# Effect of Photovoltaic System on Power Quality in Electrical Distribution Networks

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**Abstract- The study is concerned with the optimal penetration of renewable energy sources and their impacts on power quality case studies into distribution systems. Non-linear loads are the main harmonic sources in a distribution grid while the PV system constitutes power converters which are large generating source of harmonics. Therefore, both nonlinear loads and PV systems have large impact on the power quality of distribution systems. In this paper, the harmonics determined by a photovoltaic system (PV) on a distribution system are analyzed. Also, this paper aims to solve the harmonic reduction problem of distribution system which is fed from the PV system by using a number of single tuned passive filters. The ETAP software is employed to simulate a distribution system that feeds a residential area integrated with PV systems to analyze the impact and the best location of these PV to reduce these harmonics and their effect on the distribution system. Also, this paper deals to allocate the filters at the best location for eliminating the harmonics and their impact on the system. Also, this paper proposes an ETAP procedure for choice the optimal design of single tuned filters that able to reduce the effects of voltage and current harmonic contents to be within the accepted practical limits. Two proposed filter design strategies are presented. The first one considers the power factor correction as the primary objective function while the minimization of total installing costs is considered as a primary objective function in the second strategy. An actual part of residential distribution systems as a real application of Egyptian network is implemented to explain the capability of the proposed procedure to improve the power quality and to reduce the total and individual voltage and current harmonic contents to be within their accepted limits of the Egyptian code.**

***Index Terms*-Power quality, harmonics, harmonic distortion, PV systems, single tuned passive filter.**

## NOMENCLATURES

| | |
|---|---|
| $C_n$ | Capacitance of filter |
| ETAP | Electrical Transient Analyzer Program |
| $I_h$ | Current at harmonic order h |
| $I_1$ | Current at harmonic order 1 |
| $I_{sc}$ | Short circuit current |
| IHD | Individual Harmonic Distortion |
| $IHD_V$ | Voltage individual harmonic distortion |
| $K_{Ch}$ | The unit cost of the capacitor ($) |
| $K_{Lh}$ | The unit cost of the inductor ($) |
| $L_n$ | Inductance of filter at harmonic order n |
| m | Number of buses in the system |
| PB | Pass band of the filter |
| PV | Photovoltaic |
| $Q_f$ | Quality factor |
| $Q_{ch}$ | The kVA size of the capacitor |
| $Q_{lh}$ | The kVA size of the inductor |
| $Q_{fh}$ | The capacity of the h'th harmonic filter |
| $Q_{com}^{min}$ | The minimum compensation limit. |
| $Q_{com}^{max}$ | The maximum compensation limit. |
| $R_n$, | Resistance of filter at harmonic order n |
| THD | Total Harmonic Distortion |
| $THD_V$ | Voltage total harmonic distortion |
| $U_K$ | The constant cost component (MVAR) |
| $U_L$ | The inductor incremental cost (MVAR) |
| $V_h$ | The voltage at harmonic order h |
| $V_1$ | Voltage at harmonic order 1 |
| $V_i$ | Voltage at bus i |
| Voc | Open circuit voltage |
| ω | Angular frequency (2πf) |
| $X_c$ | Capacitor reactance |
| $X_l$ | Inductor reactance |

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## I. INTRODUCTION

Reduction of fossil fuel sources increases governments' interest to the importance of penetration of renewable energy sources such as wind energy and solar energy to assess power system performance [1]. One of most interested recent technologies is the solar energy which has become the most popular renewable energy source in recent years. The solar energy is extracted directly from sun by integrating photovoltaic (PV) modules to the distribution systems [2].

The rapid increase in the penetration levels of PV systems has been noticed. Solar PV power systems are being considered as a practical unconventional energy resource for many world countries as well as in Egypt [3]. Therefore, future electricity generation plans countries around the world expect more contribution of renewable energies in the electric power systems especially for PV systems. PV systems have the potential of general applications as an alternative safe and clean energy source in the nearest future [4]. The target of some utilities is to penetrate around of 20% renewable energy of total required energy by 2020 while other utilities expect 50% by the year 2050 [5].

The integration of PV system to electrical distribution networks can be divided into two main categories off-grid (stand-alone applications) and on-grid (grid-connected applications) [6]. The stand-alone PV systems provide the needed power demand for remote loads only while grid-connected applications are implemented to provide required energy for local loads and able to exchange power with utility grids. The salient features of PV systems are their ability to enhance the operation of power systems by improving the voltage profile and by reducing the energy losses of distribution feeders at lowest maintenance costs. Compared to other renewable technologies, PV systems still face major problems and may lead to undesirable effects to the system, such as overloading of the feeders, harmonic pollution, high investment cost, low efficiency, and low reliability [7]. Moreover, variations in solar radiation may cause power deviation and voltage flicker, resulting undesirable effects on high penetrated PV systems in the distribution network. Several control procedures, that controlled the produced voltage and the current of the PV array, are developed to improve the efficiency of PV systems [8].

