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Mitigation of the Effect of HVDC System on Power System Quality at Distribution Level

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Abstract- ***Recently the rapid development and improvement in the efficiency of power electronics equipments has led to the proliferation and increase of nonlinear loads such as static power converters. These equipments have been progressively utilized and open new technological solutions for some direct current applications such as High Voltage Direct Current (HVDC) system. However, these loads cause many disturbances at the distribution level because they inject high power harmonic currents. This results in an increase in losses, low energy efficiency, interference with power equipment and communication networks and voltage distortion beyond acceptable levels in many situations. Therefore, using harmonic filters is essential to mitigate power quality problems for such systems. Several schemes were proposed to perform this function such as passive filters, synchronous condenser and thyristorized static var compensator (SVC). However, resonance, high cost, slow response, and low order harmonics injection are the major limitations of these schemes. Recent development of semiconductor switches has opened the door for using Active Power filters (APFs) which have superior performance over the past mentioned methods. The current work provides a design for two different control strategies (PI-controller and Instantaneous Active and Reactive Power (PQ) method) based on hysteresis current control technique (HCCT) for such filters. The design is validated using MATLAB simulation and is tested under different transient disturbances and they mitigate most of the problems of the traditional filters. Further, It is proved that PI controller has better response than PQ theory for most of the cases.***

Index- **High Voltage Direct Current (HVDC) system, active power filter, PI-controller, instantaneous active and reactive power (PQ), hysteresis current control technique.**

I. INTRODUCTION

HVDC system is becoming an efficient technology with characteristics and profits making it especially attractive and desirable in specific applications for modern power systems instead of HVAC system. The key benefits making HVDC become more desirable and overcome HVAC problems are the following [1]:

1) Environmental advantages
2) Economical (least expensive arrangement)
3) Asynchronous interconnections
4) Power flow control
5) Added benefits to the transmission (stability, etc)

HVDC benefits can be simplified into two main reasons, namely HVDC is essential from the technical point of view (that is controllability), and HVDC investment gives less expensive (including lower losses) and/or is environmentally superior. In a typical HVDC system as in figure (1), a converter station is the most essential and the switching action for these converters is the major source of harmonics, where the operation of converters to perform AC/DC and DC/AC conversion leads to harmonic generation in the nearest buses for distribution system and also consume reactive power due to the nonlinearity nature for these converters.

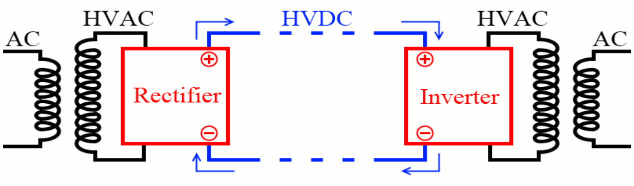

Fig.1 Representation of HVDC system.

II. HARMONIC MITIGATION TECHNIQUES

In order to regulate the permanent power quality problem, there are two general techniques for reducing or eliminating and taking out harmonics from power systems. On one hand, harmonics can be prevented from being injected by using of a powerful strategy with Y and Δ transformer-based harmonic cancellation scheme. On the other harmonics can be removed from a power system by putting harmonic filters close to the current injection source [2].

A. Harmonic Filters

The control or relief of the power quality problems may be admitted through the use of harmonic filters. Where Harmonic filters, in general, are designed to reduce the impacts of harmonic penetration when harmonic content has been exceeded in power distribution system, where the presence of harmonics and reactive power in the system has harmful effect and leads to additional power losses, poor power factor and disrupts of the grid components[2].Also harmonics cause line voltage distortion at the Point of Common Coupling (PCC) where the linear and nonlinear loads are connected as shown in the figure (2).

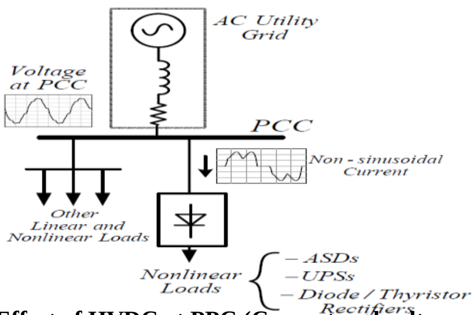

Fig. 2 Effect of HVDC at PPC (Current and voltage distortion).

