanged.

The filter has a resonant frequency of 250 Hz, so it affects mainly the 5th harmonic. This harmonic component accounts for the highest proportion (16.010%) of the individual harmonic components in the normal operating state of the grid. but reduced to only 2.372% under the effect of the filter, ensuring the standards of the value of individual harmonic distortion at voltage levels 22 kV and 35 kV. The individual harmonic components after using the filter are shown as shown in figure 11.

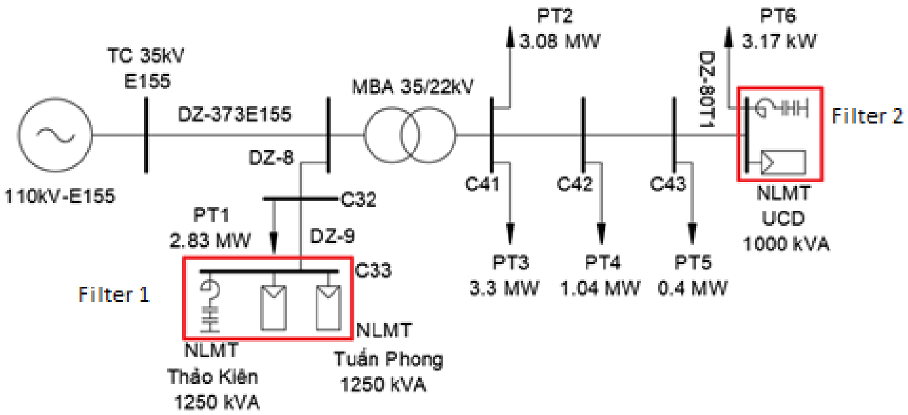

Figure 8. Filter installation in the simulated diagram

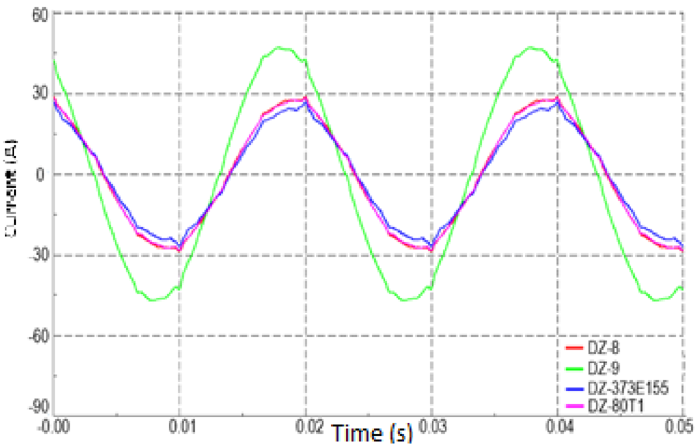

Figure 9. Current waveforms after filter installation

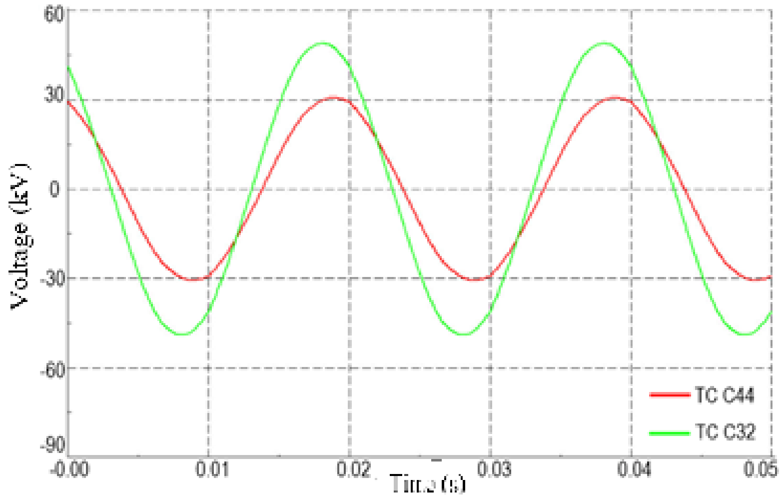

Figure 10. Voltage waveforms after filter installation

To investigate the effect of the filter rated power on the total harmonic distortion (THD), we have the results of the total harmonic distortion corresponding to the different power of each filter as shown in Table 5.

