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GRID CONNECTED SOLID OXIDE FUEL CELL AND SOLAR PHOTOVOLTIC HYBRID POWER GENERATING SYSTEM

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Abstract - *In present scenario, the interest of producing energy from renewable sources is growing rapidly. One of the major factors of using renewable sources is its negligible contribution towards environmental pollution. Decrement in the number of conventional sources is also a motivational factor towards renewable sources. Among the renewable sources solar and wind are of primary importance. But it is seen that the efficiency of production is less in case of renewable sources. In this circumstance an additional non-conventional source may be used a secondary line of defense. This work is based on a standard photovoltaic system combined in parallel with a solid oxide fuel cell. In this project work a balanced mathematical model of hybrid PV-SOFC system is proposed.*

The control action has been performed using both series and shunt active power compensation method. The series active filter is for the compensation of load voltage and shunt for load current non-linearity. The above compensation methods compensate the nonlinearity due to the non-linear load attached to the power system and make the power factor unity or nearer to unity.

Key Words: **Solar PV, SOFC, Series active filter, Shunt Shunt active filter.**

1. INTRODUCTION

The consumption of power produced is now increasing in a rapid manner. More consumption leads to a higher generation of electrical power. High generation of electrical power requires more numbers of power sources. A source may be conventional or non-conventional. Conventional sources are limited but produces high power and highly contributed to the greenhouse effect. A non-conventional source produces less power but it is pollution free.

The conventional sources such as fossil fuel, coke etc are treated as a main supplier of electrical power. But more consumption of these sources leads to a rapid decay and an advancement in the pollution index. Due to this rapid advancement in pollution level we are forced to think about the alternative ones.

Solar technology is introduced as an alternative to these conventional sources [1]. The main advantage associate with this is pollution free. The basic component of a solar photovoltaic system is a solar cell. In other words, we can say that solar photovoltaic system is a systematic arrangement of solar cells. There are various methods proposed for the calculation of maximum power point tracking i.e. the condition where the output is maximum [2][3]. Among all the methods perturb and observe(P&O) method is found to be most accurate [4]. In general, 25^0c and 1000 irradiance is taken as standard test condition for the solar photovoltaic [5]. But the major disadvantage associate with the solar photovoltaic is that the efficiency of the system is less. This is due to the atmospheric condition which is uncertain with respect to time.

To compensate the effect of atmospheric effect or to enhance the efficiency level an additional solid oxide fuel cell (SOFC) system is used [6]. The solid oxide fuel cell is connected in parallel along with the photovoltaic system. The solid oxide fuel cell consists of various blocks such as hydrogen block, oxygen block, water block, reformer block etc. [7]. Solid oxide fuel cell is a highly efficient device uses chemical decomposition to produce electricity. The combined hybrid system is used for better power output. The main factor associate with this hybrid system is the power management [8]. As the photovoltaic system is of high voltage and less current where as solid oxide fuel cell system is of higher current and less voltage power management plays a vital role.

Power management generally refers to power quality management. Power quality means the quality of power i.e. voltage quality and current quality. The voltage and current must be free from all types of harmonics. In this regard various methods have been proposed. The active power filter is one of them [9][10].

The concept of active power filter consists of reduction of both current and voltage harmonics. In this proposed model we are dealing with both the voltage and current harmonics so both active series and shunt compensation method are used.

Voltage harmonics reduction model i.e. series active power filter is used to improve the voltage profile [11][12]. The series active filter ha an ability to mitigate the voltage related problem in the distribution system. Synchronous reference frame (SRF) is used as one of the control strategies [13][14]. It is mainly used for harmonic voltage compensation [15][16]. It can be achieved by means of d-q theory. In this paper we are using a phase lock loop-based control algorithm [17][18] for mitigation of harmonics voltage. It also improves the power factor but not able to nullify the overall current harmonics.

In a circuit current harmonic arises due to various factors such as moderate frequency switching [19], change in load conditions etc. There are various methods available for mitigation of current harmonics. A fuzzy logic controller is one of them [20]. It can also be done using a hysteresis current control technique [21][22][23].

The voltage compensation consists of Park's transformation technique followed by "d-q theory" [24].

The reactive power theory was used for the simulation of three phase three wire system. It further consists of Clark's transformation technique. For shunt active power filter, we can use "p-q" theory and hysteresis current controller [25][26][27]. Enhancing the power quality is our main aim in order to get an improved power factor [28].

