# Assessment of Control Strategies for Conventional and Multi-Functional Inverter Interfacing Power Grid with Renewable Energy Sources (RES)

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**Abstract**— Recently, Renewable Energy Sources (RES) are increasingly integrated in the distribution systems based on using of power electronic converter. In this paper, a grid-connected photovoltaic (PV) system is integrated to a three phase three wire distribution system including nonlinear loads which lead to deterioration of power quality for power grid. A control strategy for renewable interfacing inverter based on Sinusoidal Source Current Control method which depend on instantaneous power theory (P-Q) theory is introduces for voltage source inverter (VSI) which utilized as a multi-functional interfacing inverter (MFI) and acts with features of a Shunt Active Power Filter (SAPF) like mitigation power quality problems and injection of the energy generated by renewable energy source through (VSI), also this control theory is implemented to a conventional interfacing inverter connected in parallel with a SAPF. Beside of control strategy, a maximum power point tracking algorithm (MPPT) is applied to the inverter to extract the available power from the photovoltaic array. The proposed system compensate the load disturbances and contributes to power quality improvement at the point of common coupling (PCC) and lead to provide the power factor correction, harmonic elimination, , and simultaneously inject the maximum power available from the photovoltaic array to the load and/or grid. The multifunctional features of the proposed control algorithm are demonstrated using simulation results where the performances of proposed PV-APF systems are carried out using MATLAB/SIMULINK software.

**Index Terms**— Renewable Energy Sources (RES), Photo Voltaic (PV), Power Quality (PQ), Multi-functional inverter (MFI), Active Power Filter (APF)

◆

## 1 INTRODUCTION

THE Renewable energy sources (RES) which termed as distributed generation (DG) such as photovoltaic (PV), and wind generation systems are integrated at the distribution levels, where the photovoltaic (PV) power generation applications can divided into two categories, stand-alone with a battery bank system appropriate for a low power system and a grid connected system which turned out to be the primary method for high power applications are today become more popular because of its reliable performance and its ability to come up with power from clean energy resources [1].

Power electronics and smart technologies play an important role for integration of (RES) into the power grid where using of renewable energy sources as distributed generation (DG) generators is especially depends on developments of power electronics technology but also the rapid increase of power electronics-based nonlinear loads connected to the utility causes serious power quality problems, by generating harmonics and reactive current in the utility. Hence, grid connected inverters interfaces DG systems are effectively used to resolve power quality issues at PCC where the combination of active filters and renewable energy sources to gain from both the advantages of renewable sources of energy and active filters dedicated to the power quality improvement, therefore the key component in PV-based DG systems is a grid-connected inverter that serves as an effective interface between the renewable energy source and the utility grid [2-3-and 4]. The multifunctional inverter (MFI) is special type of grid-connected inverter that has elicited much attention in recent years, where (MFIs) not only transfer power generated by renewable DGs sources but also provide increased functionality through improved power quality by load reactive power demand support and current harmonic compensation at PCC, and also support current unbalance and neutral current compensation in case of 3-phase 4-wire system; thus, the capability of the auxiliary service for the utility grid is improved. Where the power output from these energy resources is essentially unstable, therefor effective control strategies must be developed for the proper operation and management of new power grids embedded with DG units to maintain improvement of system quality and reliability [5-6 and 7].

In grid connected photovoltaic (PV) system, the PV-arrays are tied with the utility grid either in series or in a shunt position, however, the target compensated quantities, such as harmonics, unbalance, and reactive power, are directly related to the currents. Therefore, the shunt type topology is widely utilized because it effectively injects compensating currents at the point of common coupling (PCC).

In this article there are two cases depends on the configuration of the three-phase voltage source inverter (VSI) which is widely used as the interface between RES-based DG generators and the utility grid, where in the first case naming PV-VSI-APF or case (a) shown in figure (1-a), the voltage source inverter is used as a conventional inverter and to compensate the power quality disturbances a shunt active power filter must be implemented and connected in parallel at PCC but in the second scenario or case (b) called PV-APF shown in figure (1-b), the voltage source inverter is development and acts as a multifunctional DG inverter to introduce a power quality disturbances compensation beside of dispense on using of SAPF as in case one.

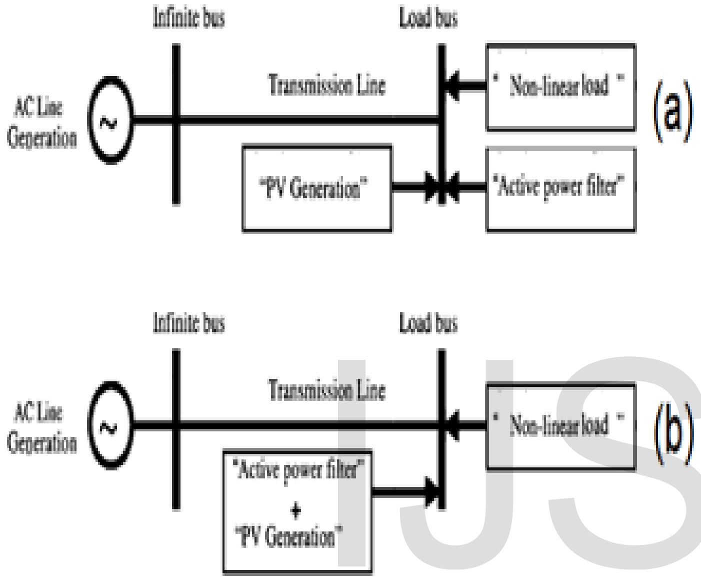

Fig. 1: System model under study [8].

## 2 SYSTEM DESCRIPTION

The proposed system consists from a photovoltaic (PV) array-based RES system connected to the utility via a dc-link of a grid-interfacing inverter (VSI), and the general scheme of PV power system described in fig (2) is consists from a PV cells which connected together to form a modules which also connected together to form a number of series/parallel strings to meet the required voltage and current and finally the PV array reaches the required and suitable power rating depends on a photovoltaic effect where the solar energy is converted into electricity through this PV array, also the electric behavior of PV cells is similar to that of a direct current source, therefore a PV field is usually modeled as a DC source[8-9-and10]. Then the PV array voltage is amplified with a boost DC/DC converter, which set to operate at optimal voltage by changing its duty cycle and implements the maximum power point tracker (MPPT) by an incremental conductance integral regulator algorithm, which applied to extract the maximum possible efficiency of the PV generator and this lead to keep the transfer power from the solar PV array to the grid at maximum point as shown in figure (3) [11-12].

