

Study and Analysis of Performance of 3-Phase Shunt Active Filter in Grid-tied PV-Fuel Cell System Employing Sinusoidal Current Control Strategy

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Abstract: - This paper describes about mitigation of power quality issues using Shunt active filter in a Grid connected hybrid energy system consisting of PV-Battery-Fuel Cell. The Shunt active filter control is based on Sinusoidal Current Control Strategy. Shunt Active Power Filters (ShAPF) is implemented in the hybrid systems to mitigate the harmonic current component as well as to recompense the imaginary or reactive power owing to their exact and reckless operation. Sinusoidal current based controller used in a ShAPF has been focused over here. Sinusoidal current control strategy is utilized to extricate sinusoidal current commencing from the source. The sinusoidal currents in addition with a stout synchronizing circuit (Phase Locked Loop or PLL circuit), custom a brief controller meant for ShAPF which is precise by a sinusoidal current based controller in order to perform like a harmonic isolator amid supply and load. Action of the ShAPF under passive load conditions using non-linear load, the performance of the sinusoidal current control technique is evaluated using MATLAB R2016a. MATLAB simulation results validate the efficiency of the power filter system to mitigate harmonic, it also offered to validate the control strategy. Total Harmonic Distortion (THD) of voltage as well as of current determines the practical feasibility of controller designed for ShAPF to deliver a harmonic separation of passive loads.

Key-Words: - Active Filters, Custom Power Devices, Distributed Generators, Harmonic Current Compensation, Power Quality, Shunt Active Power Filter, Sinusoidal Current Control Strategy

1 Introduction

There has been a tremendous growth of energy in past few years due to the advancement in technology to meet the rising demands of people and economic growth. Energy consumption determines the development of region. Considering the statistics of last two to three years, the world energy consumption has been increasing at the rate of 5.2% annually. And particularly emphasizing India, the per capita consumption is increasing at the rate of 5% annually. Moreover, the percentage contribution of energy from the Renewable Energy Sources (RES) out of total has been also increasing. Recent years have shown steady development in scientific know-how to tap energy from renewable sources rather depending on the prevalent energy

sources that are not that reliable, exhaustible and create detrimental impact on the environment. Generation of power from RES has become thrive towards attaining a Sustainable Energy World. With the advent of renewable, new buzzwords like Distributed Generators (DGs), Micro Grid, Smart Grid (SG) has changed the power market scenario. Due to a stiff relationship of population between the increasing energy demands as well as the increasing complexity in integrating the DGs with the main grid need to be ensured about the unaffectedness of the existing infrastructure, quality of supply has to be maintained and must be free from any faults or interruption. Although substantial quantity of energy is generated, but it has become very difficult as well as challenging for power engineers to reconcile the rising expectation of getting high quality of power

which is possible by the mitigation of harmonics in power system specifically caused by nonlinear loads.

Primarily due to the non-linear loads in the electrical network or system, harmonics are coming into picture which brings numerous drawbacks in the system, e.g., supply turn out to be distorted and unstable with the application of passive load along with nonlinear loads increases surges. The distorted current affects the source point of convenience which is it turn out to be very much essential in order to recompense the distortion, the harmonic and the reactive portion (imaginary part) of load parameter i.e. current. Because when the supply is not only balanced and but also biased, these complications degrade the entire power network or structure [1-3]. In today's scenario soft computing methods are widely implemented for optimizing the network used or else in control strategies. Some of the soft computing techniques like Adaptive TABU search [4-8] which is implemented to enhance the controllers, minimizing the loss power by incorporating Particle Swarm Optimization (PSO), Genetic Algorithm (GA) can also be used for optimizing the power filter. Neural Network (NN) technique can be used in filter devices. Normally, voltage bias or distortion is the outcome of current distortion that passes through linear and series impedance of distribution power system. Even though the source bus is in absolute sinusoidal form but there due to the presence of nonlinear load, it extracts a deformed current. These harmonic currents fleeting over the system impedance develops a drop in voltage for every individual harmonic component results in biased voltages seeming at the common point of coupling/Point of Common Coupling (PCC) which must be considered as vital parameters for designing various harmonic compensators. With the enhancement of semiconductor devices and so as for the sake of performance improvement in the distribution side, custom power devices have come into picture. It ensures proper flow of power and customer satisfaction in near future. This Custom Power (CP) mostly includes the use of power electronic devices such as Distributed Static Compenstor (D-STACOM), Dynamic Voltage Restorer(DVR), Unified Power Quality Conditioner (UPQC), etc., for distribution systems. Under the concept of CP, a customer is able to receive a pre-specified quality power. The term Custom Power Park focuses on the consumers who are ready to pay an optimum price for proper service i.e. high quality and uninterrupted power provided to them. Moreover, to achieve such

objectives, the distribution companies make sure that these devices work in well coordinated manner [9].

Focusing on the various Power Filters (PFs), specifically, the Shunt Active Power Filter (ShAPF) is a conceivable substitute for minimizing effects arising due to non-linear loads on the power network which passages to recompense harmonics produced by nonlinear loads. To attain compensation aims, generation of reference signal is significant meant for the design purpose as well as in control purpose of active filters. The usage of such kind of filters shields electrical apparatus which can be exaggerated by deprived/low Power Quality (PQ) and avoids the propagation of caused in stabilities in the power systems. Many control strategies has been implemented, out of which the most effective Sinusoidal current control strategy has been implemented to mitigate the harmonics and also others PQ issues generated in the unbalanced or unstable system owed to the non-linear loading condition [1]. The efficiency of discussed control strategy has been demonstrated using simulation consequences conferred. The simulation result vindicates its efficiency on analysing the THD of both current and voltage.

Concept of Distributed Generators (DGs) and its interconnection to PQ has been described in Section 2 & 3. Custom Power Devices and a basic review of various filters have been illustrated in Section 4 and 5. The concept of ShAPF of different methodologies and its different control strategies have been provided in Section 6. Detailed description of ShAPF incorporating Sinusoidal Current Control (SCC) Strategy has been analyzed in Section 7.

2 Problem Formulation

DG refers to on-site power generation that is present near to the load and have less rating as compared to the central power station. It reduces the cost of transmission lines minimizes the voltage drop. Typically the size of such generators involved is 10 MW or less. Now-a-days, dispersed generators are also coming into picture which is still smaller in size typically < 500KW [10]. Optimal placement of DGs has been presented in [11], ensuring that the losses particularly the real power loss should be less thereby eliminating any sort of dips, swells or size in the normal voltage levels.