Harmonic filters are characterized in three fundamental categories [3]:

- Passive filter
- Active power filter
- Hybrid active power filter

In general, the conventional harmonic mitigation technique is the passive filtering technique. But passive filters PFs designs require excessive system studies, relatively high cost. In addition, passive filters have numerous drawbacks, for example large size, mistuning, instability and resonance with load and utility impedances [4]-[5].On the other hand, passive filters can only correct specific load conditions or a particular state of the power system and these filters are unable to take after the changing system conditions. Hence, the APFs were introduced to overcome the problems of PFs [6].

III. ACTIVE POWER FILTERS (APFS)

APFs have additional functions over PFs to form effective and powerful solutions for many power quality problems. Most importantly, they can suppress not only the supply current harmonics, but also the reactive currents. Besides, dissimilar passive filters, they do not cause harmful resonances with the systems and additionally smaller in physical size. Thus, the APFs performance is free and independent of the power distribution system properties [7].The guideline of APF is to process specific harmonic current components that cancel the harmonic current components created by the nonlinear load. Fig .3 Shows that the components of a typical APF system and their associations.

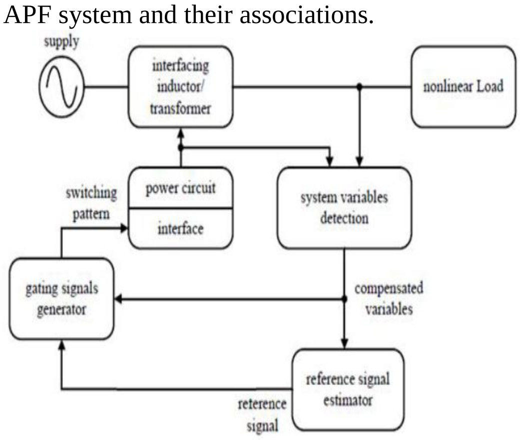

Fig. 3 Generalized block diagram for APF.

As represented in Fig.3 the information regarding the harmonic currents and other system variables are passed to the compensation current/voltage reference signal estimator to drives the overall system controller and gives the control for the gating signal generator to control the power circuit which connected in parallel, series or parallel/series configurations depending on the interfacing inductor/transformer used. Also, the improvements in control theory and application of modern control strategies in power electronics have played a significant role in the practical realization and commercial success of active power filters [4].

IV. SHUNT ACTIVE POWER FILTERS (SAPFS)

Nowadays, Shunt APFs are the most configurations broadly utilized in active filtering applications for current harmonic reduction and power factor improvement. The shunt-connected APF with a self-controlled dc bus, act as a harmonic current source to compensate the harmonic currents of nonlinear loads. As indicated in Fig.4, the controller of SAPF system detects the instantaneous load current, extracts its harmonics content and injects the compensating harmonic currents to cancel the load harmonic currents. As a result, a sinusoidal current is drawn from the utility [4].

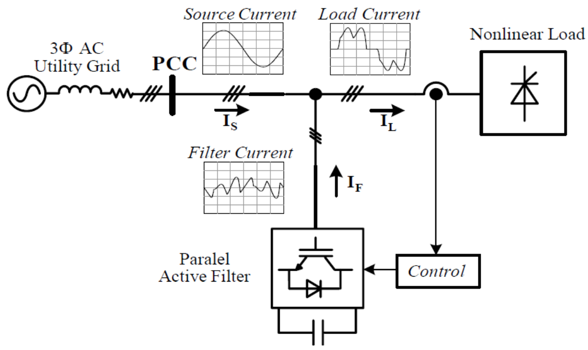

Fig.4 SAPF acts as a harmonic compensating current source [4].