According to the diagram, the harmonics passing through filter 1 are larger than those of filter 2, due to the influence of many solar sources as well as the larger total capacity of solar power sources. Therefore, the power of filter 1 is greater than that of filter 2.

From the formula (2); (8); (9); (10); (11), showing that the magnitude of the filter's rated power is inversely proportional to its impedance. Therefore, the larger the power, the more harmonics are eliminated. Therefore, the values of the individual harmonic components as well as the distortion of the current and voltage decrease with increasing the rated power of the filter as shown in Figures 9, 10, 11 and Table 5.

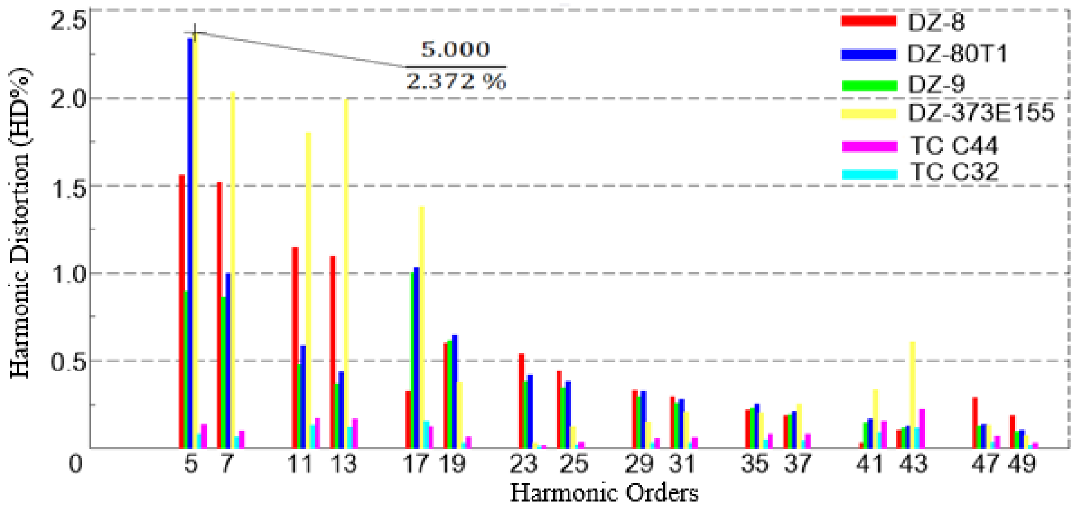

Figure 11. Individual harmonics after filter installation

However, because of the "charge-discharge" principle of the capacitor, the capacitance in the filter capacitors will increase when increasing the filter capacity, causing the peak current to increase, the lifetime of this current will also increase. longer, may cause overcurrent to damage other equipment. Therefore, it is necessary to adjust the power of both filters to achieve maximum efficiency in filtering harmonics as well as to avoid current overload. After the filter suppresses harmonics, the total harmonic distortion is already within the allowable limit.

Table 4. THD (%) after filter installtion with different rated power

Rated power of the filter		**THD (%)**		**Compliant with standard**		
Filter 1	Filter 2	After Filter 1	After Filter 2	IEC 61000-3-6 version 2.0	IEE 519-2014	Circular 39/2015/TT-BCT
0.1	0.05	12.4	6.5	✕	✕	✕
0.3	0.1	7.1	3.9	✕	✕	✕
0.5	0.15	5.0	3.1	✕	✓	✓
0.7	0.17	3.8	3.1	✕	✓	✓

0.9	0.2	3.1	3.0	✗	✓	✓
0.94	0.2	2.9	3.0	✓	✓	✓

IV. CONCLUSION

The article analyzed the influence of harmonics from renewable energy sources, specifically solar power plants, on the 110 kV power grid in Quang Nam province, thereby applying a capacitor-type passive filter to minimize the impact. The dynamics of harmonics in the grid because of its popularity, ease of use, can filter high-order harmonics and no loss at fundamental frequency (50 Hz). At the same time, analyze the impact of changing filter power on power quality to maximize filter performance while ensuring no adverse effects on other devices in the grid.

Research results show that the amount of harmonics has been significantly reduced, the voltage and current distortion has been improved, and the total harmonic distortion has been reduced from 28.3% to only 3.0%, ensuring compliance with the prescribed standards for the harmonics. harmonic distortion value. Although there has been a significant effect in reducing the influence of harmonics, the economic issue has not been mentioned, which will be analyzed in the following studies.

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