2.1 Advantages of DG

An important factor to understand the issues related to DG is to recognize the different aspects on each and every point of consideration which may be illustrated with the benefits of DG from the following aspects.

2.1.1 End-user aspect

This is the most important aspect nowadays. It is great beneficial to those who require enormous uninterrupted amount of power as these DGs act as an alternative in case of outages or power failures from main side. Moreover, extra benefit lies through proper use of waste recovery Combined Heat and Power (CHP), which improves the efficiency of the system and much energy, is saved from wastage. Another advantage is that the users can commercialize buy selling the extra power generated by their DGs provided the quality is maintained thereby providing power to inaccessible areas.

2.1.2 Distribution utility aspects

The Distribution Companies (DISCOMs) and Transmission Companies (TRANSCOMs) are generally interested to sell power through their transmission and distribution lines. But these DGs greatly reduce these costs. Even if with the increase in the demand of power with the increase in load, DGs, provides an alternative against unprecedented increase in load.

2.1.3 Commercial power producer aspect

Here, the restructuring comes into picture. Those producing power through DGs can participate in competitive bidding or selling of power against rising prices per unit consumption of power. Here, several units of DGs are required to serve the load demands independently or through grid-connection.

Research has been carried out based on several Renewable Sources. An algorithm based on Probabilistic has been presented for reducing any sort of phase unbalance and losses occurring in the system with large numbers of installed solar generator micro Feed in Tariffs (FITs) [12] The control of end-user energy storage under price fluctuations has been discussed as storage requirement is essential to satisfy the unpredictable load in [13]. Another source i.e. Fuel Cell is trending but its high cost is point of concern. But

some of the recent developments have been made in reducing the cost of Direct Borohydride Fuel Cell (DBFC) by using Ni-based anode, Chitosan membrane and binder in [14] thereby aiding in its commercialization. Fuel cell among other renewable has been used for smooth supply of power to the auxiliaries present in Thermal Power station (TPs) and making it free from any abnormalities occurring in the entire system [15]. Extracting power from wind is also trending but it is bit complex as far as configuration due to the mechanical components are involved and also at the point of reliability comparison to PV and Fuel Cell. Reliability Centric Maintenance (RCM) has come into picture that is able to track any kind of abnormalities occurring beforehand and protects any disruption of power through its proactive maintenance in the wind turbines [16]. In order to make these wind turbines to work effectively with variable wind speed and sufficiently charge the batteries, the slip power from the Doubly Fed Induction Generator (DFIG) in above synchronous operational mode is used for charging of batteries through back to back connected converters [17]. However it is essential to extricate energy from low windy areas and to overcome environmental constraints. Hence, an advanced approach for the extraction includes entire designing and experimental setup of Funnel Based Wind Energy Harvesting System (FBWEHS) has been discussed in [18]. As these sources are essential components for integration from smart grid aspect, therefore integration is a challenging issue even though IEC 61850 [19].

With recent developments in Renewable Energy System, their integration with grid has become a challenge leading to various PQ issues. A Hybrid Multi-Layer Feed Forward Neural Network (HMLFNN) technique for prediction of output coming out from Grid Connected PV system has been discussed in [20]. It indicates that the developed AIS-based HMFLNN is superior to the classical Multi Layer feed Forward Neural Network (MLFNN) in terms of prediction accuracy. Combination of all such sources along with two-way communication constitutes smart grid. Moreover, different methods and techniques involved for control purpose based on smart grid technology are summarized in [21].

Considering the real time implementation, SG project in Pondicherry is one such implementation in India that utilizes solar PV system placed at rooftop. An analysis being done taking into account the end user based on questionnaires regarding the

consumption throughout the day, space acquired for placing the PV system as well as the users satisfaction with this implementation [22]. Also a forecasting approach of load has been performed in [23], where significant improvements has been done based on the SG operation by disseminating information regarding both online short-term forecasting and long term assessments. Micro Grids (MG) are simply the subset of SGs. Moreover, low voltage Residential MGs design and Analysis has been carried out by PSCAD/EMTDC in [24]. The significant role of MG lies in the fact that it is able to take or provide power to the utility grid and to work without any dependency in case of a scarcity at the time of outage thereby leads to elimination of multiple energy conversions [25]. Energy Management System is the new phraseology that includes hardware and software for monitoring and controlling generation and loads. In [26], simulation of algorithm based on energy management with backup storage has been performed in Matlab/Simulink environment.

The bonding of the DGs and ShAPF lies with the fact that it is designed for compensation of current harmonics [27] as DG is connected in parallel to the grid. In [28], the Active Power Filter (APF) has been used that aids in compensation of harmonics and in this way the DGs helps in decreasing excessive harmonics or overloading of interface inverters. Moreover, a scheme based on two-level control has been used to improve active flow power in main buses of independently working MG.

2.2 Disadvantages of DG

Different aspects based on demerits of DGs are also present. One such aspect is the issues related to power quality. The consumers are mostly concerned about the overall costs and maintenance. However there are many unanswered questions like in a DG integrated system whether the end users are interested for operating the generators or cost of electricity in this context is actually less and more reliable or the power markets is in favor of DG or not. In spite of that it is quiet predictable that the number of DGs connected with the utility system will keep on increasing in near future [29-31]

3 Power Quality

Power Quality puts the boundaries in the deviation levels of voltage, frequency and waveform shape of power supply for proper functioning of the equipment. Without these limitations according to

the IEEE standard, equipment may mal-operate and may not produce desired output. PQ means supplying of clean and stable power supply i.e. it includes noise-free sine wave, limited voltage and frequency deviations. Due to excessive uses of Power Electronics devices, it introduces the harmonics in the system due to non-linear loads which brings the concept of PQ into the picture. Though day-by day the power electronics devices are making the system compact and reliable, but these are the primary cause of production of harmonics in the system. Several switching signals for fast operation involved in speed control, position control are present starting from portable to large equipments and devices such as printers, motors, ballasts, furnaces, elevators etc. Again, some of the important terms related to Power Quality (PQ) has been described in [32] such as Reactive Power Compensation, Harmonic Compensation, Voltage regulation, harmonic pollution, etc. Again Flicker is one of the in Power Quality problems that come into picture because of heavy loads. Further, an optimization technique for extraction of low frequency component which is the main cause of producing the waveform distortion has been presented in [33]. Power Quality issues are an inevitable thing when a number of DGs are connected. So, there is a close relation between DG and Power Quality.