The accurate detection of undesired disturbances is necessary for electrical utilities [9]. Urgent disturbances are that related to the quality of utilized generated power. Two view point about power quality definitions. In the view point of utility, the power quality is defined as the reliability and characteristic of the power supply that enable the equipment to work correctly. On the other side, consumers define the power quality as any problem in voltage, current frequency deviations that lead to failure or operation loss of customer equipment. Examples of the power quality disturbances are voltage sag, swell, surge, flickers, interruption and harmonics [10]-[12].

Electric power pollution has increased due to the power converter, distribution and transmission networks with the growth of non-linear loads like switch-mode-power-supplier and phase control rectifiers. The poor power quality occurs mainly due to the influence of harmonics and reactive power [11]. The power quality problems areised in power system and the ways to solve these problems were presented in [12]. The existence of non-linear loads and distributed generation technologies change the voltage and current waveforms their characteristics [13].

Harmonics are presented in the output PV current because of the use of power converters and variable power flow of the PV system. These currents, flowing through the impedances of the distribution system result in distortion of system voltage [14]. Harmonic reduce the power systems equipment's life. The filter design has become essential for industrial distribution systems [15]. The harmonic effects on the system are defined by the following issues [16] and [17]:

- Equipment overheating that leads to equipment failure or damage
- System malfunction or operation failure of equipment
- Protection equipment mal and fail operation
- Process disturbance

The penetration of PV systems in distribution network is one of the main sources of harmonic distortion of current and voltage waveforms. Therefore, that is becoming a huge problem [18] especially for distribution systems.

This paper is concerned on studying the power quality problem that associated with the PV penetration into distribution systems and provide a detailed comparative between the system performance. Also, this paper proposes an ETAP procedure for choice the optimal design of single tuned filters that able to reduce the effects of voltage and current harmonic contents to be within the accepted limits of the Egyptian code.

## II. POWER QUALITY INDICES

Two power quality indices are frequently measure the harmonic contents of voltage and current waveforms which are the individual harmonic distortion (IHD) and the total harmonic distortion (THD). The IHD of harmonic order h is defined the percentage of current/voltage at h order with respect to the fundamental current/voltage signals. The IHD for current and voltage signals are expressed, respectively as:

$$I_h\% = \frac{I_h}{I_1} \tag{1}$$

$$V_h\% = \frac{V_h}{V_1} \tag{2}$$

The THD is the second indicator of the distortion of a signal. It is widely used in power quality problems. For current and voltage signals, the THD is expressed in general form as:

$$THD = \sqrt{\sum_{h=2}^{H} \left( {Y_h}/{Y_1} \right)^2} \tag{3}$$

where, THD is the ratio of the r.m.s. value of all the harmonic components of the signal Y (voltage/ current), to the fundamental $Y_1$. H is generally taken equal to 50, but it's limited in most cases to 25 [19]. The IEEE limits for harmonic voltage distortion on power systems 69 kV and below is limited to 5.0% total harmonic distortion (THD) with each individual harmonic limited (IHD) to 3% [20].

Ref. [5] presented the technical design specifications and criteria, technical terms and equipment parameters that were needed to setup small-scale PV systems to the distribution networks in Egypt. Successful penetration of a PV system should achieve desires of both the small scale PV Code [21] and the Electricity Distribution Code (EDC) [22]. Both THD and IHD must not exceed the Egyptian standard limits which is harmonic voltage distortion on power systems up to 22 kV is limited to 5.0% THD with each odd IHD to 3% [5]. The impact effects of grid disturbances on the output of grid connected solar PV system were presented in [23]. Filters are good alternative solutions for harmonics reduction problem [24].

## III. PV SYSTEM STRUCTURE

The material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be PV [6]. A photon with short enough wavelength and high enough energy can cause an electron in a PV material to break free of the atom that holds it. If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current. The driving force to power PV comes from the sun, and it is interesting to note that the surface of the earth receives something like 6000 times as much solar energy as our total energy demand [6].

In the PV system, the inverter is an important component, which converts the array power from DC to AC for supplying the loads or connecting with the grid. A new product line recently introduced into the market is the AC PV module, which connected an inverter directly into module design [25]. Fig. 1 shows a grid connected PV system components.

