Solar Photovoltaic Generation Control using Integrated UAPF worked on Discrete Adaptive Filter

Krupal Kannor[1], Prof. V.R. Aranke[2]
PG Scholar[1], Assistant Professor[2]
Department of Electrical Engineering
Matoshri College of Engineering and Research Centre, Nashik, Maharashtra
Savitribai Phule Pune University, Pune

Abstract- *Whenever a photovoltaic system is properly interfaced with power grid, there are many power quality issues that need to be taken care-off. So, additional power control equipment needs to be interfaced with PV-Array, especially FACTS devices which are efficient modes to control power.*
In this study, Universal Active Power Filter and Compensator (UAPF&C) is used as power flow controller for PV-Array systems. The system under study is composed of series and shunt inverters connected back to back by a DC-link to which PV-array is synced. It compensates the voltage and current issues in inter-connected mode and islanding mode by injecting active power to grid. This system is tested in simulation environment for proofs of its ability to reduce the amount of power impurities.
Keywords- *Universal Active Power Filter and Compensator (UAPF&C), PV (photovoltaic) Array, Power Quality*

I. INTRODUCTION

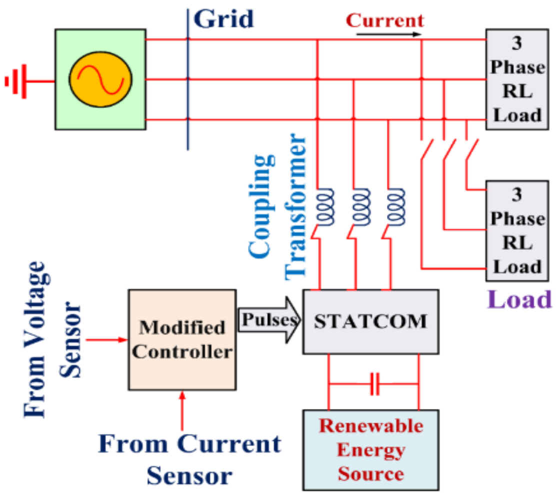


Fig.1- Scheme of Grid interfacing

Central power generation systems are facing the constraints of shortage of fuel and the need to condense emissions. Long transmission lines are main reasons for electrical power losses. Emphasis has enlarged distributed generation (DG) networks with integration of renewable energy systems into the grid, which lead to energy efficiency and reduction in emissions. With the increase of the renewable energy penetration to the grid, power quality (PQ) of the medium to low voltage power transmission system is becoming a major area of interest. Most of the integration of renewable energy systems to the grid takes place with the aid of power electronics converters.

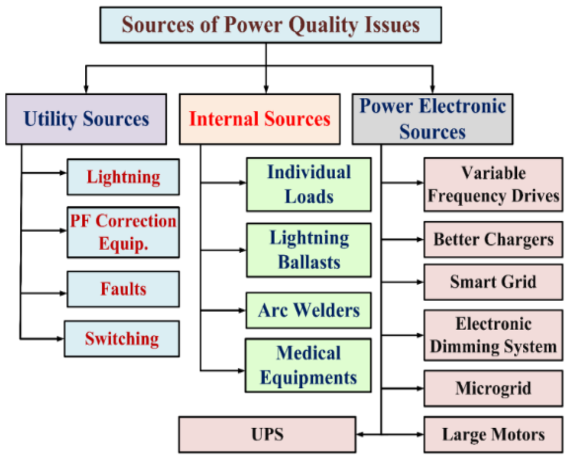


Fig.2- Possible sources of PQ problems

The main purpose of the power electronic converters is to integrate the DG to the grid in compliance with power quality standards. However, high frequency switching of inverters can inject additional harmonics to the systems, creating major PQ problems if not implemented properly. Custom Power Devices (CPD) like STATCOM (Shunt Active Power Filter), DVR (Series Active Power Filter) are the latest development of interfacing devices between distribution supply and consumer appliances to overcome disturbances and improve the power quality by compensating the reactive and harmonic power generated or absorbed by the load. Solar and wind are the most promising DG sources and their penetration level to the grid is also on the rise. Although the benefits of DG includes voltage support, diversification of power sources, reduction in transmission and distribution losses and improved power quality problems are also of growing concern.