The primary problems related to PQ due to DGs are Sustained interruption, Voltage regulation, Harmonic and Voltage sags. There is a close relation between these terms DGs and PQ. Considering both supply side and load side, there are several DGs involved so as several loads. And the power has to be transferred through a common distribution line. So, proper coordination has to be maintained from each source to satisfy the load pattern. Implementation of DGs will either enhance the PQ or deteriorate the service for end users which is a major concern now-a-days [34-37].

As PQ is the combination of Voltage and Current, the quality of voltage can be considerably improved even with a slightest level of backup storage capacity implemented in the Series Connected Photo-Voltaic Distributed Generator (SPVG). Its proposed control system has been implemented using dSPACE (DS 1103) platform with MATLAB/Simulink in real-time interface (RTI) [36]. Considering the real time implementation, a Florida-based distribution feeder has been modeled and studied by the integration of different types of DG sources based on solar and wind plants with

high variability of load and generation to observe their impact on system's PQ [38]. Furthermore, an extension of the work has been presented in [39] where a methodology has been proposed to determine the effect on the voltage quality, keeping in mind about the various cases of DG insertion as defined by a percentage of small scale presumes to be presented in the network.

Among several PQ issues, the harmonics is considered to be the primary reason for poor PQ. Therefore, it is very essential to take into consideration and rectify the PQ problems and maintain the Total Harmonic Distortion (THD) within prescribed limits as per the IEEE standards. In [40], the THD was measured at different buses and all the THDs in these cases and is found to be well within the limit which indicates to be easy to control in power system with harmonic current, through the separation of the fundamental and harmonic waves. Again current control by the suppression method also has good real-time performance and stability. By the use of the proposed Neural Learning Algorithm (NLA) an optimization technique for ShAPF, the THD is found to be 94.07% of the fundamental as compared to PI Controller. Using NLA, THD is less than 1.77% of the fundamental for all the 3-phases as compared to 1.55% using PI. In [41], application of optimization technique based on Bat Algorithm has been presented for undesirable harmonic eradication in a seven-level multilevel inverter. Again in [42], comparative study with respect to Bee algorithm (BA) and Genetic algorithm (GA) has been done that indicating the superiority of Bat algorithm which causes the low value of THD in the output voltage. Furthermore, various filters used for suppression of harmonics and selective Harmonics Elimination has been presented in [43-46]. So, for elimination of harmonics filters are an essential requirement. But gradually Custom Power Devices (CPD) including various FACTS devices is also coming into picture particularly for customer satisfaction.

4 Custom Power Devices

Controllers based on power electronics devices are used to provide power solution and its network may be either reformation type or compensation type. Former one is known as switchgear and is used for breaking, limiting and transferring of current. Based on that, the devices are known Solid State Breaker (SSB), Solid State Current Limiter (SSCL) and Solid State Transfer Switch (SSTS) whereas the

later one is used for load compensation which includes power factor correction, restricting occurrence of any unbalance etc., thereby improving the voltage quality. Custom Power Devices (CPDs) are either connected parallel/cascaded manner or in combination of the two. It consists of includes Dynamic Voltage Restorer (DVR), Distribution STATCOM (DSTATCOM) and Unified Power Quality Conditioner (UPQC). Modeling of custom power devices have been carried out in [47] that comprises of a high speed mechanical transfer switch (HSMTS); a 2-MVA DVR downstream of the HSMTS; a 4500-KVAR SVC placed on the alternate feeder to serve one of the critical customers. Although the primary purpose is to support the voltage, but their combined performance are modeled and studied in detail using Alternative Transients Program and Electromagnetic Transients Program (ATP-EMTP). The analysis of control structure in which Custom Power Devices (CPD) involves the consumption of active and reactive power has been done in [48]. This control method has been implemented on a 5-kVA framework

The main essence of Custom Power Park (CPP) lies in the fact that all the customers who are taking the power should get the advantage with the good quality of power provided to them i.e. it clearly indicates its superior quality of supply than the normal supply. For the successful and smooth operation of the park feeders and substations are used in numbers which are joined through different switches as discussed earlier. The working of the transfer switch is so fast that it is able to reduce the time of operation of any sags or swells or sustained oscillations. Since DSTATCOM and DVR are essential components of CPD, the DSTATCOM aids in elimination of any unbalance or harmonics, while the DVR helps in eradicating voltage dips or disfigurement in waveform. Today the use of CPD has not been commercialized just like HVDC lines but has a great scope for future. High Voltage Direct Current (HVDC) and Flexible AC Transmission System (FACTS) devices involve several devices such as Static VAR Compensator (SVC) systems that are used for compensation of reactive power in transmission lines. Subsequently various kind of devices like Static Compensator (SSSC), Thyristor Control Phase Angle Regulator (TCPAR), Thyristor Controlled Series Compensator (TCSC), Unified Power Flow Controller (UPFC) have been used. FACTS like Thyristor Controlled Phase Angle Regulator (TCPAR), Thyristor Controlled Braking Resistor (TCBR), and Interline Power Flow Controller (IPFC) are used for the provision of

flexible control of power flow in several lines associated with power system. [49]

In CPP, the voltage is controlled through DSTATCOM, the performance during feeder switching, the performance during total feeder loss of mini CPP has been discussed in [50]. Performance study of two different compensating devices in a CPP has been discussed in [51]. Here, the shunt compensator controls the voltage of the CPP bus and the series compensator controls the sensitive load voltage which has been shown using PSCAD/EMTDC software. Furthermore, the simulation study of the World's First Distributed Power Quality Park which is located at the Delaware Industrial Park in Delaware, Ohio has been done in Electro-Magnetic Transient Program-Analysis Transient Program (EMTP-ATP) [52]. Different Custom Power Devices has been described below.