A. SAFs topologies

The system for SAPF comprises of a controllable voltage source inverter (VSI) with power circuit and control unit ,where (VSI) based SAPF is the most commonly used type, due to its well known topology and it more efficient, more cost-effective and smaller in size compared to the current source inverter (CSI)[4].The rule of the inverter is used to charge and discharge the capacitor to provide the required compensation current, where the AC supply provides the required active power and the capacitor of SAPF provides the reactive power for the load[8].The shunt APF consists of three principal parts, namely:

- The voltage source inverter
- Coupling inductance
- DC energy storage device

As shown in Fig.5 the principle configuration of VSI based shunt APF is demonstrated and it consists of a three power Switches Bridge with a common ground, each one connected in series at (PCC) through an interfacing inductor (L_f) which used to suppressing the higher order harmonic components caused by the switching operation of the power transistors. The dc-link capacitor (C_{dc}) connected on dc-side of (VSI) is used to maintains the dc-voltage nearly constant with small ripples in steady state and serves as an energy storage element to supply real power difference between load and source during the transient period. In steady state, the

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real power supplied by the source should be equal to the real power required by the load with little power to compensate the losses in the active power filter. However, when the load condition changes, the real power balance between the source and the load will be disturbed, this real power difference needs to be compensated by the dc-link capacitor [8].

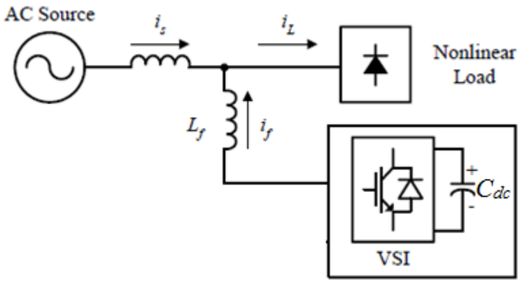

Fig. 5 Configuration of a VSI based shunt APF.

B. Basic Compensation Principle

The fundamental concept of SAPF compensation system is appropriate to any type of nonlinear load that creates harmonics such as a six-pulse rectifier converter, therefore SAPF compensates current harmonics produced by this nonlinear load due to drawing of additional harmonic current from the source, beside the fundamental component drawn by the load at PCC and cause harmonic distortion of the source current [3]. SAPF is controlled to draw/supply a compensated current from/to the utility and operates as current source injecting non-sinusoidal harmonic components with phase shifted of (180^0) as shown in Figures (6) and (7). A result, components of load harmonic currents are cancelled and the source currents becomes sinusoidal , free from harmonics and in phase with the distribution voltage source[6]-[8].

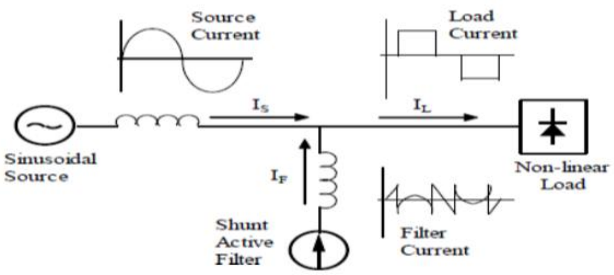

Fig. 6 The Compensating principle of SAPF [8].

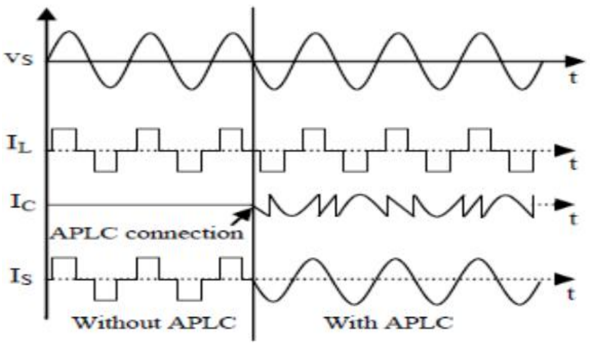

Fig.7 Waveforms for the compensation system [8].

C. SAPFs Control Strategy

Control strategy is the heart of the SAPF, and can be implemented in two stages as shown in figure (8). The first stage is the development and extraction of compensating signals (reference currents) from the distorted signals (load harmonic current) represented by the reference current extraction method which implemented by using of a controller methods in time domain with fast response such as the instantaneous active and reactive power (PQ) theory and the proportional integral (PI) controller method[8]. The second stage is represented by the current control technique based on hysteresis strategies which is the most critical part in control system for the generation of appropriate gating signals to control the switching devices of VSI focused around the estimated compensation reference signal [9].