II. PV GENERATION AND DISTURBANCES RELATED TO GRID INTERFACING

We know that the output of PV panel depends on the solar intensity; the PQ problems not only depend on irradiation but also are based on the overall performance of solar photovoltaic system including PV modules, inverter, filters controlling mechanism etc. Studies show that the short fluctuation of irradiance and cloud cover plays important role in low voltage distribution grids with high penetration of PV. Therefore, special attention should be paid to the voltage profile and the power flow on the line. It also suggests that voltage and power mitigation can be achieved using super-capacitors which result in an increase of about 20% in the cost of the PV system.

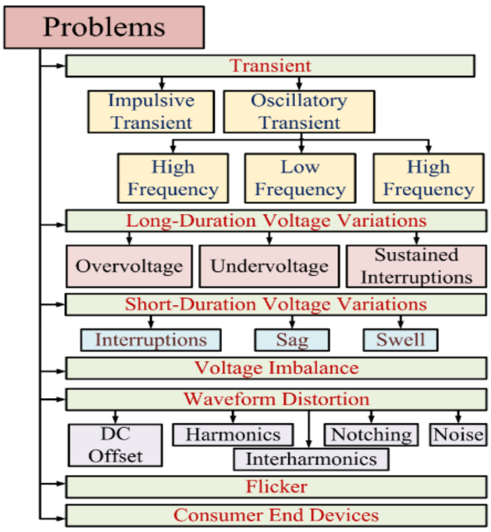


Fig.3 – Important PQ problems

Voltage swell may also occur when heavy load is removed from the connection. In case of DG, voltage disturbance can cause the disconnection of inverters from the grid and therefore result in losses of energy. Also long term performance of grid connected PV systems shows a remarkable degradation of efficiency due to the variation of source and performance of the inverter. Approximately 70 to 80% of all power quality related problems can be attributed to faulty connections. Power frequency disturbances, interference of electromagnetic, transients, harmonics and low power factor are the other categories of PQ problems that are related to the source of supply and types of load. These power electronics converters, together with the operation of non-linear appliances, inject harmonics to the grid. In addition to the voltage fluctuation due to irradiation, cloud cover or shading effects could make the PV system unstable in terms of grid connection. Therefore, this needs to be considered in the controller design for the inverter. In general, a grid-connected PV inverter is not able to control the reactive and harmonic currents drawn from non-linear loads.

III. UNIVERSAL ACTIVE POWER FILTER (UAPF)

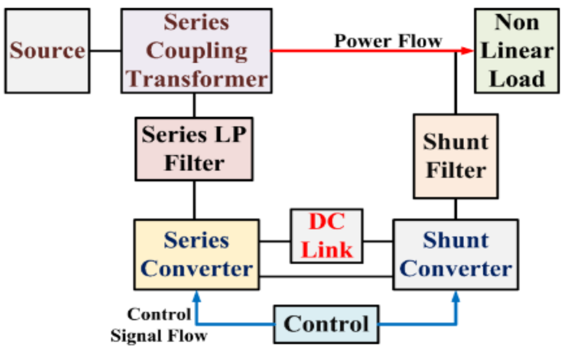


Fig.4- scheme of UPAF

Universal Active Power Filter (UAPF) system is an integration of series and shunt active filters connected back to back. Usually these two filters are connected at the DC side and they share a common DC capacitor. The series components compensate the supply side disturbances such as volt-age sags/swells, flicker, voltage unbalance, and harmonics. UPAF supplies voltage to maintain the load voltages at the target level. The shunt component mitigates the issues such as poor power factor, load harmonic currents, and load unbalance. It injects currents in the system to make the source currents balanced sinusoids in-phase with the source voltages. Figure above illustrates the principal scheme of UPAF with series and shunt active filters. UPAF compensates for distortions such as unbalanced system voltages and load currents of a three-phase system. The equivalent circuit of UPAF is shown in figure below. An unbalanced 3-phase system consists of positive, negative, and zero sequence components. The system voltage can be expressed as in equation:

$$V_S(t) = V_{s+}(t) + V_{s-}(t) + V_{s0}(t) + \sum V_{sh}(t)$$

Here subscripts +, −, and 0 represent positive, negative and zero sequence components respectively. The series converter compensates for the following components of voltage:

$$V_0(t) = V_L(t) - V_s(t)$$

Control system automatically controls the series converter so that the output converter voltage is $V_0(t)$. The nonlinear load current with distortion can be expressed as:

$$I_L(t) = I_{L+}(t) + I_{L\_}(t) + I_{L0}(t) + \sum I_{sh}(t)$$

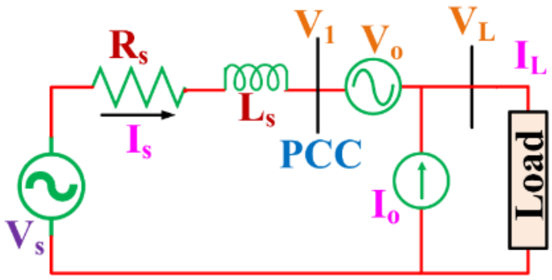


Fig.5- Equivalent circuit of UAPF

The shunt converter provides compensation of the load harmonic currents to reduce voltage distortion. Output current with harmonic, negative and zero sequence currents controls the shunt converter so that load current distortions can be nullified. The current component which is compensated by the shunt converter is given by equation:

$$I_0(t) = I_L(t) - I_s(t)$$

IV. METHODOLOGY WITH DISCRETE ADAPTIVE FILTER

In this study, an adaptive filer based technique is utilised for control of three phase-three wire PV integrated UAPF system The adaptive filter considered is a fourth order quadrature signal generator. Two adaptive filters are used to estimate the fundamental positive sequence components of distorted load currents. These positive sequence components are then used to estimate reference signal for the shunt active filter of PV-UAPF system. The method has reduced computational burden and has good dynamic response. The series active filter of the PV-UAPF is controlled using synchronous reference frame theory based technique to compensate for voltage sags/swells at the PCC. A maximum power point tracking (MPPT) algorithm, mostly P&O technique is used to operate PV array at its peak power point. Since this is a single stage system, the MPPT algorithm generates the reference DC-link voltage. The main advantages of the system are as follows:

- Multi-functional system providing pollution free clean energy based on solar PV power along with clean power quality.
- The power generated from PV array, supplies load power thus reducing active power demand from supply system.
- The sampling of positive sequence currents obtained by adaptive filter based on zero crossing of load voltage enables estimation of magnitude of active component of all phases with one sampling.
- The system protects sensitive loads from PCC voltage sags/swell while maintaining grid current within IEEE 519 standard.
- The system performance is robust under various disturbances in the load, voltage sags/swells at the PCC and solar irradiation.

The shunt active filter control is presented in figure above. The primary task in the control of a shunt active filter is generation of reference currents. In this work, the shunt active filter is controlled using indirect current control wherein the reference for the shunt active filter is the grid current, which should only contain fundamental and active power component. The shunt active filter control blocks involve three sub-blocks i.e. DC control block, load active current evaluation block and PV feed forward block. Two adaptive filters are used to extract the fundamental positive sequence components of the load current. The basic structure of adaptive filter is shown in figure. This basic structure is a fourth order system consisting of a quadrature signal generator with a gain K and resonant frequency, ω_s. The input to the filter is a sinusoidal input given as:

$$x(nT_s) = X_m \sin(\omega_c kTs + \varphi_c)$$

where T_s is sampling time of the system, X_m is magnitude of sinusoidal wave. For the input $x(nT_s)$, the adaptive filter provides two signals which are in quadrature with each other,

$$x_1(n+1) = -x_1(n) + \mu(n)$$

$$qx_1(n+1) = qx_1(n) + tan\left(\frac{\omega_s T_s}{2}\right)\mu(n)$$

where, q is a quadrature shift operator. The frequency adaptive law of the system is given as,

$$\omega_s(n+1) = \omega_s(n) - \gamma\left[tan\left(\frac{\omega_s(n)T_s}{2}\right)\right][x(n) - x_1(n)]qx_1(n)$$

Since $\omega_s(n)$ is time adaptive, the adaptive filter is a nonlinear filter. The factor Ks is chosen based on compromise between steady state accuracy and dynamic performance. In this work, Ks is chosen as 0.5. The value of γ used in the system is 0.0002. The signal frequency changes from 50Hz to 48Hz and back to 50Hz. The adaptive filter is able to track the step change in frequency within 0.1s.