4.1 Distributed Static Compensator

Schematically a D-STATCOM (Distribution Static Compensator) basically comprises of a two-level Voltage Source Converter (VSC), a DC backup for storage and a coupling transformer which is connected in parallel to the distribution system. VSC is being used for the conversion of DC voltage to AC output voltage. Coupling transformer is used for linking this voltage to the AC system. By properly controlling the phase angle and magnitude of this device, control of both active and reactive power is obtained in the entire system. Again the VSC configured in parallel with the AC system provides proper regulation of Voltage, reactive power compensation, power factor correction and most importantly harmonics elimination [53]. The entire design, real time implementation, of a medium-sized two level three-leg D-STATCOM voltage-source converter topology have been carried out in [54]. In [55], a control scheme has been proposed for improvement of PQ through mitigation of sag/ dips in independently working micro grid on injection of reactive power using D-STATCOM in MATLAB/Simulink. In [56], a new control algorithm has been presented for D-STATCOM which has the provision for individual control of positive and negative sequence currents and control of direct-axis and quadrature axis current components using PSCAD. In addition to that, D-STATCOM using Zig-Zag transformer being controlled by Synchronous Reference Frame (SRF) working in two modes of operation has been used in [57]. Again, VSC based D-STATCOM has been

implemented using a real-time digital simulator in [58]. Main advantages lie in its modularity that has been proved using a 5 KVA installation of D-STATCOM.

4.2 Dynamic Voltage Restorer

The DVR is an economic and beneficial way of mitigation of power Quality problems such as dips/sags, thereby protecting the equipment. It restores the voltage levels and is capable of working in different condition of operation. Considering the level of voltage, it can work for low voltage as well as high voltage levels. A series connected methodology of DVR has been presented [59-60]. The working of DVR is that it is able to control the load voltage without allowing any sort of disturbance to occur. Moreover, DVR as a whole works as a regulator, restorer and conditioner of voltage [61]. Focusing on the controller part, the proposed predictive controller has better performance with respect to the proportional integral controller and proportional resonant controllers. Here, the optimization technique being applied i.e. predictive controller allows voltage to maintain its level and so as the THD is well within 1% which has been presented in [62]. In [63], Ant Colony Optimization Techniques has been used based on PI controller (ACOP) whose advantages are time response is more faster and its control behaviour is much better with respect to the classical PI and also gives provision of a faster DC voltage response for different voltage disturbances.

Since, CPD ensures enhanced quality and reliability of supply to the consumers through which other entities in restructuring environment get benefited. But the harmonic elimination being the prior issue needs filter that are applied on various components in Power system.

5 Filters

In general filters are to minimize harmonics arising due to repeated switching of Power Electronics devices used. On the basis of basic classification different types of filters are passive filters which include passive elements such as capacitor and inductors and active filters. For detection of any kind of abnormalities occurring in the system filters are highly required when converters or inverters are used. Focusing on the Digital filters, notch filters has been designed in [64] for damping out harmonics. Based on that both simulations and experiments have also been carried to prove the

effectiveness of such filter that is able to produce required amount of lead or lag in phase around the resonant frequency for the stability of the system. For any design of Filter, realization and stability are required. In [65] selective filters such as harmonic selective filters have been used to separate low frequency harmonic component from fundamental component. A comparison between another set of filters has been done in [66] i.e. Adaptive, Weiner and Kalman filters in which Kalman Filter is best among all able to reduce THD by more than 50% and an extended Kalman filtering approach has been used in [67] for the frequency estimation due to the presence of noise, notch and harmonics in the system. Optimization techniques and algorithms used to enhance the performance of filters which includes Bee Colony Optimization, Fuzzy logic and Differential evolution, Unscented Kalman Filter (UKF), Particle Swarm Intelligence (PSI), Genetic Algorithm (GA) [68-71].

5.1 Classification of Filters

5.1.1 Shunt Active filter

Shunt Active Filter (ShAPF) is connected in parallel comprising of non-linear load whose harmonic currents are required to be compensated. The principle of operation of ShAPF is based on production of current harmonics equal in magnitude but in phase opposition i.e. 180° to the harmonics present in the grid. ShAPF along with compensating reactive power also mitigates harmonics and distortion [72-73]. ShAPF have more benefits in comparison to Series Active Filters (SAF) on the basis of their form and function.

Coming over the applied control techniques, in [74] the control technique of the ShAPF has been developed consisting of two current inside loops and a DC-bus voltage outside loop. Since, Lyapunov function is used to solve any problem due non-linearity so, in [75], the control strategy based on Lyapunov function has been used along with the ShAPF. The experimental validation of the ShAPF system has been done using a DS1104 DSP of d-SPACE and tested for different condition of operation. Again in [76] another experimental verification has been done for ShAPF consisting of dual parallel topology based APF where 110-V, 50-Hz mains providing power to a 3 kW load has been considered. FLC and AHBC technique based ShAPF has been represented in [77-78]. In addition to that Real time implementation using Real Time Digital Simulator (RTDS) has been done in such a manner that both transient and steady-state filter

response is very fast and effective The details regarding ShAPF incorporating SCC Strategy has been explained in Section VII.

5.1.2 Series Active filter

Series Active Filter (SAF) is usually used to solve any deviation in voltage and other PQ related issues. They are more competent than shunt compensators as they are able to compensate current issues. The SAF is series connected with the power supply. In [79] SAF is used as booster of voltage as SAF compensates for voltage as a Constant Voltage Source (CVS) [80]. A single-phase SAPF has been developed based on SPMC. It has been designed in such a manner that it can operate bidirectional without any use of DC capacitor. In addition to that, implementation is simpler in terms of hardware control [81]. Since, undesirable oscillation is one of the prominent phenomenon in classical Sliding Mode Control (SMC) so, in [82] sliding mode controller-2 (SMC-2) named based on the degree of system 2 due to the use of sensors and actuators has been used for improving the performance of the filter and thereby helps in reducing tracking error distortion, suppressing chattering, and noise. Furthermore, the THD of source current is drastically reduced below 1.7% and for the transient condition of load the THD for the proposed controller-based filter is reduced from 26.7% to 2.16%

Focusing on the experimental analysis, operation principles voltage mitigation for the third-harmonic has been done through a 3 KVA experimental setup. Two controllers have been used. One is Controller of the Active Filter and another is Mitigation and DC Capacitor Voltage Control [83]. Another, implementation and testing of a proposed Shunt Active Filter (SAF) has been carried out using a 2-kVA IGBT present in three-phase inverter leading to fast response of filter during sudden variation in the load conditions and its steady state condition is obtained very fast i.e. less than two cycles [84].