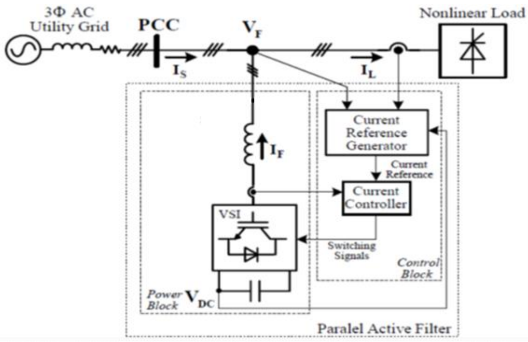

Fig. 8 General control system diagram of the SAPF [4].

Figure (9) represents atypical nonlinear load current and its harmonic content, which is the SAPF current reference. The accuracy of the generated current reference is a critical issue in the performance of the current controlled SAPF [4].

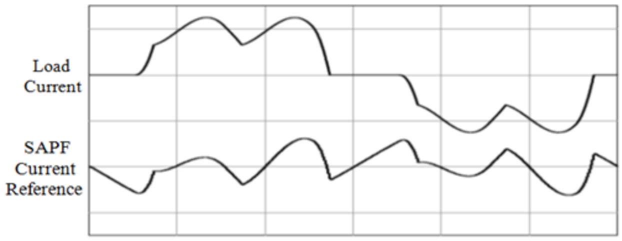

Fig. 9 The typical load current and SAPF current reference [4].

V. SAPF CONTROLLER BASED ON (PQ) THEORY WITH HYSTERESIS BAND CURRENT CONTROL TECHNIQUE (HCCT)

The control algorithm for reference current signal generation is based on the integration of (PQ) theory, which widely used due to its flexibility and effectiveness in harmonic suppression and dynamic power factor correction, but this takes place just under the assumption that the three-phase system is balanced and the source voltage waveform is perfectly sinusoidal and free from all harmonics. Where the PQ theory is based on a set of

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instantaneous values of active and reactive powers defined in the time domain [6]. Fig. 10 illustrates the operation of the SAPF controller with (PQ) theory, where the inputs to the controller are the load currents, source voltages which used to calculate an active and reactive power [6]. Where the (PQ) theory is based on "α-β" transformation of voltage and current signals to extract the harmonic active and reactive powers by using of low-pass filter, then compensating currents are derived by using reverse "α-β" transformation. Due to excellent dynamic performance, controllability and simplicity the Hysteresis band current controller technique (HBCC) is adopted to controls the switches of the (VSI) asynchronously to ramp the current through the inductor up and down, Where in this technique a signal deviation (H) is imposed on the reference signal to form the upper and lower limits of a hysteresis band (HB) and then the compensation or measured actual injected currents generated from the filter are compared with the estimated reference currents on an instantaneous basis to maintained it inside a defined rejoin(HB) around the desired reference current introduces from (PQ) theory as shown in figure (11).and then the error signal is then compared against this hysteresis band using a comparator to produce and generate switching pulses for the inverter as shown in figure (12) [3].

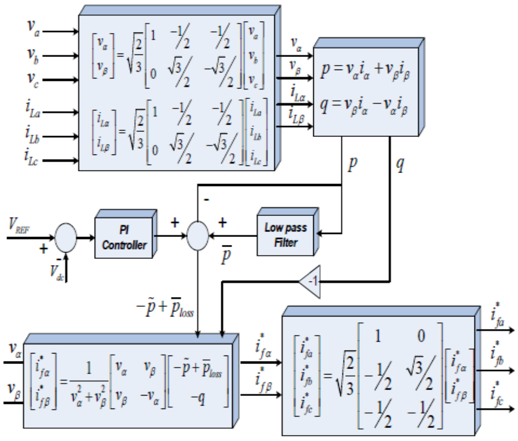

Fig. 10 The control algorithm for the calculation of reference Currents of the compensator [6]