The dc - bus is connected to a three-phase DC/AC voltage source inverter which converts DC power across storage devices into three phase AC power and then injected it into the utility or directly supplies the nonlinear load at the PCC [7-13].

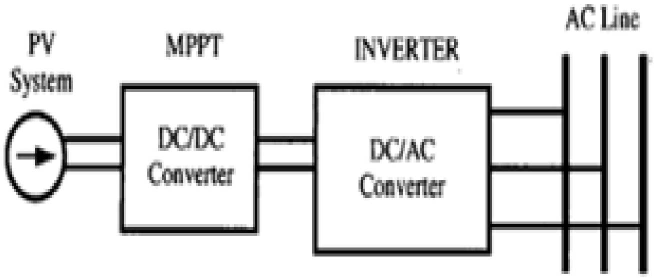

Fig. 2: General scheme of PV power system [8].

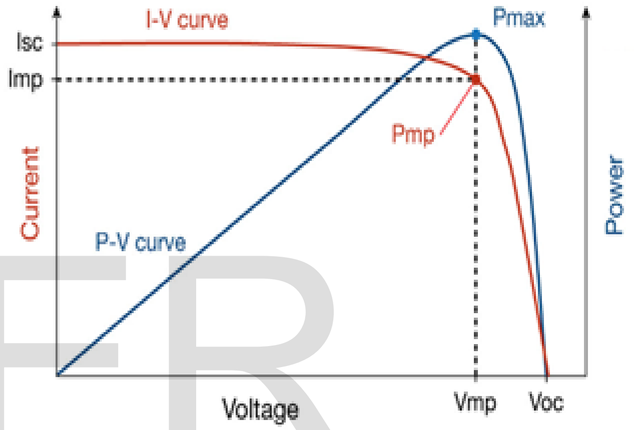

Fig. 3: I-V characteristics, and P-V characteristics [12].

The major issue in a three-phase system is the compensation for the reactive power and harmonic currents when connected with non-linear loads, therefore a new active filtering technique was proposed to make power quality disturbances compensation based on using of shunt active power filter (SAPF), Where Active power filters (APF) are electronic devices that allow to improve the electric power quality and compensate power unbalances, also current harmonics not only in the load but also in the generation source are filtered using this SAPF [8].

Also, a three-phase, three-wire (3P3W) VSI-based multifunctional inverter (MFI) is proposed as shown in Figure(4), Where active power filters use a similar inverter to that used in the solar system through PV technology as indicated in figure(2). Based on that characteristic, this innovative proposal tends to carry out the integration of an active power filter with a PV generating source and through this integration a double aim is fulfilled: first, the power quality is improved through the compensation capacity of active power filters and second, an additional contribution of active power is supplied by PV power systems. Therefore, operation and maintenance costs are reduced as well as those energy losses of transmission and distribution systems and this proposed [8].

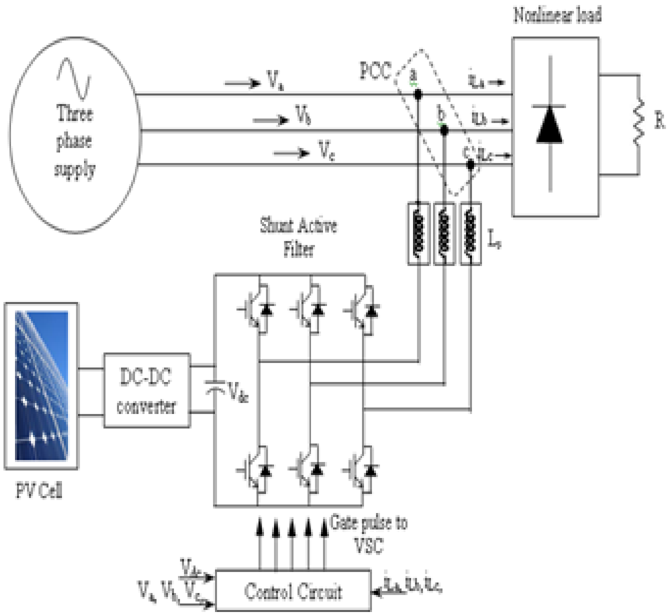

Fig. 4: proposed three-phase three-wire VSC based MFI interfacing with PV system [14].

Shunt APFs are the most configurations broadly utilized in active filtering applications and act as a harmonic current source to compensate the harmonic currents of nonlinear loads, where the controller of SAPF system detects the instantaneous load current and extracts its harmonics content, then injects the compensating harmonic currents to cancel the load harmonic currents. As a result, a sinusoidal current is drawn from the utility, free from harmonics and in phase with the distribution voltage source, where the rule of the inverter is to charge and discharge the DC side capacitor to provide the required compensation current, and the AC supply provides the required active power and the capacitor of SAPF provides the reactive power for the load as indicated in figure (5) [15].

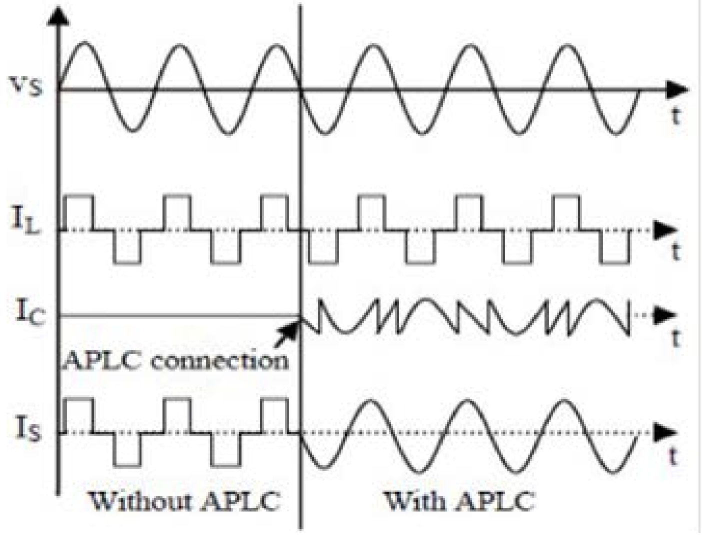

Fig.5: Compensation system waveforms [15].

## 3 CONTROLLER FOR DC/AC CONVERTER

The control strategy is the heart of the VSI which works as ashunt active power filter whether it is applied in case(a) or (b) as detailed in figure (1), and this control strategy is implemented in two steps,where the first step is the extraction of the reference compensating signals from the load distorted signals represented by the reference current extraction method which implemented by using of a controller algorithm called the Sinusoidal Source Current Control Strategy based on the instantaneous active and reactive power (PQ) theory [15-16].