5.1.3 Hybrid Power Filter

Hybrid Power Filters (HPFs) are basically the amalgam of Active and Passive filters which helps in considerable reduction in the rating and expenditure on filters. These filters are able to damp out harmonic resonances rather than compensating for only harmonic currents [85-86]. Different novel methods and topologies for harmonic suppression and PQ improvement have been done in [87-94]. Nowadays, series hybrid active power filter (SHAPF) are being mostly used more in recent due

to its multi-tasking features and also rating of lower inverter is less. So, control techniques for THD reduction, reactive power compensation of SHAPF has been presented in [95-111]. Moreover, work based on of Hybrid Infinite Impulse Response (HIIR) filter and Finite Impulse Response (FIR) has been presented in [112-114]. The various Optimization technique algorithms used are Artificial Neural Network (ANN), Filtered algorithm based on x-least mean square, PSO and Adaptive Neuro-fuzzy dividing frequency control [115-118]. Practical implementation based on 12-pulse rectifier, parallel hybrid power filter and an experimental design of ShAPF has been done for 110 V, 50 Hz, three-phase four-wire system using a novel control scheme with decomposition of voltage vectors into power components [119-121].

As there so many issues related to PQ issues such as sags, swells, notches, unbalancing, UPQC being one of the important devices i.e. capable to resolve all the problems associated with the system [122].

5.1.4 Unified Power Quality Conditioner

UPQC is again the amalgam of Series and Shunt Active Filters. The series active filter helps to mitigate any harmonics produced in between transmission and distribution level apart from protecting the system from any kind of arousal of unbalance voltage, flickering etc. Further the ShAPF helps in absorbing harmonic current, reactive power compensation and to controlling the dc link voltage among these two active filters [123-124]. In [125], an algorithm has been used known as exponential composition algorithm (ECA) along with UPQC for compensation of issues related to power quality. Use of optimization Techniques has shown improvement in performance of UPQC such as in [126]. Here, proposed control technique has been shown where, ANFIS along with UPQC is used for further improvement in performance rather than conventional PI Controllers. The role of combination of UPQC and DGs under different modes of operation of DG in following PQ standards has been shown in [127].

There are several work has been carried out so far by many researchers over the UPQC across the globe almost following a common topology, but various control techniques used are very important in the altogether functioning of the UPQC. The swift exposure to the disturbances with an efficient accuracy and processing the signal is considered as an important character of controller, based on which performance of this equipment is evaluated as fast

as possible. In actual sense to consummate the required performance there must be regulation for the inverter switching pattern which is obtained by generating reference signals for both voltage and current. Several control strategies and new techniques have been proposed by different researchers which are quite easily adopted by the UPQC system. Apart from that many advanced control strategies have also been pictured such as controller based on state feedback, model reference adaptive controller, model predictive control, Sliding Mode Controller (SMC), self tuning controller and neural networks, etc. With similar construction as that of UPQC, UPFC is one of the adoptable FACTS devices used in case of transmission systems. Then it is an obvious question as why UPQC? The answer may be as both the devices contribute simultaneous series and shunt compensations with the help of respective series and shunt inverter. Only difference is that a UPFC works under balanced and relatively distortion free transmission system whereas UPQC operates under relatively unbalanced distribution systems with very high harmonic contents because of the excessive use of Power Electronics (PE) interfaces [128].

Apart from UPQC, UPFC being another one of the important Flexible AC Transmission System device is used for the improvement of the power system operation and delivery.

5.1.5 Unified Power Flow Controller

It helps in controlling various power system parameters, such as bus voltages and power flows. Apart from UPFC operating as shunt, series and phase angle controller, the main function is the proper balance of active and reactive of power flow [129]. A load flow analysis model of UPFC has been done in [130] and study has been made based on the placement of this device to avoid congestion management and finding an economic viable solution. Further, in [131] a novel UPFC without use of any transformer has been presented which has several advantages such as in terms of cost, response time, THD, efficiency etc. Moreover, its validation has been done on a setup of 4160 V. In [132], a novel control method has been presented that has proved its effectiveness better than conventional Proportional Integral (PI) controller in terms of its smooth performance variety of operating conditions, requirement of parameters and tuning required. In [133], a real-time implementation has been presented based on the performance of UPFC and its location in the system.

Simulations have been carried out using a real-time hardware or software laboratory (RTHSL).

UPLC is the advanced version of UPFC i.e. it provides the function of UPFC along with the mitigation of active harmonics.

5.1.6 Unified Power Line Conditioner

Because of its advanced functioning abilities, this compensating device is otherwise named so. The simulations carried out in [134] and the experimental results prove that its performance is better as compared to the conventional approach. In addition to that, both power circuit and control circuit has been presented. UPLC has been used in a single-phase high-frequency AC (HFAC) micro grid. Again in [135] by the hybridization of both UPQC and UPLC better power flow is obtained and also issues related to quality of power is curbed in Micro grid and filtering is based on p-q theory. Again proper control of active and reactive power in is obtained in grid-connected micro grid. Further, its extension has been done in [136] based on experimental analysis comprising of 1-phase high frequency Micro grid of 1kW capacity. Since, UPLC consists of both series and shunt filters so, series active filters helps in controlling the active and reactive power whereas, shunt active filter helps in harmonic currents and reactive power compensation.

6 Shunt Active Filter

Though the basics of Shunt Active Power Filter (ShAPF) being one of the filters has been already described in Section V, but Gyugyi and Strycula in 1976 first presented the novel conception of shunt active filtering. At the present time, it (ShAPF) has become a reality and remains no more a dream, and they are heavily and frequently used in commercial process entire over the sphere/world. Controllers of ShAPF govern in actual time the recompensing references current value, in addition it also force the PWM inverter in order to achieve it correctly. In this manner, active filtering is able to be discriminating as well as adaptive. In other confrontations, it can compensate merely the harmonic component (current) of particular nonlinear load, besides it can record the fluctuation in harmonic contented continuously [137].

6.1 Configuration of ShAPF

The ShAPF generally consists of two distinct main block i.e. PWM converter and Active filter controller as shown in Fig. 1. PWM converter, mainly accountable to process power and synthesize the compensating values of current which has to be drained from the network and Active Filter controller is accountable for processing signal and to define the real time instant compensating current values, which is passed on continuous manner to the PWM converter section. Generally ShAPF works in a closed loop method. It sense current that flows through load (i_l), and computes the instant values of the compensating/shunt current reference value i_c^* for converter section Pulse Width Modulation (PWM). Either Voltage Source Converter (VSC) or Current Source Converter (CSC) can be used in ShAPF. CSC can be used for its robustness but in today's scenario shunt active filter that are used in commercial purpose almost uses voltage source converter (VSC) owing to its higher efficiency, initial cost is low as compared to Current Source Converter (CSC), and reduced physical dimensions. It must be distinguished that, no supply is given to the converter, simply an energy storing component (capacitor for Voltage fed Converter or inductor for Current Fed Converter) is linked at dc end of the converters because shunt active power filter should perform like a compensator. In additional verses, the exchange of average energy should remain zero among the power filter and the power system.