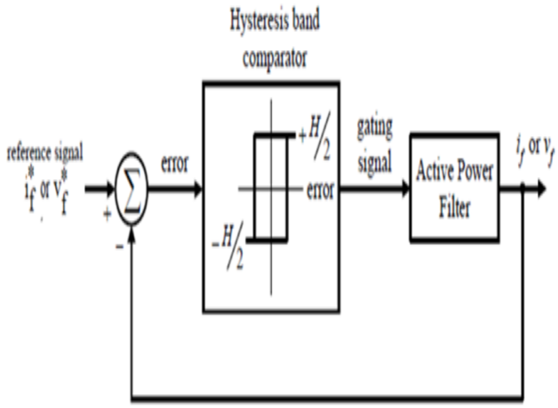

Fig.11 Block diagram of hysteresis control technique [3].

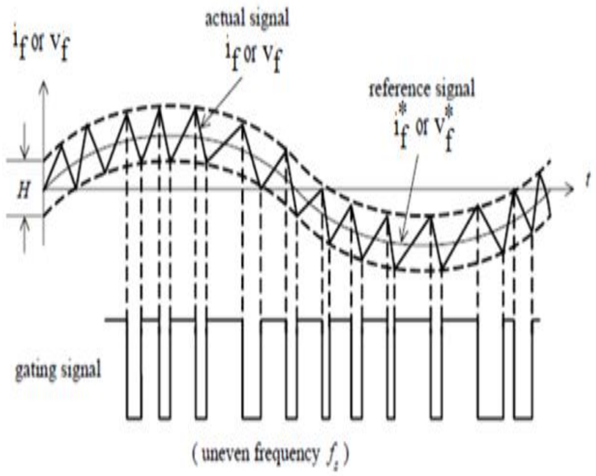

Fig.12 Gating signal generation by HCCT [3].

VI. SAPF CONTROLLER BASED ON (PI-CONTROLLER) METHOD WITH HYSTERESIS BAND CURRENT CONTROL TECHNIQUE (HCCT)

Taking into account and based on the voltage value at the capacitors in the DC side of the SAPF, a simplified (PI) control method based on a closed loop control algorithm is required to generate reference source current in phase with AC source voltage to result in unity power factor of the source current, where the reference current of SAPF is extracted from distorted line current using the unit current (sine) vector alongside PI controller [8]-[10]

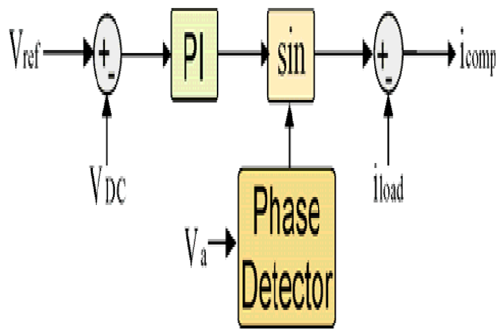

Fig. 13 SAPF Control scheme with PI controller method.

This control algorithm decreases sensors and complexity by sensing only dc-link voltage, three-phase supply voltages and currents (no need to sense load currents and compensation currents) [8]-[10].where the routine PI-controller is used to estimate the required magnitude of reference source current, and to control the dc-link capacitor voltage of the inverter by comparing the actual capacitor voltage with a set reference value and the error signal is then sustained through a PI controller, the output of PI controller has been considered as peak value of the supply reference current (Imax) which multiplied by the unit sine vectors u(t) to be in phase with the source voltages and obtain the reference supply currents (Is*= u(t) × Ism*), which subtracted from the detected actual

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load currents to get the reference compensating currents (ic*=is*- icon) as shown in figure (13).Then the reference compensating currents and the actual currents are compared by using of a hysteresis band current controller technique HCCT which discussed above to generate appropriate switching signals of the (VSI) [8]-[11].