The second step is represented by the current control technique based on using of the hysteresis strategy which implemented for the generation of appropriate gating signals to control the switching devices of VSI based on the estimated compensation reference signal in the first step [15].

### 3.1 The Sinusoidal Source Current Control Strategy

The controller design is particularly difficult if the shunt active power filter (SAPF) is applied in power system in which the supply voltage itself has been distorted with voltage harmonics and/ or unbalanced at the fundamental frequency, therefore the control algorithm which implemented for shunt active power filter (SAPF) must designed to satisfy simultaneously the following optimal compensation characteristics which lead to have sinusoidal and balanced compensated currents and to draw (only) constant instantaneous real power from the source ,but in the presence of voltage unbalances or voltage distortions, it is impossible to satisfy simultaneously both previous conditions, therefore a decision must be made based on the choice of guarantee constant real power drawn from the source or guarantee sinusoidal and balanced compensated current to the source [16-17].

In order to make the compensated current become sinusoidal and balanced, the SAPF should compensate all harmonic components as well as the fundamental components that differ from the fundamental positive –sequence current which supplied by the source.In order to determine this positive-sequence component of the load current, apositive-sequence detector is added to the orignal PQ algorithm that applied for the constant instantaneous power control strategy [16-17].

The proposed controller in this paper is the sinusoidal source current control strategy which implemented as a compensation method that makes the active power filter compensate the harmonic current of a non-linear and lead to make the compensated source current sinusoidal and balanced and the control block diagram for this algorithm is shown in figure (6) [16-17].

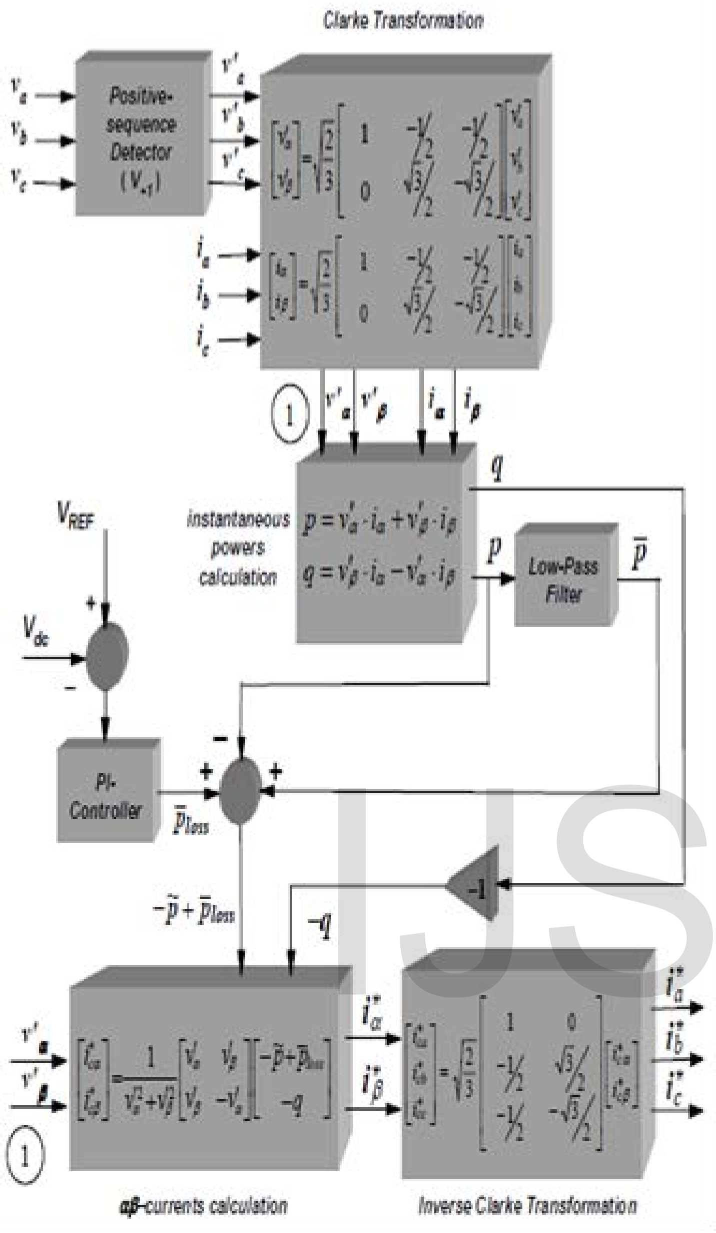

Fig.6: The control block diagram for the sinusoidal source current control Strategy [16].

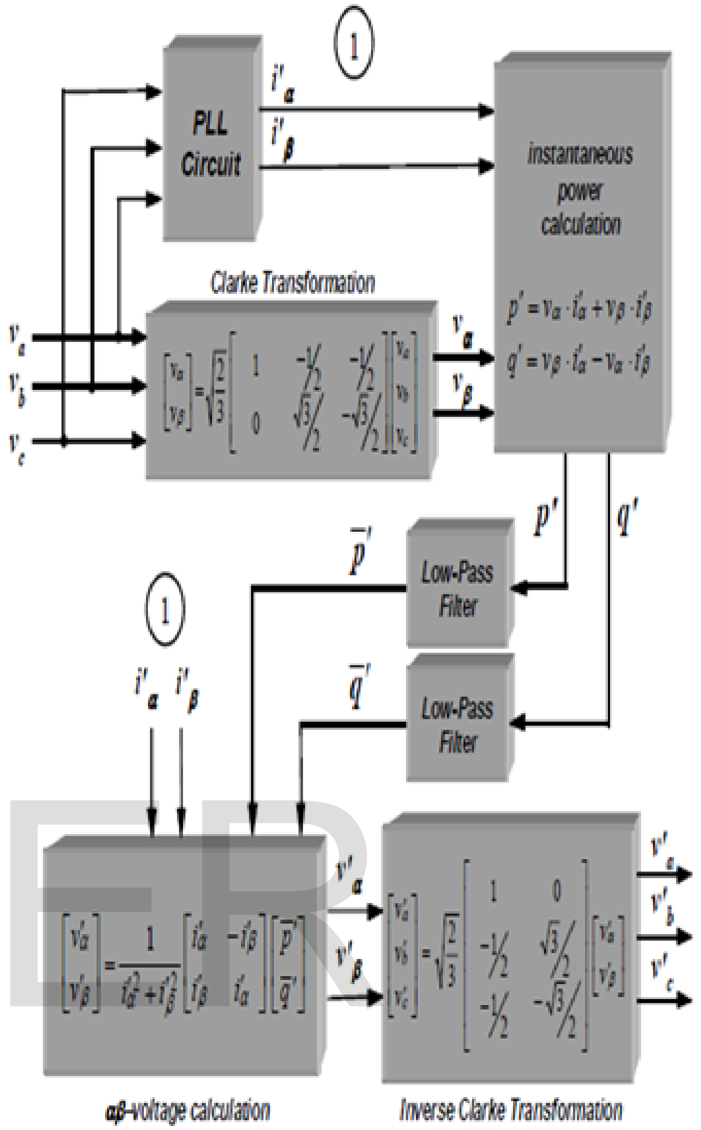

Fig.7: The control block diagram for the positive – sequence voltage detector [17].