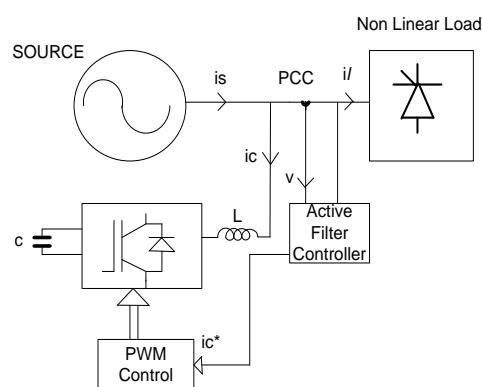


Fig.1 Block Diagram of SAPF

6.2 Different Control Approach

Several control strategies have been used based on SAF. It started with Unity Power Factor (UPF) control Strategy which was considered to be the best as far as distorted waveform was considered. Moreover, a comparison with Classical compensation Strategy was done and Simulation was based on Monte Carlo and Analysis Transients Program (ATP) [138]. Again, a new control algorithm for 3-phase, 4-wire for unbalanced system was done in [139], where application of $\alpha\text{-}\beta\text{-}0$ was considered in the presence of inverters and capacitors but in the absence of DC source. Its extension was done in [140], which was simple due to absence of symmetrical components to transform 3-phase to $\alpha\text{-}\beta\text{-}0$ and only positive sequence was supplied. Further, its extension was done using Direct current Static VAR compensator (DCSVC) control based on Neutral point clamped VSI. Two DCSVC were proposed using xy -coordinate and $\alpha\beta$ -coordinate [141]. Next, the locations of placing the ShAPF become an important issue. So, control system approach was done, where the best place was found to be the feeder in distribution system for damping out harmonic propagation [142]. Here, the use of Analog Circuit simulator (ACS) has been done and voltage detection is done in time-domain. A comparison study between voltage source and current source active filters on the basis of power circuit diagram, constraints of semiconductor devices, quality of filtering, ruggedness, versatility and load subjected to transient changes has been done in [143] and its extension has been done where drawbacks of current source over voltage source has been done which includes high on-state loss and inefficient inductive energy. Further overvoltage clamp is required which complicates the current source described in [144].

In general, the effectiveness of any control strategy for any kind of filter is determined by to what level the THD is less i.e. $\leq 5\%$ according to IEEE 519 standard. New control techniques were developed on the basis of simplicity, robustness and better suppression of harmonics. One such was using Fuzzy Logic Controller (FLC). It proved to be better than the conventional PI Controller because it reduced the requirement of mathematical model as it was based on linguistic approach. INTEL 8031 was used and THD within specified limit [145]. Again, a comparative study between Hybrid (combination of 3 phase tuned LC filter for 7th harmonic frequency + 3 phase Voltage Source Pulse with Modulated

inverter) and ShAPF in a adjustable speed drive system of 480 V was done. It proved out to be advantageous in terms of high efficiency, less switching ripples & EMI emission [146]. An extension of $d\text{-}q\text{-}0$ was done using Adaptive Hysteresis Band Current Controller (AHCC) in [147]. The main difference between the Fix Band Hysteresis Current Control (FBCC) and AHCC is that the switching frequency at an instant remains definite in the proposed method contrary to conventional FBCC method. Further, adaptive ShAPF along with (Artificial Neural Network) ANN has been used to lock the triple harmonics in [148]. Considering the real component only, 3-phase SHAF using $I\cos\phi$ algorithm was used. This algorithm was applicable in all operating as reactive, balanced/unbalanced, and nonlinear loads [149]. A control technique designed in [150] is a non-linear one that uses two inside current loops and a DC bus voltage regulator loop present outside and there is no interconnection between these loops. Performance is good in both steady-state and transient operations. The ShAPF with LCL filter has been used as it offers higher suppression of harmonics by utilizing considerable less passive filtering constituents and also leads to smaller drop in voltage harmonic drop across the passive output filter that ultimately lessens any possibility of over modulation. The effectiveness of the methodology has been proved by experimental testing in [151] in terms of proper damping of oscillations, overall stability, and smoothness of transient response.

7 Sinusoidal Current Control Strategy

The control technique executed in the ShAPF defines the physical compensation features of the power filter. There exist several methods for designing a control technique for active filtering. Undoubtedly, the Instantaneous Power Concept or theory practices a precise effective base for design of regulators (controller) for the power filter.

Three different control techniques or strategies are as follows

7.1 Constant instantaneous power control Strategy:

In this strategy the Shunt active filter compensates a definite portion of the power that is oscillating real power. This strategy is applicable only when there are no active power oscillations.

7.2 Sinusoidal current control Strategy

It is used to draw a sinusoidal current from the source. The main advantage of this strategy is that the distortion produced in three phases is minimum in comparison to other strategies.

7.3 Generalized Fryze Control Strategy

This strategy is normally used to minimize the rms value of current through which the same volume of energy can be transferred similar to the distorted current. This strategy has minimum ohmic loss.[152]

7.3.1 Active Filter for Sinusoidal Current Control

Active Filter Controller for sinusoidal current control includes positive voltage detector which includes Phase Lock Loop (PLL) circuit, DC voltage regulator, Instantaneous Power Calculation Block, Compensating Power Selection block and Compensating Reference Current Calculation Block.

7.3.2 Positive sequence voltage detector:

At load terminal the value of three phase voltage mainly consists of Positive Sequence Component. If there will be either negative sequence or Zero Sequence component then three phase voltage can be unbalanced and may also comprise harmonics from other components. Thus it is necessary to determine fundamental positive sequence voltage for this Sinusoidal current control technique and it is possible through positive voltage detector.

7.3.3 Phase-Locked-loop (PLL) circuit:

Power circuit continuously tracks fundamental component of frequency of measured system voltages. This synchronizing circuit automatically defines the frequency of the system as well as the phase angle of positive sequence component of input signal.

7.3.4 Instantaneous Power Calculation Block:

This block computes the instant values of power of the passive load/nonlinear load.