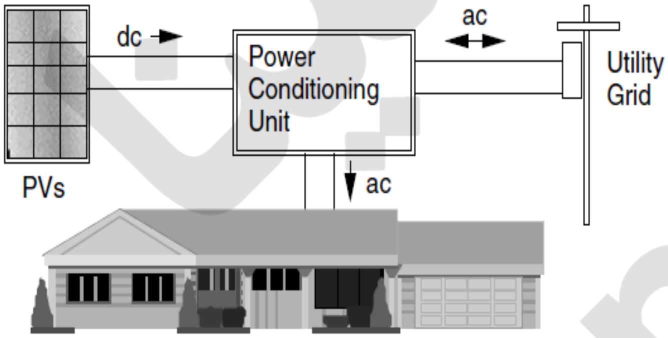


Fig. 1 Grid connected PV

## IV. SINGLE TUNED PASSIVE FILTER

The shunt filter is installed to trap the harmonic current to enhance the load power factor [26]. To avoid the influence of harmonic it is necessary to put one filter or more and the most popular harmonic filter in industrial application is single tuned filter. It consists of a capacitance and an inductance and a resistance connected in series with each other. An ideal passive single-tuned filter is said to be tuned on the frequency that makes its inductive and capacitive reactance to be equal [27].

In the paper, the single tuned filter is used to avoid a certain harmonic current to enter into the system network. However, design equation of single tuned filter is given by [17] as:

$$Z_n = R_n + j(\omega L_n - (\frac{1}{\omega C_n})) \tag{4}$$

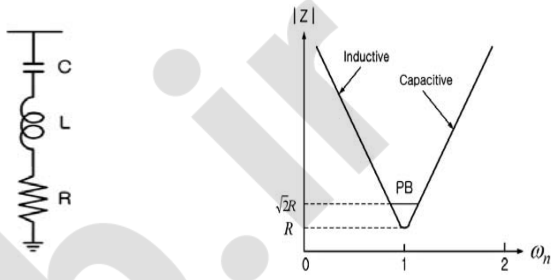
At a resonance frequency:

$$\omega L_n = \frac{1}{\omega C_n},\ Z_n = R_n \tag{5}$$

An ideal single-tuned filter is said to be tuned on the frequency that makes its inductive and capacitance reactance to be equal to each other Fig. 2(a) shows the filter circuit and Fig. 2(b) their impedance characteristic [19]. If h is the ratio between fundamental frequency & harmonic frequency, then the value of capacitance & inductance can be found out by following equation which represents the relationship between harmonic and component of filter [17]:

$$X_{lh} = h \times 2\pi f \tag{6}$$

$$X_{ch} = 1/(2\pi f\ h) \tag{7}$$



(a) Circuit (b) Impedance characteristic

Fig. 2 Characteristic of single-tuned filter

At the tuning of filter, the impedance value of filter must be low. There is only way to minimize the impedance of filter by cancelling the two reactance connected in the circuit through the resonant condition

$$X_{lh} = X_{ch} \tag{8}$$

Equation (8) presents the relationship between harmonic and passive component which is very much important aspect for designing of filter [17]. Other important issue that must keep into mind for designing filter is the quality factor which is the ratio between the reactance at the resonant condition and resistance of the circuit as:

$$Q_f = X_c or X_l / R \tag{9}$$

where, $Q_f$ is the quality factor and R is the resistance of filter in ohm. For a normal distribution system, the typical value of quality factor is in the range 15 to 100 [17].

## V. OPTIMAL DESIGN OF SINGLE TUNED FILTER

The optimum location and sizing of passive filters in distribution networks was employed in [28] using genetic algorithm (GA). In this paper, on the basis of ETAT package which is dependent on GA for solving such optimization problems, two design strategies are proposed to obtain the best performance of single tuned filter. The first one aims at correcting power factor and the second strategy minimizes the initial cost of the filters. The initial filter cost is expressed as [19]:

$$\min \sum \left( K_{ch} Q_{ch} + K_{lh} Q_{lh} \right) \qquad (10)$$

where $K_{ch}$ and $K_{lh}$ represent the unit cost of the capacitor and inductor, respectively. Also, $Q_{ch}$ and $Q_{lh}$ denote the kVA size of the capacitor and inductor, respectively for h'th harmonic filter. The harmonic filters provide a large percentage of reactive power for the power factor correction. When the capacitor, $Q_{com}$ kVAR, is installed in a system with a real power load P kW, the power factor can be improved from $Pf_0$ to $Pf_1$, as [19]:

$$Q_{com} = P \times (\tan(\cos^{-1} pf_0) - \tan(\cos^{-1} Pf_1)) \qquad (11)$$

The capacity of a single-tuned filter can be set as:

$$Q_f = Q_{com} \qquad (12)$$

For parallel single-tuned filters, the capacitor corresponding to the h'th harmonic filter can be distributed as [15]:

$$Q_{fh} = Q_{com} \times \frac{I_h}{\sum I_h}, h = 2, 3, .... \qquad (13)$$

where, $I_h$ is h-order harmonic current and $Q_{fh}$ represents the capacity of the h'th harmonic filter. Also, the filter capacity $Q_{fh}$ contains the capacity of capacitor $Q_C$, and inductor $Q_L$. The harmonic filters have the following relationships:

$$Q_c = Q_f \frac{h^2}{h^2 - 1} \qquad (14)$$

$$Q_L = Q_c - Q_f \qquad (15)$$

Therefore,

$$Q_L = \frac{1}{h^2} Q_c \qquad (16)$$

Another limitation for the filter design is the reactive power supplied to the system which must not exceed the system demand to mitigate the voltage arise, which may be disposed to occur in the case of light-loading condition. Therefore, the filter capacitors are selected such that the reactive power supplied by them does not exceed a specified value

$$Q_{com}^{\min} \le Q_f \le Q_{com}^{\max} \qquad (17)$$

The operational harmonic distortion constraints are limited by the maximum limitation according to IEEE Std 519-1992 and the Egyptian requirements as:

$$THD_V \le THD_V^{\max} \qquad (18)$$

$$THD_I \le THD_I^{\max} \qquad (19)$$

$$IHD_V \le IHD_V^{\max} \qquad (20)$$

$$IHD_I \le IHD_I^{\max} \qquad (21)$$

$$V^{\min} \le V_i \le V^{\max}, i = 1, 2, \ldots, m \qquad (22)$$

## VI. SOLUTION METHODOLOGY

ETAP is a fully graphical power system assessment program [28]. In this paper, the ETAP is employed for power factor correction and is developed to minimize the initial cost of design single tuned filters [29]. The optimization problem presented in Esq. (10) -(22) is solved using genetic algorithm. Iterative sequential allocation of PV at different distribution system nodes followed by optimization the sizing of the PV systems using GA. A comparative between the technical and economical specification is employed to choose the most suitable location for installing PV system that enhance the voltage profile, improve power factor as well as installing least economical single tuned filters. The steps of the proposed PV allocation procedure are:

1) Modelling the residential suburban using ETAP package
2) Running the load flow for initial case with the penetration of PV systems.
3) Apply power factor improvment strategy or minimizing the installing cost strategy.
4) Check the IHD and THD constraints,
5) Using GA, obtain the optimal sizing of PV system and the related single tuned filter considering the proposed model in (10) - (22).
6) Repeat the steps 2-5 until all requirements are fully achieved.

## VII. APPLICATIONS

### *A. Test distribution system*

An Egyptian suburban distribution feeder is used for feeding a residential area that was interactive residential PV systems nearby Cairo city [3, 4]. In this system there are 5 buses, loads will be added at bus 0 with value equal 870 kW as utility loads these loads belongs to the system, loads connected with buses 1, 2, 3, 4 are residential loads, the substation rating is 3MVA, 11kV, the loads types are 80% motor and 20% static, power factor equal 85%. Fig. 3 shows the single line diagram of the tested feeder.

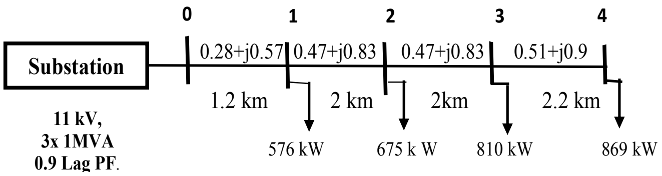


Fig. 3 Single-line diagram of tested residential feeder

### *B. Paper assumptions*

In this paper, the use of PV module of 40.7 $W_{peak}$, comprised of multi-crystalline Solar cells from Kyocera-KC40T has been selected as one of the commercial panel. Also, it has a model in ETAP software package. The specifications of the module are summarized in Table 1.

TABLE 1: KYOCERA-KC40T PV MODULE SPECIFICATION

| Item Description | Item specification |
|---|---|
| Peak power @ standard test conditions (STC) (W) | 40.7 |
| Voltage @ peak power (V) | 17.61 |
| Current @ peak power (A) | 2.31 |
| Voltage [open circuit] (V) | 21.51 |
| Current [short circuit] (A) | 2.48 |
| Number of cells for one module | 36 |

The total output from the PV array equals 3256 kW/ dc after inverter equal 2930 kW/ac with PV penetration equal 77.105%. $I_{sc}$, $V_{oc}$ are the most important items to make an array.

The sizing of the filter is done according to the minimization of the filter initial cost under the standard rating of single-phase capacitors and the costs that released by ABB [24],[30]. In this study the value of $U_K$ and $U_L$ is considered 500$ and 90 ($/MVAR) then ($K_{lh}$) will be 0.59 $/kvar with capacitor loss factor 1%. The capacitor unit cost ($K_{ch}$) was taken equal 11 $/kVar and inductor unit cost will be calculated by:

$$\text{Inductor cost} = U_K + U_L \quad (\text{MVAR}) \qquad (22)$$

### *C. Studied cases*

Four studied cases are considered in this paper. These cases are described as follows: The base case (Case 0) is considered without any PV, Case 1 consider the PV at bus 4, Case 2 considers PV at bus 3, Case 3 considers the PV at bus 2, and in Case 4, PV is allocated at bus 1. Two design strategies are presented for choose the filter sizing on the basis of the previous studied cases.