V. SYSTEM SIMULATION AND RESULTS

The configuration of a PV-UAPF system is shown in figure below. This is a three phase system consisting of a shunt active filter and series active filter with a common DC-bus. The shunt active filter is interfaced near the non-linear load whereas the series active is interfaced in series with the PCC. Other major components of the system include interfacing inductors, ripple filters and injection transformers. The PV array is coupled directly to the DC-bus of PV-UAPF system. A diode is used while integrating the PV array with PV-UAPF to prevent reverse power flow into PV array.

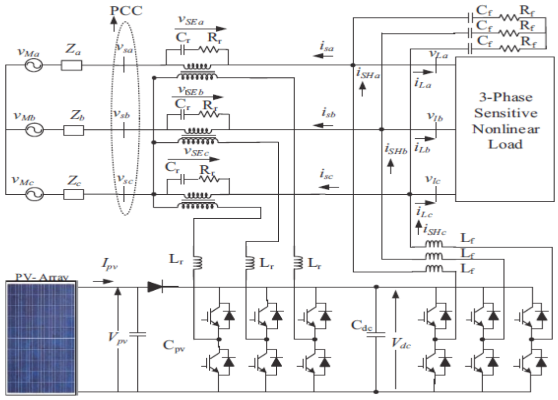


Fig.6 - System Configuration of Solar PV Integrated Unified Active Power Filter

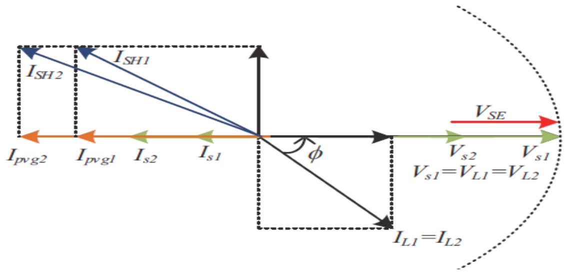


Fig.7- Phasor Representation of PV-UAPF system operating with a linear load

The phasor representation of operation of PV-UAPF is given in figure below. The signals under nominal condition have subscript '1' while signals under PCC voltage sag condition are represented with subscript '2'. The load voltage (V_{L1}) and PCC voltage (V_{s1}) are equal under nominal conditions. The load current (I_{L1}) lags behind VL1 with a phase angle φ. During sag condition, the series active filter injects a voltage (V_{SE}) in phase with the PCC voltage (V_{s2}) to maintain load voltage (V_{L2}) in same magnitude and phase as that of nominal PCC voltage (V_{s1}). The shunt active filter current (I_{SH1}, I_{SH2}) is a combination of load reactive power and current corresponding to PV array power injection (I_{pvg1}, I_{pvg1}). The PV power generation is more than the load active power demand, and consequently the excess power is fed into the grid.

Table 1 – Experimental Values

Parameter	Values
PCC voltage	v_s = 220 V, f = 50 Hz
Grid Impedance	Z_a, Z_b, Z_c=0.7 Ω,477μH
Nonlinear Load	Rectifier with R-L: 1.12 kW
DC-bus Voltage	V_{dc} = 360 V
DC-bus Capacitor	C_{dc} = 3.3 mF
Shunt Active Filter Inductor	L_s = 4 mH
Series Active Filter Inductor	L_{se} = 0.5 mH
MicrolabBox Sampling Time	T_s = 33.33 μs
DC-bus PI contoller	K_p = 0.8, K_i = 0.2
Series Compensator PI controller	K_{pD} = 2; K_{ID} = 400
	K_{pQ} = 2; K_{IQ} =400
LPF cut off frequency	f_{LPF} = 10 Hz;
PV Array	P = 4.8 kW,
	V_{oc} = 415 V, I_{sc} = 14 A
	V_{mpp} = 360.23 V, I_{mpp} = 13.329 A
MPPT Parameters	T_m= 0.04s ,δV_{pv}= 0.5 V