7.3.5 Compensating Power Selection Block

This block selects some portion of real and imaginary power of the given nonlinear load which is to be compensated by the power filter.

7.3.6 DC Voltage Regulator

DC Voltage Controller defines a supplementary quantity of active power for which an extra energy flows into the capacitor for keeping its value of voltage around a static reference value.

7.3.7 Compensating Current Reference Calculation Block

This block helps in defining the instantaneous value of compensating or shunts current reference from compensating powers and voltages.

7.3.8 Control Block Diagram

Fig.2 Illustrates control block of sinusoidal current control technique with three phase shunt active filter. Three phase instant voltages and currents phases of balanced or unbalanced source in the abc-reference frame is converted into instant voltages and currents on the $\alpha\beta$ -axis [7]. It can be noted that the instantaneous phase voltages V_a, V_b and V_c corresponding to $(V+1)$ phasor component of the fundamental positive-sequence voltage are converted into the α - β coordinates by using the Clarke transformation block. Then, the set two phase component (α - β component of both current and voltage) are used for calculating active and reactive power (instantaneous powers) and also used for calculation of two phase compensating current. The compensating powers that is oscillating portion of real power (\tilde{p}) and imaginary power $q = \tilde{q} + \tilde{q}$ are also used in the current calculation block in order to determine exactly all α - β components of currents in the load current that generates $-\tilde{p}$ and $q = \tilde{q} + \tilde{q}$ with $V+1$.

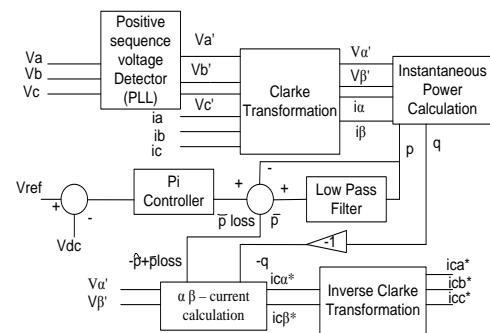


Fig.2 Block diagram of sinusoidal current control strategy

The three phase voltage can be converted into two phase voltage by means of Clarke transformation as shown in matrix form and this two phase voltage further participate in power calculation module in

order to determine both active and reactive power along with two phase current (i_α and i_β).

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v'_a \\ v'_b \\ v'_c \end{bmatrix} \quad (1)$$

In Similar manner, three-phase line currents can be converted in to two phase by using Clarke Transformation it also help in determining real and imaginary power along with two phase voltage (v'_α and v'_β).

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

The benefit of implementing the Clark transformation is that it separates the zero-sequence components from the abc-phase components as per Instantaneous Power Theory which is well defined for three-phase network in both the condition that is in presence of neutral conductor as well as in absence of it. Three instant powers that is zero-sequence component, the active component p , reactive component q , the instant phase voltages and line currents can be represented in matrix format as shown below:

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v'_\alpha & v'_\beta \\ 0 & v'_\beta & -v'_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

From matrix active and reactive power is given as follow

$$p = v'_\alpha \cdot i_\alpha + v'_\beta \cdot i_\beta \quad (4)$$

$$q = v'_\beta \cdot i_\alpha + v'_\alpha \cdot i_\beta \quad (5)$$

Both active and reactive power consists of average component and Oscillating component given by

$$p = \bar{p} + \tilde{p} \quad (\text{average power} + \text{oscillating power}) \quad (6)$$

$$q = \bar{q} + \tilde{q} \quad (\text{average power} + \text{oscillating power}) \quad (7)$$

We need to compensate oscillating constituent of real power and imaginary power which may affect the system.

DC Voltage Controller defines an additional quantity of active power that causes an extra drift of energy to the capacitor for keeping its value of voltage around a static reference value as shown in Fig.2. Very small quantity of average active power (P_{loss}) is drained in continuous manner from the power network for supplying switching loss plus ohmic losses in the converter section or else, the same energy would be provided by dc link capacitor connected across converter which would discharge at continuous manner. Boost converter is used in shunt active power filter, so it is necessary to keep value of dc voltage higher than that of peak value ac bus voltage which would assure the controllable property of the (PWM) current control Fig.2 active power of nonlinear load must be measured frequently and continuously and it must separate into two component that is average and oscillating component. This is obtained by the compensation power selection block. In real time operation, the separation of active and reactive power is analysed by a low-pass filter. Reference currents $i_{c_a}^*$, $i_{c_b}^*$ and $i_{c_c}^*$ for switching of PWM inverter is set up from Inverse Clarke Transformation. The switching scheme of IGBT's is set up by relating the reference currents and continuously sensing the currents from lines. $\alpha\beta$ - Current Calculation can be calculated as follow:

$$\begin{bmatrix} i_{c_a}^* \\ i_{c_b}^* \end{bmatrix} = \frac{1}{v_\alpha'^2 + v_\beta'^2} \begin{bmatrix} v'_\alpha & v'_\beta \\ v'_\beta & -v'_\alpha \end{bmatrix} \begin{bmatrix} -\bar{p} + p_{loss} \\ q \end{bmatrix} \quad (8)$$

These two values of compensating currents are two phase currents which are then converted into three phase currents by means of inverse Clarke transformation. Three phase compensating currents can be calculated by using inverse Clarke transformation.

$$\begin{bmatrix} i_{c_a}^* \\ i_{c_b}^* \\ i_{c_c}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c_0}^* \\ i_{c_\alpha}^* \\ i_{c_\beta}^* \end{bmatrix} \quad (9)$$

Matlab/simulink model

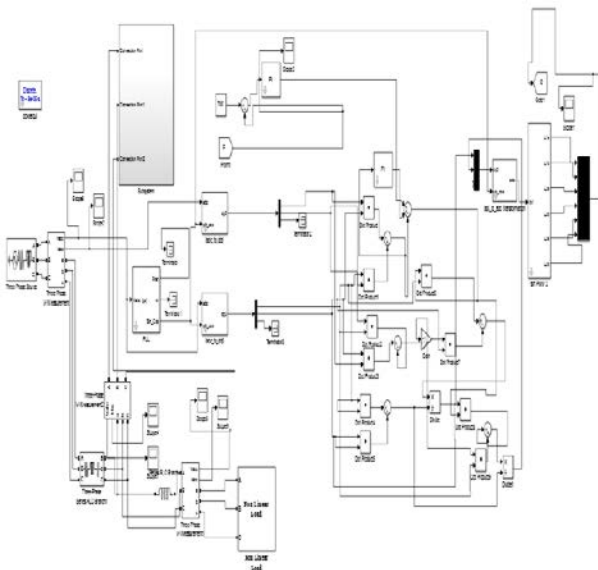


Fig.3 Matlab simulation of shunt active filter supplying non-linear load with sinusoidal current control strategy

8 Results and Discussion

The operational analysis of SAPF for a 3-phase, 3-wire system has been done in MATLAB/SIMULINK environment. Both power circuit and control circuit for 3-phase 3-wire system considering load passive and non-linear are modelled. The system consists of a hybrid network of PV-Fuel Cell-Flywheel. Here variable irradiance condition has been considered. Several simulation studies for the entire system have been done taking into account the parameters which are shown in Table I given below.