After the controlling part grid synchronization is also important. Grid synchronization means the reduction of difference between voltage, frequency and phase angle between the generated output and supply. In simple term grid synchronization is the process of matching speed and frequency of source to the running network.

1.1 PV System

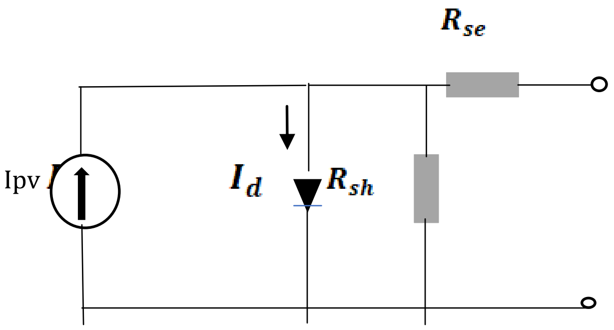


Fig -1: Equivalent circuit of solar cell.

A photovoltaic cell is basically a semiconductor device. It combines a p-type and an-type semiconductor doped together. In p-type semiconductor, electrons are the majority charge carriers. Holes are the majority charge carrier in n-type semiconductor. The site facing the sun is kept thinner then the other site facing. It increases the conduction rate. The two junctions are separated by a depletion region. The depletion region contains no charge carriers.

When sun light incidence on the depletion region, it breaks the neutral atoms present in the region. The neutral atoms break in to holes and free electrons.

There is an already existing electric field from the n-type region to the p-type region. This electric field creates a force on the charge carriers. Hence the electron moves towards the n-type and holes towards p-type region. If an external conducting path is provided i.e. metal fingers, the charge flows through an external circuit. Datasheets generally bring information about the characteristics and performance of PV devices with respect to the so-called standard test condition (STC), which means an irradiation of 1000 W/m2 with an temperature at 25 ◦C

1.2 SOFC

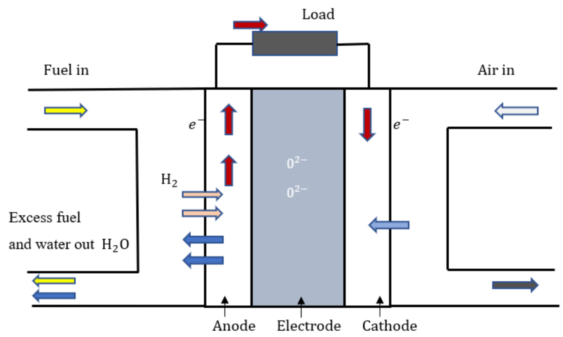


Fig -2: Physical structure of SOFC

In Solid Oxide hydrogen fuel cell, fuel is supplied to anode region and air is supplied to the cathode. Air molecules further produced oxygen ions. Similarly fuel burns inside anode and produces hydrogen ions. The two regions are separated by means of an electrolyte. The electrolyte allows the oxygen ions to cross the junction and reacts with the hydrogen ions under the process called oxidation and releases electrons. If there is an electrical connection between the electrode. By maintaining the oxygen deficiency level and overall neutral charge, thus generating useful electrical power from the combustion of the fuel. The only by product of this process is a pure water molecule (H_2O) and heat, as shown in Fig. 2.

1.3 Hybrid system

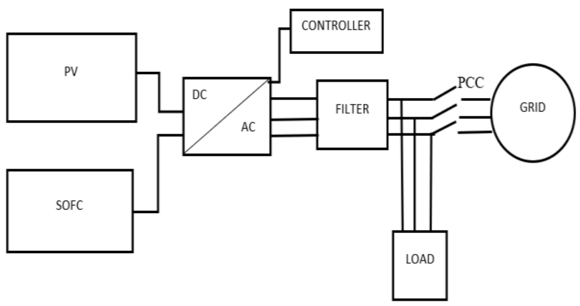


Fig -3: Block diagram representation of a hybrid system.

Among the renewable sources, solar energy is the most promising as it is cost-effective. But problem arises due to a large variation in the environmental condition over time. To overcome this issue, photovoltaic systems are integrated with some other power sources like fuel cell, hydrogen generator etc. The main advantage of combining a fuel cell to a photovoltaic system is the high efficiency, fast load response and fuel flexibility. In this paper an hybrid (solid oxide + solar photovoltaic) system is designed.