### *D. Results and Comments*

Table 2 shows the voltage total harmonic distortion for the studied cases with penetration of PV.

TABLE 2: VOLTAGE THD FOR DIFFERENT PV LOCATIONS

| Bus | Voltage | Fund% | Case0 | Case1 | Case 2 | Case3 | Case 4 |
|---|---|---|---|---|---|---|---|
| 0 | 11 kV | 100 | 30.5 | 30.88 | 31.06 | 31 | 29.23 |
| 1 | | 97.9 | 29.01 | 29.43 | 29.57 | 29.46 | 27.28 |
| 2 | | 82.55 | 18.09 | 18.69 | 17.85 | 17.06 | 16.86 |
| 3 | | 78.96 | 16.76 | 17.15 | 15.79 | 15.85 | 15.6 |
| 4 | | 71.92 | 14.93 | 13.24 | 14.03 | 14.03 | 13.84 |

According to IEEE Std 519-1992, the maximum $IHD_V$ is limited by 3%. Several studied cases will be applied on the system to analyze the effect of connecting PV on the utility specifically the harmonic contents. From cases 0-4, at case 0 the PV is not connected it is noticed that voltage THD at bus 0 equal 30.5, at bus1 equal 29.01, at bus 2 equal18.09, at bus3 is 16.76 and at bus4 is 14.93. Bus 0 which is near the utility has the biggest voltage THD values and bus 4 which is far from the utility has the smallest values of voltage THD.

1) Filter sizing according to power factor correction

For cases 1-4, the PV addition leads to different harmonic orders 11, 13, 23, 25, 35, 37, 47 and 49. It should be filtered to keep the system clean from their effect, the harmonic orders are and for that the single tuned filter will be used, bus 0 has the greatest voltage IHD at each harmonic order and the greatest value of voltage IHD at bus 0 at harmonic order 11 with value equal 16.76% while locating PV at bus 3 and it is noticed that at case2 Bus 0 has the greatest values of IHD at harmonics orders 11, 13, 23, 25, 35, 37, 47 and 49 as presented in Table 3. The level of fundamental component is reduced from 100% at the source node to around 71.92% at node 4. The total voltage levels are preserved within the acceptable IEEE limits ( ± 6%).

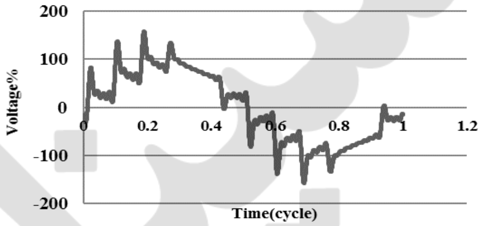
TABLE 3: VOLTAGE INDIVIDUAL HARMONIC DISTORTIONS FOR DIFFERENT PV LOCATIONS AT 11 KV VOLTAGE LEVEL