VII. TWO BUS NETWORK SIMULATION RESULTS

Simulation for the proposed scheme is very important and powerful tool to study the Dynamics of the system, where the complete SAPF system is composed mainly of three-phase source, nonlinear load and voltage source converter (VSC) with control techniques using (PQ) and (PI) controller methods based on hysteresis current controller technique (HCCT). MATLAB/SIMULINK is developed as a simulation tool to implement the proposed SAPF and study its performance for harmonic and reactive power compensation at PCC in power distribution system. The proposed scheme is first simulated without filter to find out the total harmonic distortion (THD) for the source current, then it is simulated with the SAPF to observe the difference in THD of supply current and comparing between these results obtained from two controller methods.

A. System Description

The simulated system shown in figure (14) is a three phase balanced and sinusoidal distribution voltage source, nonlinear load represented by a three phase non controlled bridge rectifier fed from AC utility grid and the SPAF is connected to the PCC. The parameters of the grid and rectifier in addition to the SAPF are given in table (1).

TABLE (1). PARAMETERS OF THE ANALYZED SYSTEM

Quantity	Parameter	Symbol	Value
AC utility grid	(Grid Line voltage)	V_S	380V (L-To-L)
	(Grid Line frequency)	f_S	50Hz
	(Grid Line inductance)	L_S	1mH
	(Grid Line resistance)	R_S	1f Ω
Diode rectifier Nonlinear load	DC Load resistance	R_{dc}	100 Ω
Shunt active Power filter (SAPF)	Filter resistance	R_F	0.01 Ω
	Filter inductance	L_F	5.12mH
	SAPF DC capacitor	C_{dc}	8mF
	DC link reference voltage	V_{dc}	650V

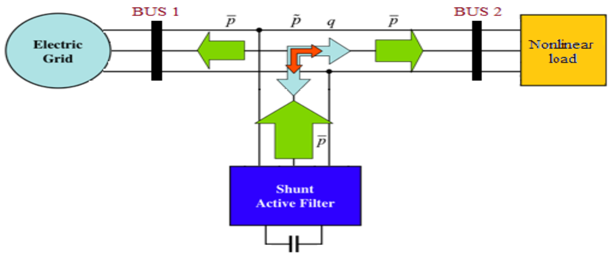

Fig.14 Two Bus system with SAPF.

B. Results without SAPF compensation

Running MATLAB/SIMULINK model for the system described above and take simulation waveforms for supply current which equal to load current and the SAPF current equal to zero as shown in figures (15), take results for supply voltage and system power factor before insertion of SAPF in the system, also take the harmonic spectrum for phase supply voltage and phase supply current as shown in figure (16) and its details illustrated in table (2).

TABLE (2). SPECTRUM DETAILS FOR SYSTEM SIMULATION

Factors		Without connected SAPF	
		With(PI)	With(PQ)
Supply phase voltage (Vs)	Total (RMS) Value	220.2	220.2
	DC Component	0	0
	AC (RMS) value	220.2	220.2
	Fundamental (RMS) value	220.2	220.2
	Harmonic (RMS) Value	1	1
	T.H.D (%)	0.4545	0.4545
Supply phase current (is)	Total (RMS) Value	42.6134	42.6116
	DC Component	0.0051	0.0054
	AC (RMS) value	42.6134	42.6116
	Fundamental (RMS) value	40.9955	40.9951
	Harmonic (RMS) Value	11.6306	11.6255
	T.H.D (%)	28.3704	28.3582
System power factor (%)	Supply	96.54%	96.56%