The proposed system model is given in figure 1. In the above model, solar photovoltaic system is supplied with 25^{0}c temperature and 1000 irradiance as standard values. The solid oxide fuel cell is supplied with a current input resulting from the net measurement of system current of the hybrid system. Then the system output is given to an inverter model. This resulting ac power is further used to fulfil the desire load demand.

2. Control Algorithm

Power quality has become a huge issue in the both industrial as well as domestic sector. It generally arises due to a sudden change in load demand. Power quality is a qualifying index of both voltage and current for the industrial as well as household consumers. It has a huge impact towards the sensitive loads. Any distortion in power quality leads to an equipment failure or faulty operation. A certain power quality problem may not be a serious one for a specific class of people, but may be a major concern for another class.

2.1 Shunt active filter

Active filters are generally dealing with current and voltage harmonics related problems. They are also implemented to deal with the power quality issue i.e. voltage sag, voltage swell, flickering etc. Active filters are classified in to two categories such as series active power filter and shunt active power filter and hybrid active filter. Series active power filter are used for compensation of voltage harmonics where as shunt for current harmonics and hybrid filter for both voltage and current harmonics.

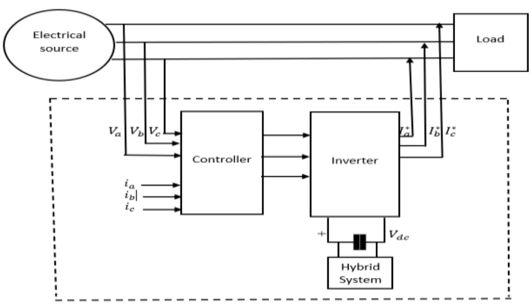


Fig -4: Physical structure of SAF.

2.1.1 Reactive power compensation theory

The generalized theory of "Instantaneous reactive power flow" in three phase circuit is termed as instantaneous power theory, also known as p-q theory. It is based on instantaneous three phase power system. The p-q theory is based on an algebraic transformation technique i.e. Clarke's transformation. In this transformation technique, the three phase voltages and currents in the $a-b-c$ coordinates get transferred in to $\alpha-\beta-0$ coordinates, followed by calculation of instantaneous power components i.e. p and q

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \ldots\ldots\ldots\ldots(1)$$

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

The relation between power components to the corresponding αβ-frame can be written as,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

$P_0 = V_0 * i_0$ (instantaneous zero-sequence power)

$P = V_\alpha i_\alpha + V_\beta i_\beta$ (instantaneous real power)

$q = V_\alpha i_\beta - V_\beta i_\alpha$ (instantaneous imaginary power)

Now,

Real power (P) = $\overline{P} + \widetilde{P}$

Imaginary power (q) = $\overline{q} + \tilde{q}$

Where,

$\overline{P}$-Fundamental component of real power

$\widetilde{P}$-Alternating component of real power

$\overline{q}$-Direct or fundamental component of reactive power

$\tilde{q}$- Alternating component of imaginary power

The fundamental component contains the actual value of both voltage and current, alternating components contains its corresponding harmonics values.

2.1.3 Compensation technique

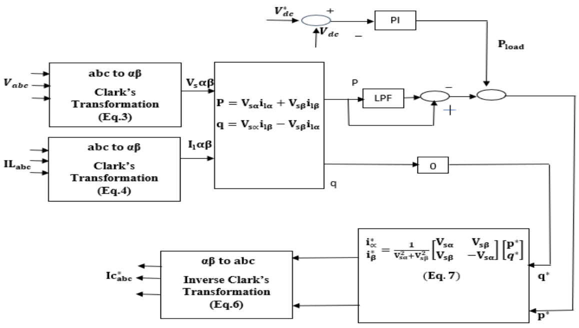


Fig -5: Control structure of SAF

The compensating current is calculated by using:

$$\begin{bmatrix} i_\beta^* \\ i_\alpha^* \end{bmatrix} = \frac{1}{V_{s\alpha}^2 + V_{s\beta}^2} \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ V_{s\beta} & -V_{s\alpha} \end{bmatrix} \begin{bmatrix} \bar{P} + P_0 + \bar{P}_{loss} \\ 0 \end{bmatrix} \quad \text{.......(7)}$$