| Bus # | Fund. % | Harm. order | Case 0 | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|---|---|
| 0 | 100 | 11 | 16.27 | 16.72 | 16.76 | 16.65 | 15.23 |
| 1 | 97.9 | | 15.70 | 16.18 | 16.17 | 16.02 | 14.42 |
| 2 | 82.35 | | 11.70 | 12.15 | 11.45 | 10.93 | 10.75 |
| 3 | 78.96 | | 11.42 | 11.47 | 10.49 | 10.50 | 10.33 |
| 4 | 71.92 | | 10.69 | 9.34 | 9.97 | 9.98 | 9.82 |
| 0 | 100 | 13 | 14.95 | 15.23 | 15.34 | 15.27 | 14.10 |
| 1 | 97.90 | | 14.35 | 14.66 | 14.73 | 14.63 | 13.29 |
| 2 | 82.35 | | 9.98 | 10.38 | 9.84 | 9.39 | 9.25 |
| 3 | 78.96 | | 9.45 | 9.69 | 8.88 | 8.89 | 8.75 |
| 4 | 71.92 | | 8.71 | 7.73 | 8.20 | 8.20 | 8.07 |
| 0 | 100 | 23 | 10.81 | 10.82 | 10.94 | 10.96 | 10.47 |
| 1 | 97.90 | | 10.22 | 10.24 | 10.35 | 10.35 | 9.72 |
| 2 | 82.35 | | 5.54 | 5.68 | 5.53 | 5.29 | 5.27 |
| 3 | 78.96 | | 4.87 | 5.01 | 4.66 | 4.65 | 4.6 |
| 4 | 71.92 | | 3.77 | 3.49 | 3.61 | 3.60 | 3.58 |
| 0 | 100 | 25 | 10.39 | 10.39 | 10.49 | 10.51 | 10.09 |
| 1 | 97.90 | | 9.80 | 9.81 | 9.91 | 9.92 | 9.35 |
| 2 | 82.35 | | 5.12 | 5.23 | 5.11 | 1.90 | 4.88 |
| 3 | 78.96 | | 4.44 | 4.56 | 4.26 | 4.25 | 4.24 |
| 4 | 71.92 | | 3.31 | 3.08 | 3.18 | 3.17 | 3.16 |
| 0 | 100 | 35 | 8.42 | 8.41 | 8.46 | 8.49 | 8.28 |
| 1 | 97.90 | | 7.88 | 7.87 | 7.92 | 7.94 | 7.61 |
| 2 | 82.35 | | 3.53 | 3.57 | 3.54 | 3.40 | 3.42 |
| 0 | 100 | 37 | 7.96 | 7.95 | 8.00 | 8.02 | 7.85 |
| 1 | 97.9 | | 7.44 | 7.43 | 7.48 | 7.49 | 7.20 |
| 2 | 82.35 | | 3.52 | 3.28 | 3.26 | 3.14 | 3.15 |
| 0 | 100 | 47 | 6.57 | 6.57 | 6.58 | 6.60 | 6.52 |
| 1 | 97.90 | | 6.10 | 6.09 | 6.12 | 6.13 | 5.95 |
| 0 | 100 | 49 | 6.31 | 6.31 | 6.33 | 6.34 | 6.27 |
| 1 | 97.90 | | 5.85 | 5.85 | 5.87 | 5.88 | 5.72 |

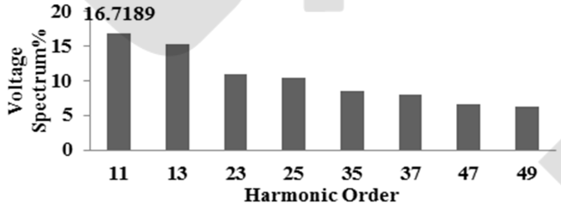
Before locating filter, Fig. 4(a) shows the bus0 waveform with PV at bus 4, and Fig. 4(b) shows the bus0 spectrum with locating PV on bus 4, after locating first filter on bus 0 and filter sizing is estimated by ETAP for deleting harmonic order 11. Harmonic filter sizing is estimated according to power factor correction from 85% to 95%, 1-Phase kVar is the filter 1-phase capacitor kvar equal 253 kVar, Xl is the impedance of XL1 in ohm/phase equal 3.95 Ω/phase, Vc is the computed capacitor peak kV using the sized filter parameters equal 18.985 kV, $I_L$ is the computed inductor current by ETAP using the sized filter parameters equal 58.51 A (rms).

It was noticed that harmonic order 11 was deleted as shown in Fig. 5(a) which_bus 0 waveform after deleting the harmonic which order is11, and Fig.5 (b) shows the bus0 spectrum after deleting the harmonic order is11but there is many harmonics still existing. Other each harmonic order needs a filter to delete it. Harmonic order 11 disappeared but harmonics 13, 23, 25, 35, 37, 47, 49 still there. After removing harmonic 11, it was noticed that the largest value for the VIHD at harmonic order 25 takes value equal 6.47 %.

Table 4 shows the filter sizing parameters for every harmonic order, after locating second filter to delete harmonic order 25. It is noticed that all harmonics deleted except harmonic order 13 so a single tuned passive filter is used for deleting harmonic order 13.