TABLE 1

SIMULATION PARAMETERS

Load Resistance	10Ω
Grid voltage (RMS)	230V
DC Link Capacitance	2000μF

Fig.4 shows the Injected current by the shunt active filter. Its associated waveforms reveal how SAPF compensate the abnormalities in the supply side. Moreover, current THD of grid injected voltage side was found to be 1.40% due to the compensation procedure of SHAF. Fig. 5 shows the grid injected voltage and current. In addition to that

the FFT analysis result of the system is shown in fig. 6.

In addition to that the FFT analysis result of the system is shown in Fig. 6.

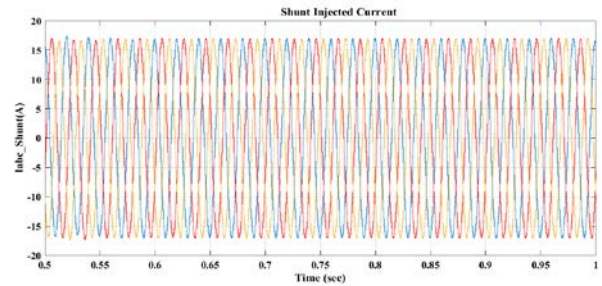


Fig.4. Injected Current by Shunt Compensator

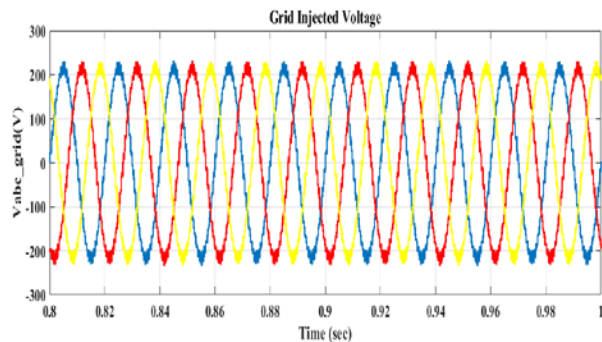


Fig.5(a). Grid Injected Voltage

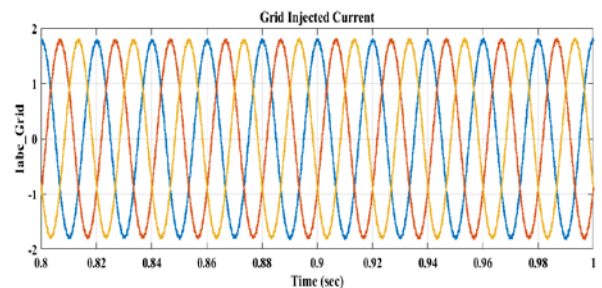


Fig.5(b). Grid Injected Current

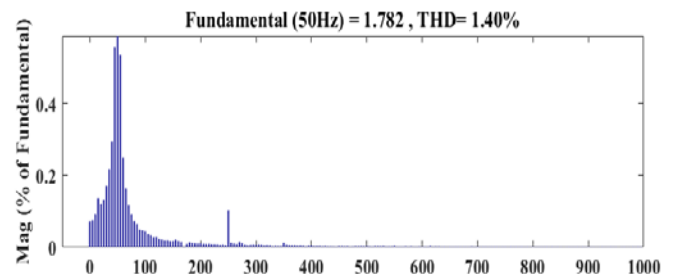


Fig.6. Harmonic Analysis of Grid Injected Voltage Waveform

Fig.7(a) and (b) show the PV output voltage and current waveform. Fuel Cell and battery voltage are connected to common DC Link so they have the similar waveform as the PV output Voltage.

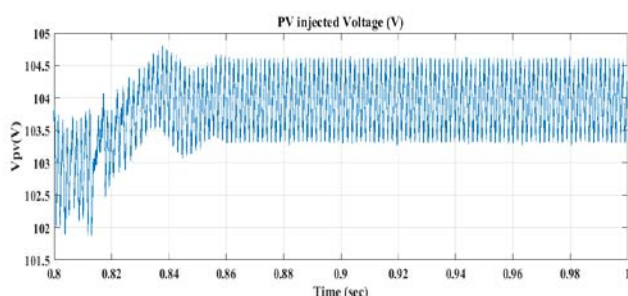


Fig. 7(a). PV Output Voltage

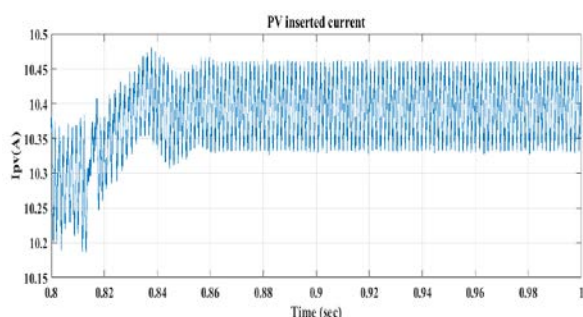


Fig. 7(b). PV Output Current

The results show that, the injected current waveform of the shunt active filter is sinusoidal which the basis of sinusoidal current control strategy is. Besides it provides effective injection of power to the grid in interconnected mode which is desirable.

9 Conclusion

A concept oriented study of ShAPF using SCC has been carried out for 3-phase and 3-wire system using passive and non-linear load. Even though the voltage and current in three phases are subjected to disturbance in transient state, the control strategy leads to drawing of constant current by the load during steady state condition. Moreover, the THD value in source current is low i.e. 1.40 % being much less than the expected value thereby showing the effectiveness of the above study. Further extension can be done based on Generalized Fryze current control strategy.

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