Where,

i_α^* = compensation current in α − frame

i_β^* = compensation current in β − frame

2.2 Series active power filter

A series power filter connected in series with the power distribution system is called as series active power filter. It is used for compensation of distortion caused by the nonlinear loads in the existing system. It provides a high impedance to the existing harmonics in the power system. The series active power filter is used for voltage compensation purpose. It supplies a voltage component in series with the main voltage supply, hence acts as a controlled voltage source. It compensates for both under voltage and over voltage condition on the load side. The main features of series active power filter is to protect sensitive loads from voltage sags, swell and harmonics. The rated power of series active power filter is comparatively smaller than the load, however the apparent power of series active power filter may increase to a certain value during voltage compensation.

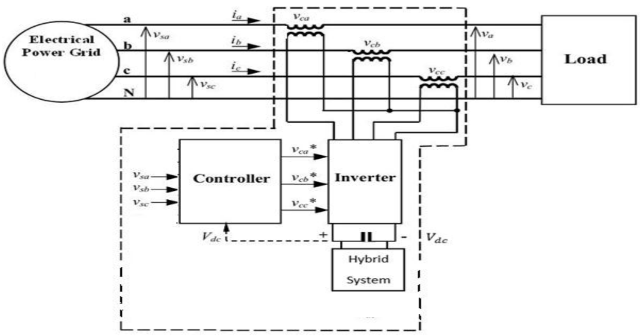


Fig -6: Physical structure of SAPF.

The block diagram consists of a three-phase supply, series active power filter, a nonlinear load and a series transformer. The transformer may be arranged in star or delta. The star system allows us to use two different voltages. For example, in a 220/440-volt system, it provides 220V between the neutral and one of the phases and 440V across any two phases. A delta system provides one voltage magnitude. The connection of nonlinear load may increase level of harmonics in the existing system. Due to which the voltage and current gets distorted. These distortions may lead to severe problem; hence it needs to be compensated. In this regards a series active power filter is connected in the source side. The series active power filter injects the voltage harmonics component in order to maintain the power supply. For improved harmonics compensation performance and power factor improvement series active power filter is used.

Series active power filter is cheaper and can be easily implemented. It is of lighter weight and highly efficient.

2.2.1 Control scheme of SAPF

The simple control strategy for a series active power filter is shown below. It comprises of PLL based unit vector template, current control unit, signal generating unit and reference voltage generator.

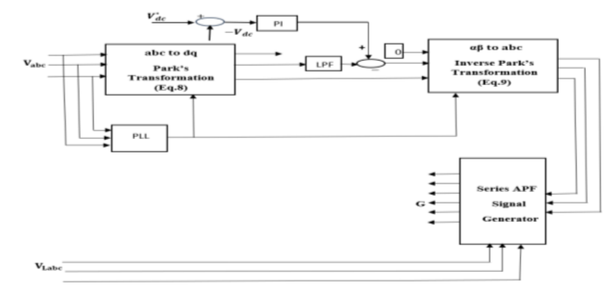


Fig -7: Control structure of SAPF.

A phase lock loop (PLL) is used for synchronization of measured positive sequence component of the current with self-generated current. The output of phase lock loop provides a calculated value of direct axis and quadrature axis components of voltage and current.

The control structure of series active power filter is based on Park's transformation technique. In this method, the reference voltage generated is compared with the output voltage of series active power filter.

The Park's transformation technique is given below

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(wt) & \sin\left(wt - \frac{2\pi}{3}\right) & \sin\left(wt + \frac{2\pi}{3}\right) \\ \cos(wt) & \cos\left(wt - \frac{2\pi}{3}\right) & \cos\left(wt + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{...(8)}$$

The inverse Park's transformation technique is given as

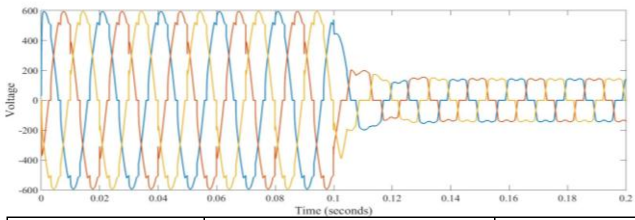
$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \sin(wt) & \cos(wt) & 1 \\ \sin\left(wt - \frac{2\pi}{3}\right) & \cos\left(wt - \frac{2\pi}{3}\right) & 1 \\ \sin\left(wt + \frac{2\pi}{3}\right) & \cos\left(wt + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \quad ....(9)$$