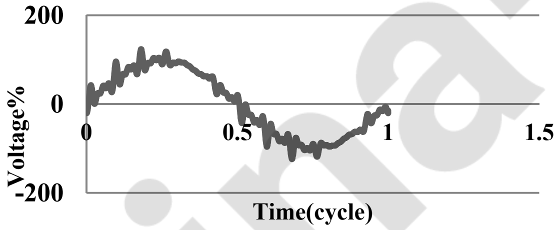


(a) Waveform

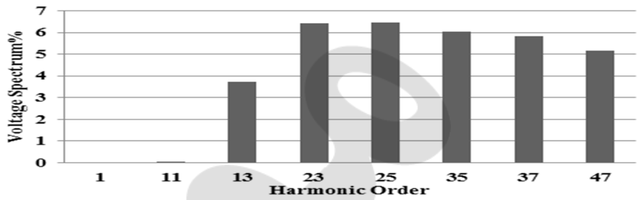


(b) Spectrum

Fig. 4 Bus 0 waveform and spectrum with PV only before considering filter



(a) Waveform



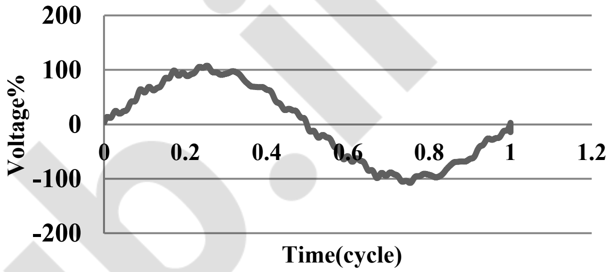
(b) Spectrum

Fig. 5 Bus 0 waveform and spectrum with first filter

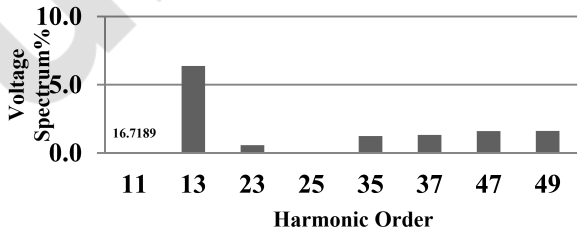
TABLE 4: FILTERS SIZING ADJUSTMENT ACCORDING TO STRATEGY 1

| Filter number | Harmonic order | 1-Phase kVar | XL1 ohm/phase | Vc kv | IL Amp |
|---|---|---|---|---|---|
| 1 | 11 | 253 | 3.95 | 18.983 | 58.51 |
| 2 | 25 | 253 | 0.76 | 17.032 | 58.44 |
| 3 | 13 | 253 | 2.83 | 18.439 | 58.48 |

Fig. 6(a) shows the effect of locating the $2^{nd}$ filter on the bus 0 spectrum Fig. 6(b) shows the effect of locating the second filter at the bus 0 waveform. After locating the three filters at bus 0 as shown in Fig. 7, Fig (8) shows that by using the three filters the harmonics which exceeds the limits were deleted, and it can be noticed the difference between the voltage waveforms and voltage spectrums between Fig. 8 and Fig.4.



**(a)** Waveform



**(b)** Spectrum

Fig.6 Bus 0 Waveform and Spectrum after installing two filters

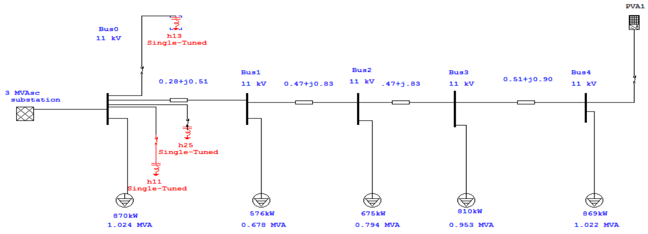
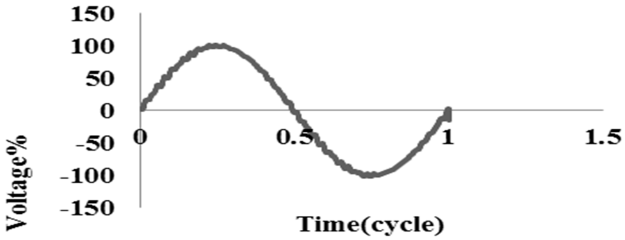
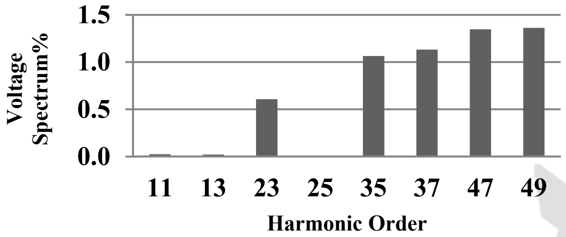


Fig. 7 Tested distributed feeder with the three filters on bus0



**(a)** Waveform

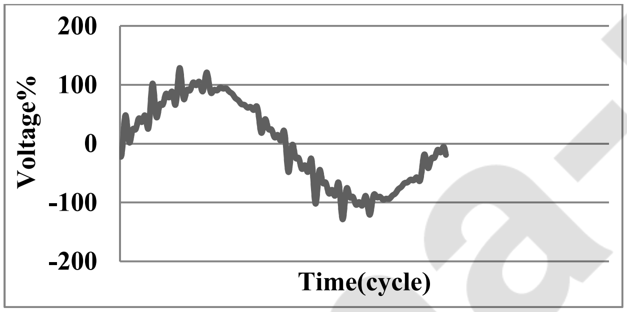


(b) Spectrum

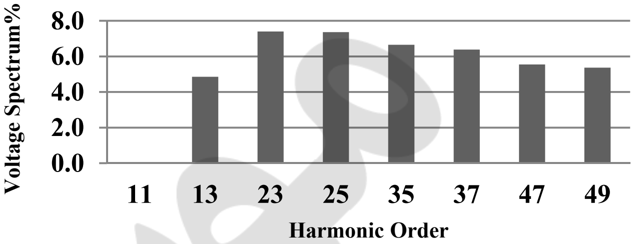
Fig. 8 Voltage waveform and spectrum after locating 3 filters