The detection of the fundamental positive – sequence components for the source phase voltages is necessary in the sinusoidal source current control Strategy, where these components lead to produce average real power which supplied by the source and the positive – sequence voltage detector detailed in figure(7). based on important part called the phase locked loop (PLL) synchronizing circuit which tracks continuously the fundamental frequency of the system voltages and determine automatically the system frequency and phase angle of the fundamental positive – sequence components of a three-phase system input voltages and this PLL block diagram shown in figure (8) lead to allow a proper operation under distorted and unbalanced voltage waveforms [17].

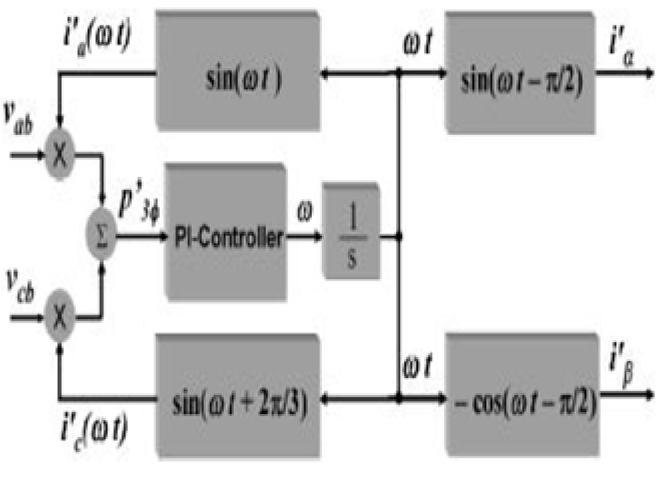

Fig.8: The control block diagram for the synchronizing PLL circuit [17].

### 3.2 Hysteresis Current Control Strategy

The Hysteresis band current controller technique (HBCC) is adapted to control the switching devices of (VSI) so that the output current remains between pre-defined bands around the desired reference current and lead to generation of the suitable gating signals for the (VSI). Furthermore, the implementation of this control scheme is simple and widely used due to its simplicity, fast response, excellent dynamic performance, and controllability of the peak-to-peak current ripple within a specified hysteresis band. In this technique the controller forces the compensation signals to follow its estimated reference signal within a certain tolerance band, where a fixed signal deviation (H) is imposed on the reference signal to form the upper and lower limits of a hysteresis band (HB) and then the actual measured currents are compared with the estimated reference currents on an instantaneous basis to maintained it inside a defined rejoin (HB) around the desired reference current and then the resulting error signal is then subjected to this hysteresis band using a comparator to produce the switching pulses for the inverter and this Hysteresis current controller is implemented as shown in the figures (9), and(10) [15-18].

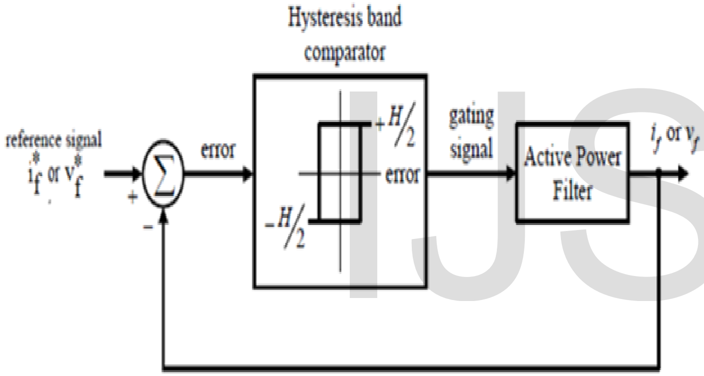

Fig.9: Block diagram of (HBCC) [15].

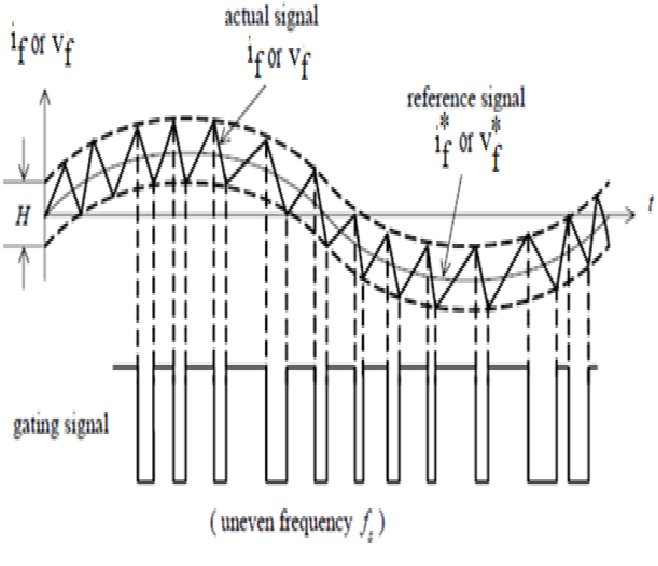

Fig.10: Gating signal generation by HCCT [18].

### 3.3 The instantaneous power calculations

Based on the previous control algorithm detailed in figure (6) which based on ‘‘ PQ ” instantaneous power theory, and according to the this power theory, the variables ‘‘ P ” and ‘‘ q ” express the real and imaginary powers that are to be injected or compensated in the network, where each one of these variables has an average and an alternating ‘‘oscillating” component. The SAPF alone does not absorb nor supply energy, since it only generates the alternating component of p and both components of q to compensate the system. The PV array will generate the average component of p that should be added to the components provided by the SAPF [8-14- and 17].