VI. RESULTS AND DISCUSSION

Figure presents the performance of the adaptive filters in extraction of fundamental positive sequence component of load currents. The main waveforms recorded are phase 'b' load current (i_{Lb}), load current in α − β domain ($i_{L\alpha}$,$i_{L\beta}$) and α component of fundamental positive sequence load current $i+_{L\alpha 1}$. The load current is nonlinear and load of phase 'b' is removed, creating an unbalanced load condition. The adaptive filter technique is able to extract fundamental positive sequence component of load current within a one-cycle.

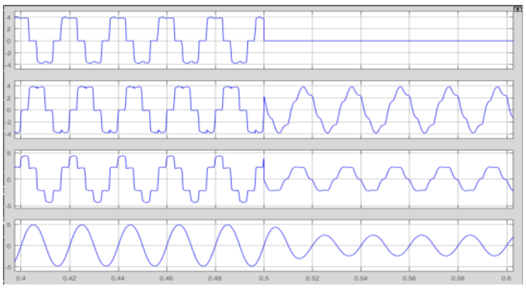


Fig.8 - Salient Signals in Extraction of Fundamental Positive Sequence Load Current using Adaptive Filter

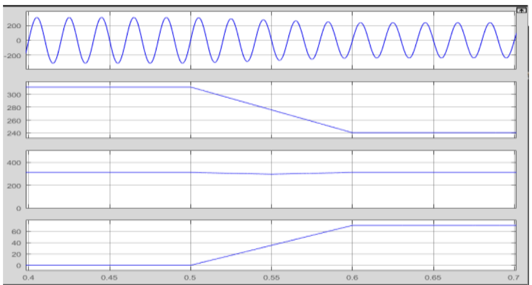


Fig.9- Reference Generation of Series Active Filter

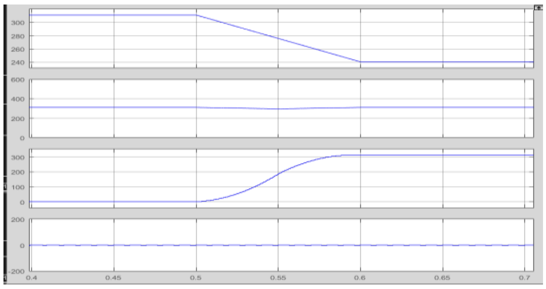
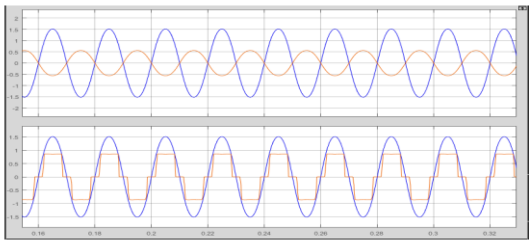
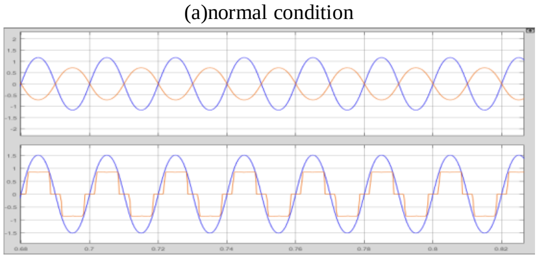