### 2) Filter sizing according to strategy 2

As shown in Fig. 4, it was detected the harmonics of orders11, 13, 23, 25, 35,37,47 and 49 without adding any filters. The detected harmonics exceed the standard limits. In the second strategy, the filters are located at bus 0 and their sizing is obtained according to initial cost minimization. It was noticed also that harmonic 11 has the biggest value of voltage spectrum percentage. After first filter first harmonic with order 11 as shown in fig. 9 was deleted then after second filter harmonic 23 was deleted as in fig. 10. Finally, after installing three filters harmonic with order 13 was deleted by locating three filters as shown in Fig. 11. The higher orders harmonics of voltage signals are reduced below 3% There are more harmonics but do not exceed the limits. Table 5 shows the filter sizing parameters for every harmonic order according to initial cost minimization.

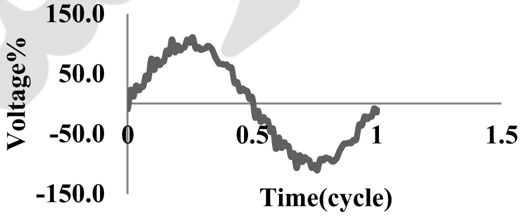


a) Waveform

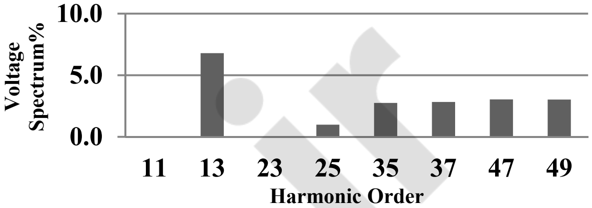


b) Spectrum

Fig. 9 Bus0 waveform and spectrum with PV after first filter according to strategy 2

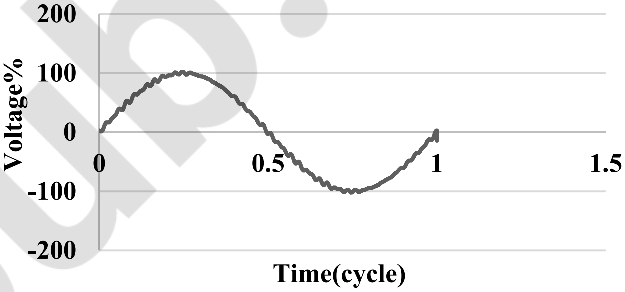


a) Waveform

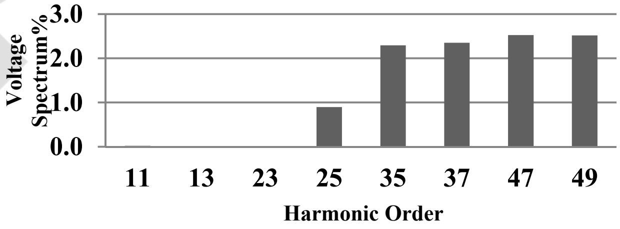


b) spectrum

Fig. 10 Bus 0 waveform and spectrum after two filters according to strategy 2



a) waveform



b) Spectrum

Fig. 11 Bus 0 waveform and spectrum filters according to strategy 2

TABLE 5: FILTERS SIZING ADJUSTMENT ACCORDING TO STRATEGY 2

| **Filter number** | **Harmonic order** | **1-phase kvar** | **XL1 ohm/phase** | **Vc kv** | **IL Amp** | **Initial Costs($)** |
|---|---|---|---|---|---|---|
| 1 | 11 | 183 | 5.47 | 20.256 | 56.25 | 2016.22 |
| 2 | 23 | 126 | 1.81 | 18.746 | 54.92 | 1387.06 |
| 3 | 13 | 168 | 4.26 | 19.853 | 55.86 | 1850.51 |

## VIII. CONCLUSIONS

In this paper, an actual part of Egyptian network is employed for correcting power factor and minimizing initial cost using ETAP in the presence of PV. Results (THD, IHD, harmonics orders, IEEE limits, filters sizing) are obtained and analyzed. Three filters have been located to solve the problem of harmonics which exceeds the IEEE limits. The study explained the effect of PV on power system by applying some cases, the bus near the utility has the largest value of total harmonic distortion for the voltage. The best location for PV is far away from the utility the best location for the filter is at the bus located near the utility, single tuned filter avoids a specific harmonics current to enter into the system network. Two design strategies are provided for single tuned filter design the first preserve the power factor at the optimal range while the second strategy reduce the initial cost while other constraints in the system are preserved below its boundary recorded in the IEEE and Egyptian codes.

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