The instantaneous power flow for the proposed system under study which previously mentioned above in figure (2) can be detailed, where in first case the conventional VSC is applied as a multi-functional inverter with SAPF characteristics, where the generated power from PV array ($P_{PV}$) become (PPV = $V_{PV}$ * $I_{PV}$) and for a lossless VSC the losses at the DC/DC boost converter and at the DC/AC VSC are ignored and the PV power become ($P_{PV}$ = Pdc= Pvsc ), where the power generated at the DC side of the VSC is constant value and the power at the AC side is instantaneous value and includes two parts represented as active or real part (Pvsc) and reactive or imaginary part (qvsc) and each of these has an average and an oscillating component and (Pvsc) is expressed as[9]:

$$P_{vsc} = \bar{p}_{vsc} + \tilde{P}_{vsc} \qquad (10)$$

Where the average real power represents the energy per unit time that is transferred in one direction only and has to be supplied from the utility if the PV does not provide enough of this power to the load demand, and this power is effectively converted into work, and oscillating real power represents the oscillating energy per unit time that is exchanged in two direction between VSC and load, also the average imaginary power corresponds to conventional three- phase reactive power or power exchanged between the system phases and does not contribute to transferred or exchange power between the system and the load, while oscillating imaginary power is exchanged among three phases and this undesirable power component should be compensated [9].

Where, the nonlinear load demands have two components ($P_L$), and ($q_L$) and each one have real and imaginary parts as in equations:

$$q_L = \bar{q}_L + \tilde{q}_L \, , \quad P_L = \bar{p}_L + \tilde{P}_L \qquad (11)$$

In the first case, there is an instantaneous power balance among the three parts (supply, VSC, and load) at the point of common coupling (PCC), where the controller make the VSC can generate and supply the undesirable powers to the load and the rest of the required power is supplied from the utility which supply only average part of the real power ($P_{Uti}$) and then the pure sinusoidal currents are taken from the source based on APF functions, where the D C/AC VSC of PV-APF combination will supplies all components of the imaginary power of the load and also compensates harmonics and oscillating components of the real power for the nonlinear loads in addition to it supplies one part of the average component of real power demand and the other part of load real power is received from the utility which provides only the average components [9].

The balanced relation among instantaneous powers in the first case is shown in figure (11), and represented by the following equations:

$$\begin{cases} p_{\mathrm{Uti}} = \bar{p}_{\mathrm{Uti}} \\ q_{\mathrm{VSC}} = q_L \\ p_{\mathrm{VSC}} + p_{\mathrm{Uti}} = p_L \\ \bar{p}_{\mathrm{VSC}} + \bar{p}_{\mathrm{Uti}} = \bar{p}_L \\ \tilde{p}_{\mathrm{VSC}} = \tilde{p}_L . \end{cases} \qquad (12)$$

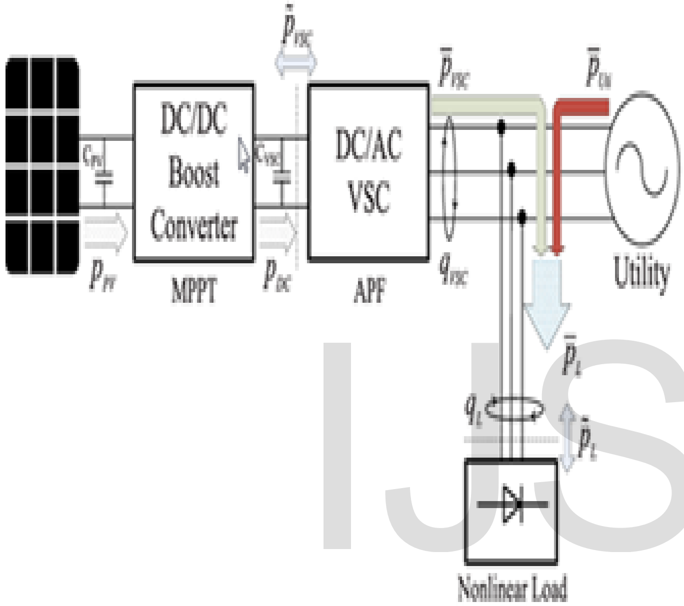

Fig.11: Instantaneous power flow among the PV-APF Combination system [9]

Also, an extra amount of real power (Ploss) is calculated by the dc-link voltage regulator and supplied from the utility or PV array which causes additional flow of energy to (from) the dc-link capacitor (CVSC) in order to keep its voltage around a fixed reference value.

Also, for the second case implemented with the proposed system under study, the compensation equation in this case is different as comparing with the first case, where in this case the SAPF in adding in parallel with non-linear load and lead to provide harmonic elimination and reactive power compensation and the PV array side is only compensate the required average part of the load real power beside the utility, but the reactive and oscillating powers for load demand are taken from the SAPF, where the VSC which used as the interface between RES-based PV and the utility grid become used as a conventional converter provide only the injection of the active power generated from PV array, and this case is known as PV-VSC-APF and showing in figure (12).

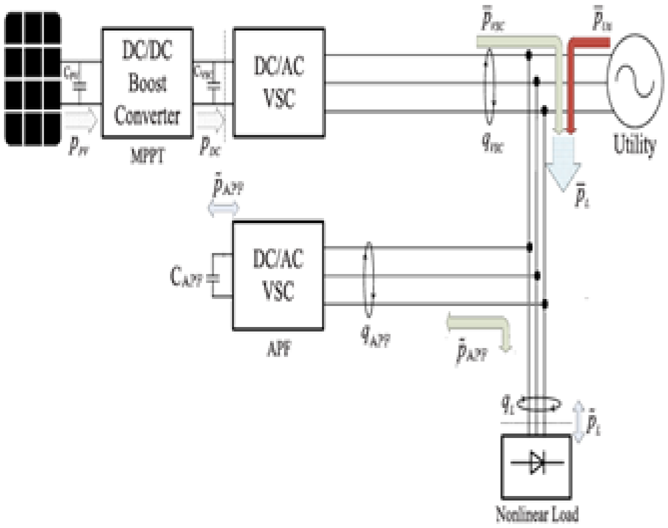

Fig.12: Instantaneous power flow among the PV-VSC-APF Combination system.

## 4 PROPOSED SYSTEM AND SIMULATION RESULTS

### 4.1 Proposed system

The proposed system is based on the system described in Fig. 1, where these two cases detailed above are simulated under MATLAB/Simulink to validate its ability to filter out the harmonic of nonlinear loads and lead to provide harmonic elimination and reactive power compensation.The main parameters of the proposed system used in the simulation study are indicated in Table (1) which represent an AC utility grid with three phase balanced and sinusoidal distribution voltage source, nonlinear load represented by a three phase non controlled bridge rectifier and the SPAF is connected to the PCC beside PV array which interfacing power through multi-functional or conventional voltage source inverter VSI.