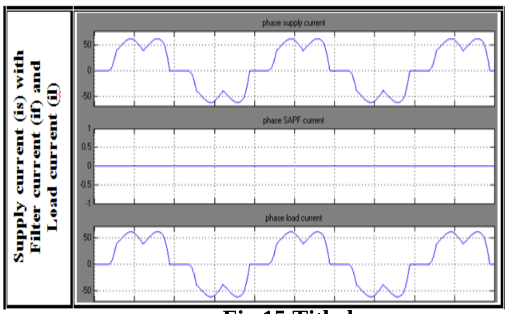

Fig.15 Titled

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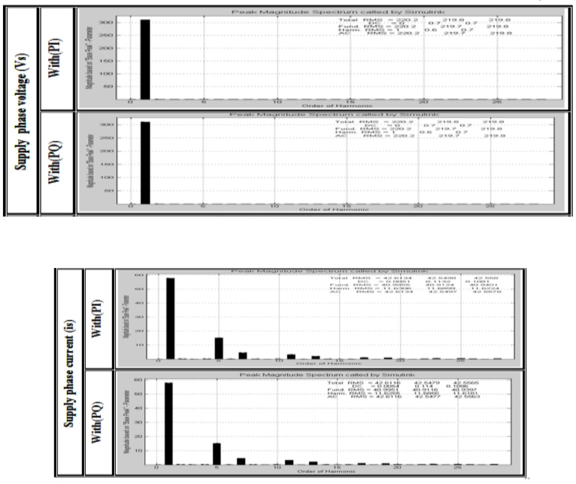
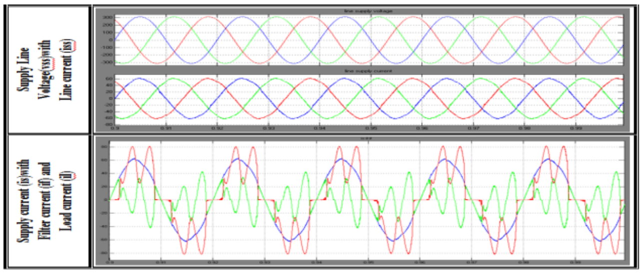


Fig. 16 Spectrum analysis for phase supply voltage and phase supply current.

C. Results with SAPF compensation

Running MATLAB/SIMULINK model for the system with compensation occurs by SAPF and take simulation waveforms for supply voltage, supply current, load current, SAPF current, and dc link capacitor voltage, as shown in figures (17) and (18), take results for supply voltage and system power factor after insertion of SAPF in the system, also take harmonic spectrum for phase supply current shown in figure (19) and harmonic spectrum for phase supply voltage have the same results mentioned above because supply voltage signals are sinusoidal, comparing between two controller techniques with waveforms and details illustrated in table (3) and showing in figure (20).