For a three phase three wire system, neutral or ground is neglected. Park's transformation can be written as;

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(wt) & \sin\left(wt - \frac{2\pi}{3}\right) & \sin\left(wt + \frac{2\pi}{3}\right) \\ \cos(wt) & \cos\left(wt - \frac{2\pi}{3}\right) & \cos\left(wt + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Table -1: Series Active Filter

Series Active Filter		
Source	Voltage	420V
	Frequency	50Hz
	3Ø line inductanc	$1e^{-3}$H
Load	3Ø load resistance	20 ohms
	3Ø line inductance	$10e^{-9}$H
dc-link	Capacitor (Cd1=Cd2)	$2200e^{-3}$F
Series active	Filter resistance	5.5 ohms
	Filter inductance	5H
	Filter capacitance	$750e^{-6}$F



2.3 Simulation Results

Fig -1: Source voltage with variation in load without compensation

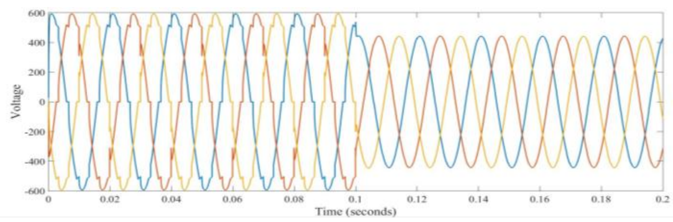


Fig -2: Source voltage with compensation

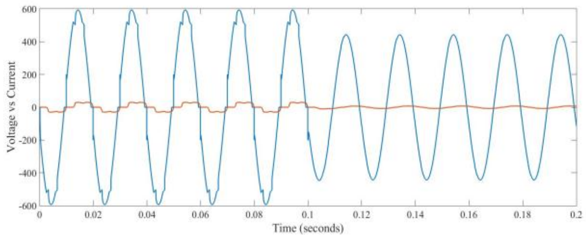


Fig -3: Source voltage vs current after compensation

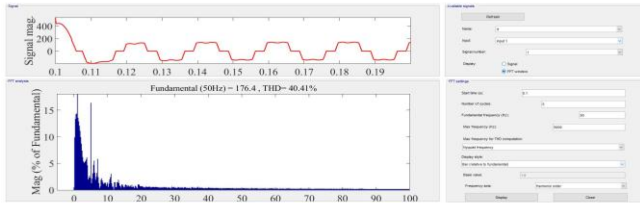


Fig -4: THD before compensation

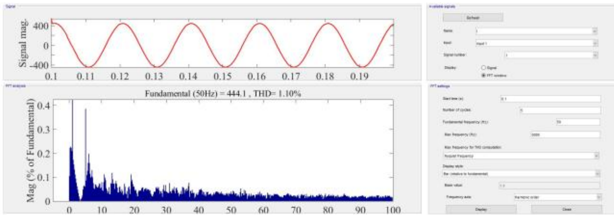


Fig -5: THD after compensation

Table -2: S Active Filter

Shunt Active Filter		
Source	Voltage	420V
	Frequency	50Hz
	3Ø line resistance	0.01 ohms
	3Ø line inductance	$1e^{-6}$H
Load	3Ø load resistance	30 ohms
	3Ø load inductance	$10e^{-6}$H
	3Ø line resistance	18ohm
	3Ø line inductance	$1.5e^{-12}$H
dc-link	Capacitor (Cd1=Cd2)	$2200e^{-3}$F
Shunt active power filter	Filter resistance	5.5 ohms
	Filter inductance	0.8H
	Filter capacitance	$750e^{-6}$F

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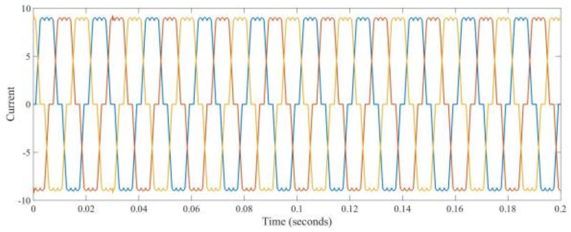