The simulation system is run in a period of 0.5 sec, where the important time instances are detailed for the proposed two cases, where the important time instances for the first case are:

1) Form 0 sec to 0.1 sec the utility grid will supply nonlinear load without compensation
2) At 0.1 sec, turn on MPPT and VSC with conventional dq-current controller.
3) At 0.2 s, activate MPPT to interface PV through conventional VSC and also switch on SAPF with PV and SAPF controller based on Sinusoidal Source Current Controller.
4) At 0.35 s to 0.5, switch off PV array form the system and test SAPF compensation based on Sinusoidal Source Current Controller.

The important time instances for the second case are:

1) form 0 sec to 0.1 sec the utility grid will supply nonlinear load without compensation.

2) at 0.1 sec, turn on MPPT and VSC with conventional dq-current controller.

3) at 0.2 s, activate MPPT to interface PV through multifunctional inverter VSC and PV-APF simulation mode is based on Sinusoidal Source Current Controller.

4) at 0.35 s to 0.5, switch to APF simulation mode without PV array based on Sinusoidal Source Current Controller

TABLE (1)
PARAMETERS OF THE ANALYZED SYSTEM

| Quantity | Parameter | Symbol | Value |
|---|---|---|---|
| AC utility grid | Line voltage | VS(L-L) | 380V |
| | Line frequency | f S | 60Hz |
| | Grid inductance | LS | 100nH |
| | Grid resistance | RS | 0.9mΩ |
| Non-linear load | DC resistance | RDC | 5 Ω |
| | DC inductance | LDC | 150mH |
| | AC inductance | LAC | 0.01mH |
| Sun Power SPR-305-WHT PV-array | Maximum power | Pmax(pv) | 100kW |
| | Solar irradiance | (W/m^2) | 100 |
| | Temperature | (deg. C) | 25 |
| | Interfacing resistance | Rpv | 1.8 mΩ |
| | Interfacing inductance | Lpv | 500 mH |
| | DC Link capacitor | Cdc | 12nF |
| | DC link voltage | Vdc | 500V |
| (SAPF) Present in case (1) only | Interfacing resistance | RF | 5 mΩ |
| | Interfacing inductance | LF | 6 mH |
| | DC Link capacitor | Cdc | 1μF |
| | DC link voltage | Vdc1 | 500V |

## 4.2 Simulation results

Running MATLAB/SIMULINK model for the proposed systems described above in two cases and take simulation waveforms for utility (supply) current, non-linear load current, PV current, and SAPF current which applied in case (1) only and also observe the instantaneous real and imaginary power of the system in each case. From point of view of power quality, the utility current is the most important value that should be considered, therefore the total harmonic distortion (THD) in the utility current is analyzed using Fast Fourier Transform (FFT) to make a comparison between the obtained values in each mode of operation and also the utility phase current and voltage are superimposed to showing the effect of active power filter in modifying power factor and finally observe the advantages of the proposed controller to make harmonic reduction and power factor correction and lead to power quality improvement.

The waveforms for system currents among all parts are shown in figures (13) and (14), which showing that the ability of controller in both cases to compensate the load demand, where at starting time of simulation from 0 to 0.1sec and PV completely switched off, the utility current is exactly equal to the nonlinear load current and has the same distortion in load current in both cases and has (THD=29.89%). After that when conventional d-q current controller mode starting at 0.1sec and MPPT and d-q controller turned on till 0.2sec the utility current become distorted and has (THD=256.63% in case (1)) and (THD= 297.70% in case (2)), where these values are value higher than its value taken when load supplied only from the utility. When MPPT is activated and PV is turned on from 0.2 to 0.35 sec and supplying power whether it used with SAPF and interfacing through conventional VSI in case (1) or through multi-functional inverter in case (2) the THD in the utility current become (THD=4.27% in case (1)) and (THD=4.02% in case (2)), finally when PV is turned off and switched out from the entire system from 0.35 to 0.5 sec the power taken from PV become zero and all load demand become taken from the utility and Cvsc whether in the presence of SAPF in case (1) or not in case (2) the distortion in the utility current become (THD = 2.65% in case (1)) and (THD=4.29% in case (2)), where all spectrum of THD are showing in figures(15) and (16), and its results are detailed with system power factor results in table (2) .

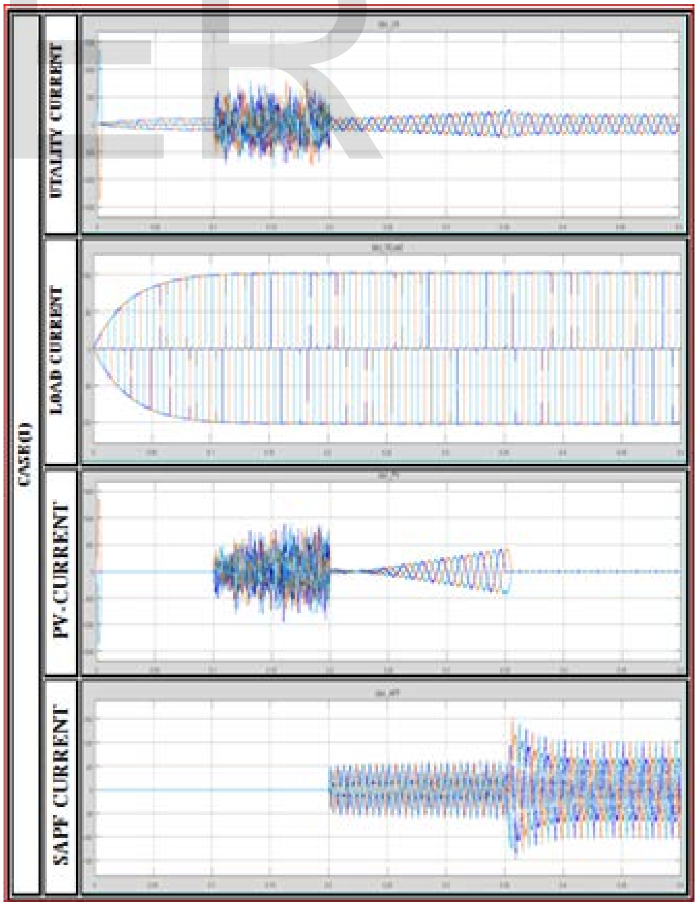

Fig.13: all system currents for case (1)