With (PI) controller method based on HCCT



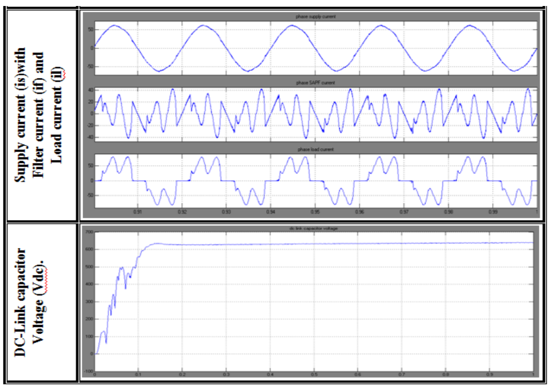


Fig.17 Titled With (PQ) controller method based on HCCT

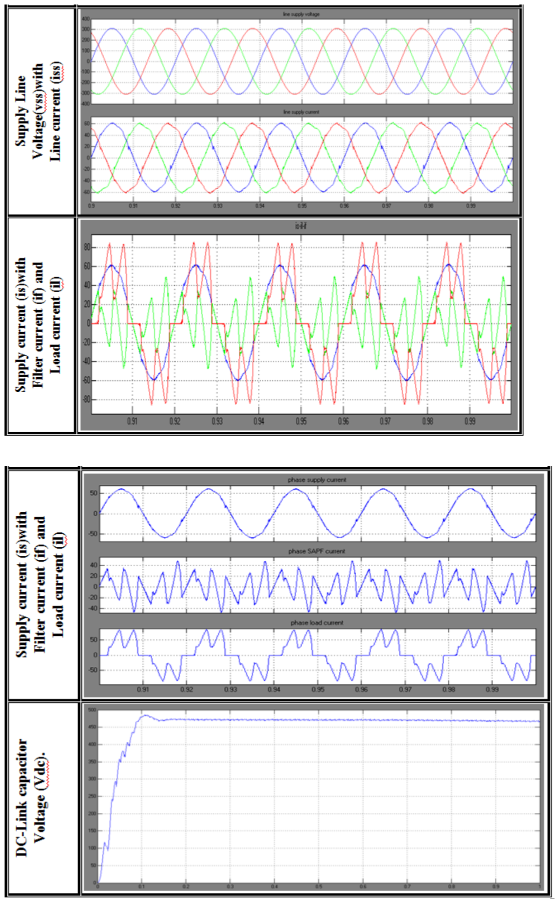


Fig.18 Titled Comparison between (PI) and (PQ) controller methods based on HCCT

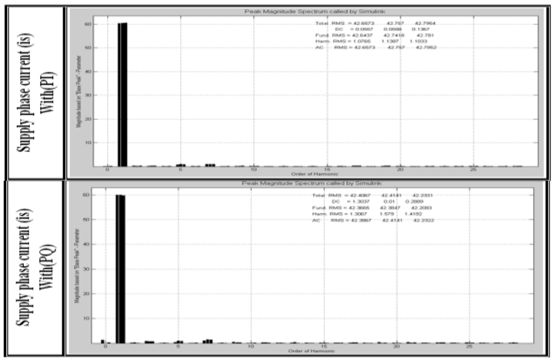
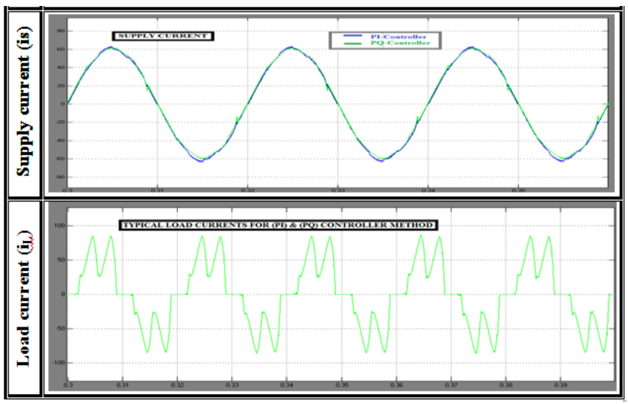


Fig. 19 Spectrum analysis for phase supply current with SAPF compensation.



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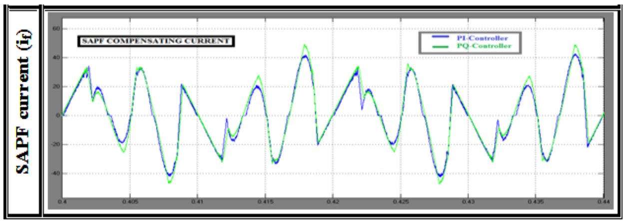

Fig.20 Titled

TABLE (3) SPECTRUM DETAILS FOR SYSTEM SIMULATION.

Factors		With connected SAPF	
		With(PI)	With(PQ)
Supply phase current (is)	Total (RMS) Value	42.6573	42.4067
	DC Component	0.0557	1.3037
	AC (RMS) value	42.6573	42.3867
	Fundamental (RMS) value	42.6437	42.3665
	Harmonic (RMS) Value	1.0765	1.3067
	T.H.D (%)	2.5244	3.0843
System power factor (%)	Supply	100%	99.99%

VIII. CONCLUSION

The current work provides a design of two control strategies for SAPF, where the Simulation results showing that, the performance of (PI) and (PQ) controller methods based on HCCT, are able to generate the proper compensating reference current to satisfy the requirements of harmonic suppression and reactive power compensation to get power factor improvement and mitigation of power quality problems for distribution system including nonlinear load. where without SAPF compensation system, the harmonic spectrum showing higher values for THD in the supply current reaches (28.3 %), but using of the SAPF is able to reduce the THD in the source current to an acceptable values within the power quality standard, and not exactly zero because internal switching of the compensator itself generates some harmonics, also observing that the performance for (PI) control method is approximately better than (PQ) control method where THD with (PI) reaches (2.52%) but with (PQ) the THD reaches (3.08%).Finally, simulation results proved the viability of using these control methods with SAPF which become able to compensate the harmonics and reactive power of the distribution system and to produce sinusoidal source current with unity power factor and free from harmonics.

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