Fig -6: Load current

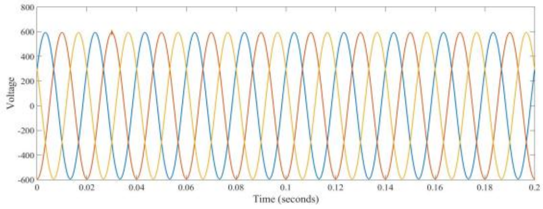

Fig -7: Load voltage

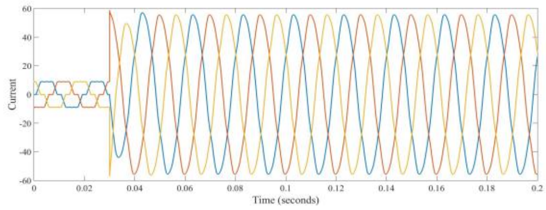

Fig -8: Source current with compensation

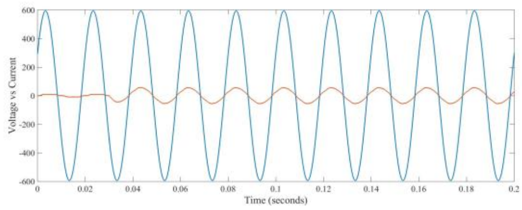

Fig -9: Source voltage vs current with compensation

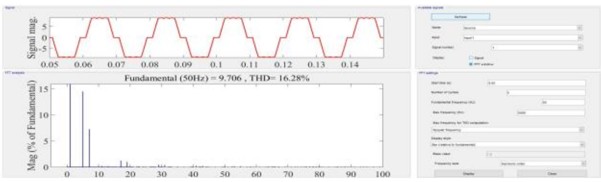

Fig -10: THD without compensation

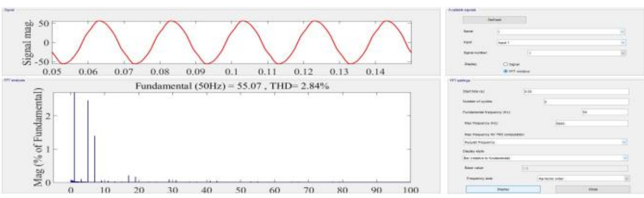

Fig -11: THD with compensation (450 cells)

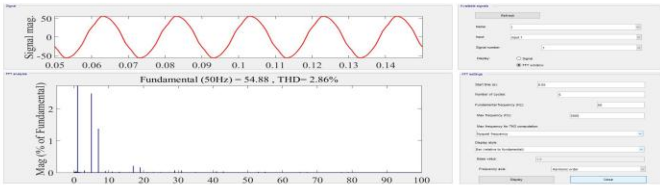

Fig -12: THD with compensation (350 cells)

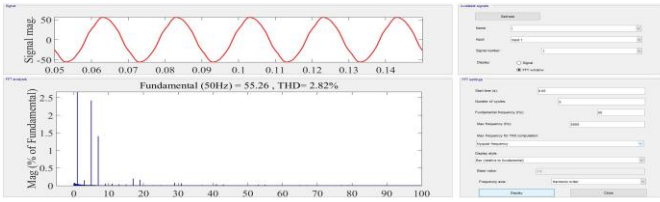

Fig -13: THD with compensation (550 cells)

Comparison for various numbers of cells in SOFC			
No. of cells	DC Voltage (volts)	DC Current (Amp)	THD
350	330.3	9.834	2.86
450	427.2	12.77	2.84
550	524.7	15.1	2.82

3. CONCLUSION

In this paper, the investigation has been carried out for a grid connected hybrid photo voltaic and solid oxide fuel cell system.The functional operation consist of both series and shunt active power filters inorder to maintain an unity or nearer to unity power factor. During application of series power filter,the non-linearity present due to the non-linear load in the voltage profile is compensated succesfully.On the other hand shunt power filter compensates the harmonics present in tne current profile.The voltage comensation method was performed using d-q theory and current compensation via p-q theory.From the above we can also conclude that, series compensation compensates the load harmonics present in the voltage profile .But inorder to achived a better power factor we must also apply shunt compensation technique for compensation of the current profile.

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