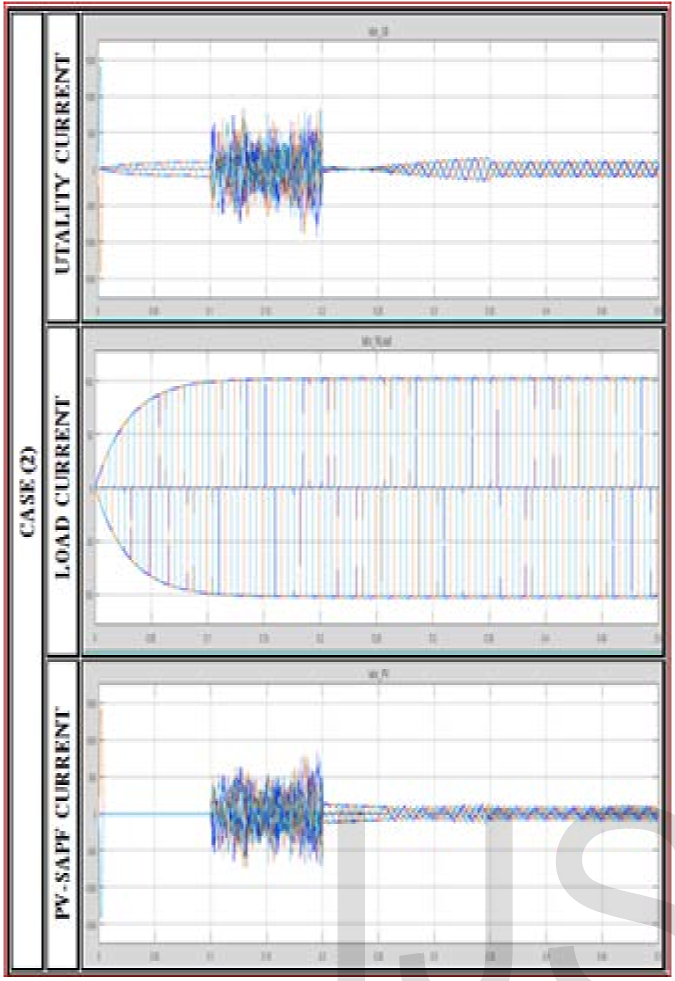

Fig.14: all system currents for case (2)

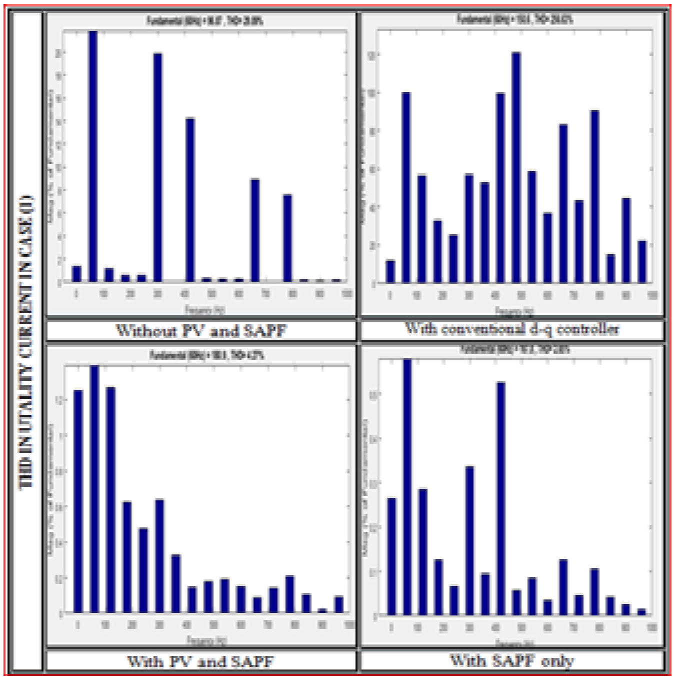

Fig.15: Spectrum analysis for case (1)

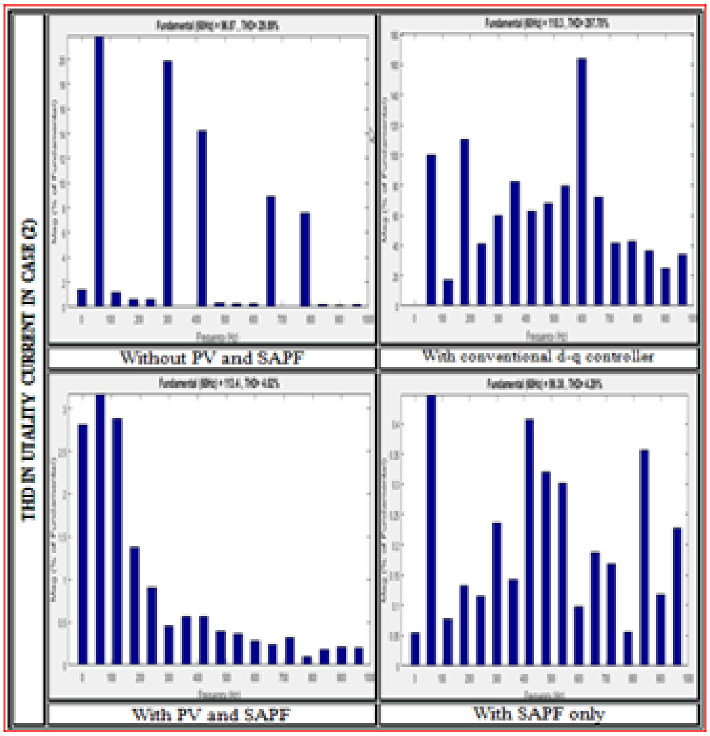

Fig.16: Spectrum analysis for case (2)

TABLE (2)
SYSTEM RESULTS FOR THD AND POWER FACTOR

| Mode | | THD (%) | P.F (%) |
|---|---|---|---|
| **Case (1)** | Without PV and SAPF | 29.89 | 0.8494 |
| | With Conventional d-q Controller | 256.63 | 0.9284 |
| | With PV and SAPF | 4.27 | 1 |
| | With SAPF Only | 2.65 | 0.9348 |
| **Case (2)** | Without PV and SAPF | 29.89 | 0.8494 |
| | With Conventional d-q Controller | 297.70 | 0.7025 |
| | With PV and SAPF | 4.02 | 1 |
| | With SAPF Only | 4.29 | 1 |

The proposed control strategy are proved its worth and ability for power modification of power factor and the utility waveforms for the phase current and voltage in both cases are shown in figure (17). Finally The instantaneous real power balance (p) and imaginary power balance (q) among all system parts, including the PV unit, SAPF, utility, and nonlinear load, are shown in figures (18) and (19).