Fig.10 - Control Signal Generation of Series Active Filter

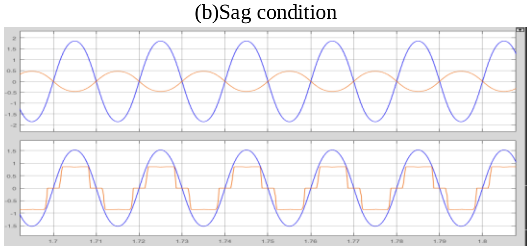
Figure above presents the series active filter control signals. The signals captured are v_{sab}, V_{sd}, V_{Ld} and V_{sed}. The internal signals are recorded during dynamic condition when there is a sag in PCC voltage. It can be observed that during sag, the d-axis component of PCC voltage reduces, however, the load voltage component remains at same level. An appropriate voltage is injected by the series active filter to maintain the load voltage at its desired regulation level. From figure above, it can be noted that the series active filter injects only d-axis component voltage while the q-axis component remains zero. This means that the PCC voltage and series compensator voltage are in-phase, which results in load voltage also being in-phase.



(a)normal condition



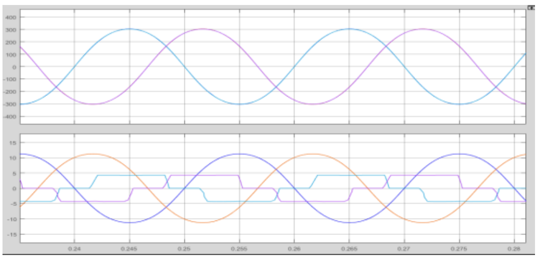
(b)Sag condition



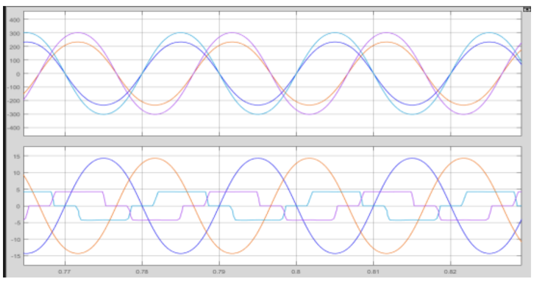
(c) Swell condition

Fig.11 - Steady State Per Phase Signals of PCC and Load Side in a PV-UAPF Compensated System

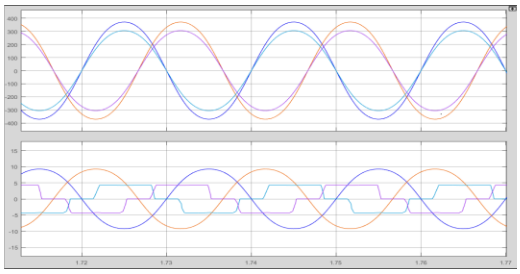
The steady state PV-UAPF system capability in load compensation and voltage regulations, is evaluated under conditions of nominal conditions, PCC voltage sags/swells. The steady state waveforms of a phase of PV-UAPF are given above. The recorded signals are v_{sa}, i_{sa}, v_{La} and i_{La}. In order to present both load side and PCC side information, only phase 'a' signals are recorded. The PCC current contains only fundamental active component while the load current is of a nonlinear quasi square wave shape. The voltage at load side is regulated and maintained in-phase with voltage of PCC during all conditions. Figure below show the behavior of PV-UAPF system under nominal, sag and swell conditions. It can be observed that though the THD of the load current is approximately 28%, the grid current THDs are maintained below 5%. The grid current meets specifications of IEEE-519 standard. Moreover, the power factor at PCC is approximately unity. The voltage at the load side is maintained at the desired RMS value of 220 V even though the voltage at PCC undergoes variation from 170 V during sag condition to 270V during swell condition. The total power at the PCC side is negative due to the fact that the surplus PV array power is being fed into the PCC.



(a)Normal Condition



(b) Sag Condition



(c) Swell Condition

Fig.12 -PV-UAPF Response under different conditions

VII. CONCLUSION

The performance of adaptive filter-based PV-UAPF system under both steady state has been studied. Sampling of fundamental component of load current obtained through adaptive filter enables fast extraction of fundamental active component of Non-linear load currents for all phases in one sampling. Only two adaptive filters are required to extract magnitude of active component of three phase load currents. This method reduces computational resources while achieving good steady state performance in extraction of fundamental active component of non-linear load current. The system performance has been found to be satisfactory under various disturbances in load current, PCC voltage and solar irradiation.

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