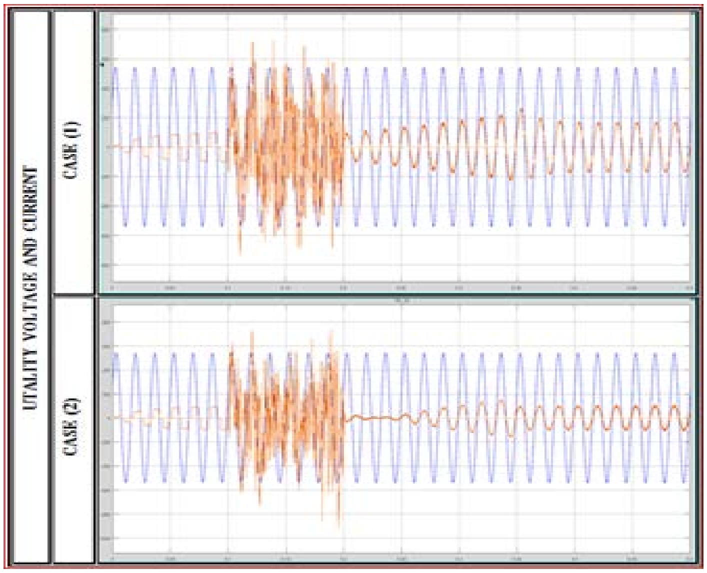

Fig.17: Utility phase voltage and current

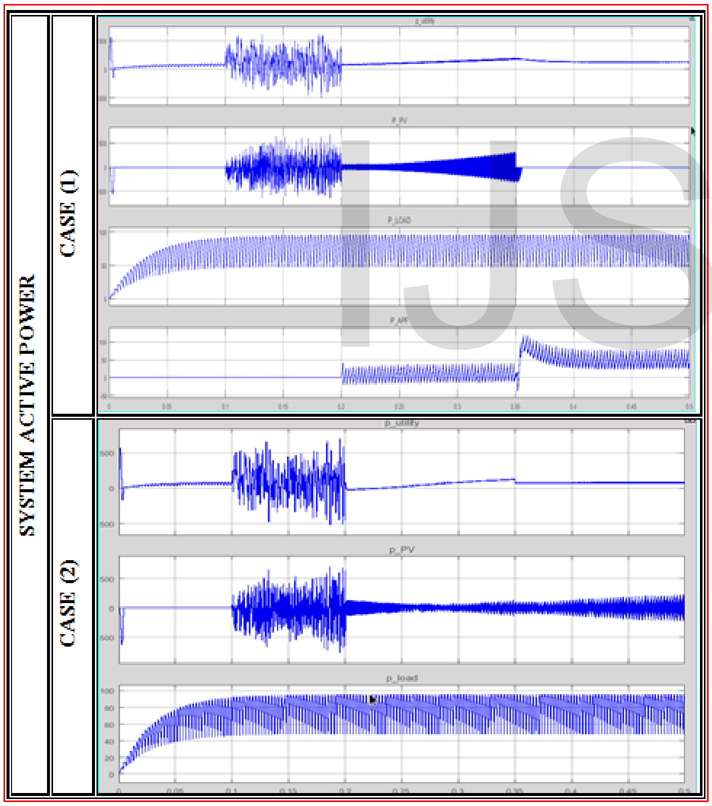

Fig.18: The instantaneous real power balance (p).

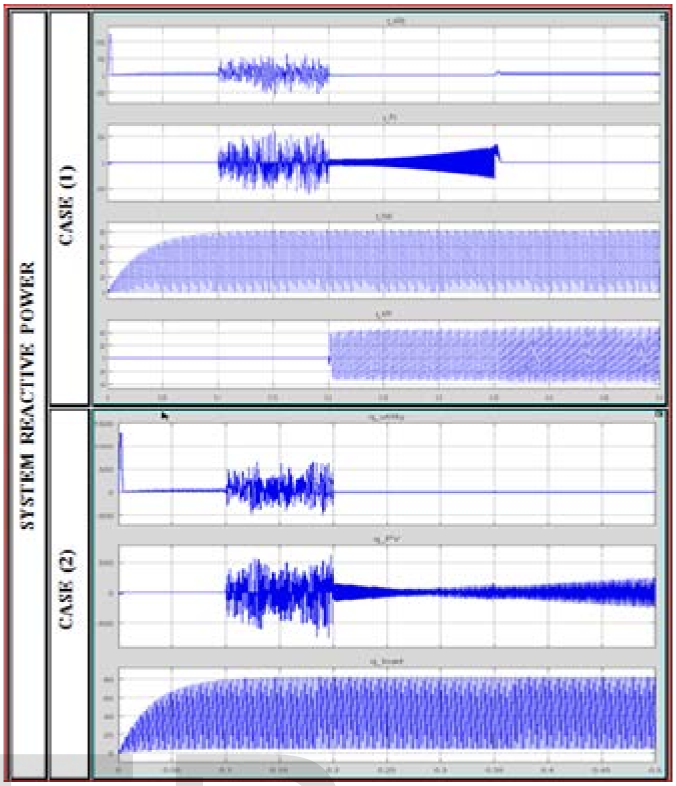

Fig.19: The instantaneous imaginary power balance (q).

## 5 CONCLUSION

The proposed controller of sinusoidal source current control strategy which based on the instantaneous active and reactive power (p-q) theory is introduces and applied on a conventional voltage source inverter (VSI) which utilized in the first case as a shunt active power filter (SAPF) connected in parallel with the photovoltaic array which interfacing with the utility grid through a another conventional inverter and this topology achieve beside mitigation of power quality problems but also improving the reliability requirements for the system. Also this controller is applied in the second case on the interfacing inverter making it as a multi-functional inverter with features of interfacing renewable energy source with the utility besides solving of power quality problems and also this topology achieve the cost reduction for the system. Finally from the simulation results taken from two cases the controller performance showing its ability to mitigate power quality problems beside of interfacing the renewable energy sources (RES) which integrated with the distribution system at PCC and as a results from power quality view point the conventional controllers should not applicable to utilized when the RES connected with a nonlinear load.

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