Analysis of Grid Connected Fuel Cell Generation and Enhancement of Power Quality by Using Shunt Active Power Filter

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Abstract **-** The excessive use of power electronics elements in power distribution system creates the power quality problems because of its own non-linear (V-I) characteristics and switching instants. That quality of power can be improved by usage of the compensators and active power filters. This paper gives the Simulink model of shunt active power filter with fuel cell for improvement of quality of power. Harmonic currents produced by non-linear loads are compensated by shunt active filter and maintain the source current sinusoidal. The control strategies in this are Constant Instantaneous Power Theory, Generalized Fryze Current Control Theory and Synchronous Reference Frame Method and all control techniques are compared for Different Loads and for Different Supply (Balanced as well as Unbalanced) condition is simulated using MATLAB/SIMULATION tool box. SAPF eliminates the harmonics by injecting equal but opposite current harmonics components at the Point of Common Coupling (PCC).

Keywords **-** Shunt Active Filter (SAF), Fuel cell Hysteresis Band current controller (HBCC), PI controller, Instantaneous Reactive Power (IRP) theory.

I. INTRODUCTION

Harmonic parameter is one component of periodic wave form consists of frequency with multiple integrals of fundamental frequency. Harmonics are produced by the modern power electronics devices. The usage of the power electronics devices [1] at the load side as well as the source side is increases because of the tremendous changes in the semiconductor technology. The more use of power electronics components gives the problems like generation of harmonic components, efficiency of the system is low, reactive power disturbance , less power factor and disturbance the other consumer etc. This problem increases in future years also; hence need to mitigate such type of problems as early as possible.

Basically two approaches are there for the mitigation of such power quality issues, the first approach is the condition of load, the load is having less immune harmonics. Those Equipments are made less sensitive, practically first approach is not possible. The second approach is power line conditioning. This approach gives power line conditioning system is installed at the Point of Common Coupling (PCC) that counteracts or suppresses the undesirable result produced by non-linear loads.

The renewable sources interconnected with the main supply can influence the power quality at the Point of Common Coupling and can pollute the electrical network with harmonic components that must not exceed the stipulated limits.

Traditionally passive filters deal harmonic generation and reactive power disturbance problems. But it has given lot of disadvantages like fixed compensation characteristics, large size resonance problem etc. so the solution given by traditionally passive filters are less attractive. To overcome these disadvantages shunt active filters (SAF) are used. Shunt active power filters allows the harmonics currents compensation, compensation of unbalance conditions, and correction of power factor. Shunt active power filters gives better solution than the traditionally passive filters. SAF is operated as current source and produces the harmonics currents which is equal and opposite phase components than harmonic currents produced by the power electronics devices or by nonlinear loads. The simulation implementation of a shunt active filter is proposed in this, with Constant Instantaneous Power Theory, and Generalized Fryze current control strategy, Synchronous Reference Frame Method.

II. SHUNT ACTIVE POWER FILTER

The Shunt Active Filter (SAF) is connected in parallel with the nonlinear load. The connection diagram of shunt active filter in Power System is shown in Fig. 1[2]. In The shunt active filter, Voltage Source Converter (VSC) is implemented and DC-link capacitor is connected to VSC. The function of DC-link capacitor is to provide the reactive power imbalance and needed to compensate the harmonics components. The basic operation of shunt Active Power Filter is required voltage sensors and current sensors for sensing Alternating voltage and Alternating current flow on DC-link capacitor voltage at the inverter terminals and from source to load. Based on The control strategy, the control theory calculates the harmonic current. The switching devices in voltage source converter switches according to and inject equal but opposite compensating harmonic current components. The compensated harmonic component is calculated by the IRP theory controller. An inductor is connected in series with the active power filter to reduce the ripple currents.

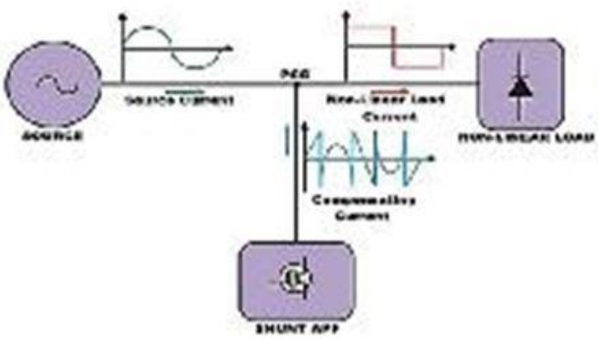

Figure 1: Block diagram of SAF

III. PROTON EXCHANGE MEMBRANE FUEL CELL

Many papers have researched in the mechanism and experience models of the fuel cells. Different modeling methods have different complexities according to the number of parameters that may be discussed. We also can see the develop history from these papers. All in all, the most specific experience model we can refer to is

$$V=E_0-R*I-m\exp(nI)-h[\ln(I)+\ln(P_a/P_{O_2}) \quad (1)$$

Where E0 is the thermodynamic potential of the cell;
I is the working current, Pa and P_{O_2} are the working pressure of the stack and oxygen partial pressure on the catalyst layer; m, n, R and h are parameters by experience. The terms ln(i) h × and mexp(nI) are due to simulate the polarization voltage drop during a large current density. When we come to the chemical-mechanism model, the output voltage of a single cell can be defined by the following expression

$$VFC=ENernst-Vact-Vohmic-Vcon \quad (2)$$

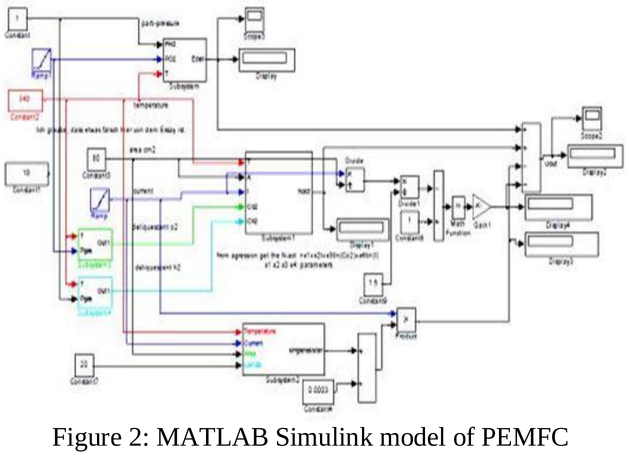

Figure 2: MATLAB Simulink model of PEMFC

IV. CONTROL STRATEGIES

a) Constant Instantaneous power theory - Akagi proposed Instantaneous reactive power Theory [3-4]. This theory is based on the transformation of three phase quantities (a-b-c) into two phase quantities in α-β frame and the Instantaneous active and reactive power is calculated in this frame. Sensed source voltages Vsa, Vsb and Vsc and Sensed load currents iLa, iLb and iLc are given to the controller. These parameters are processed and to generate the reference current signals (i*fa, i*fb, i*fc) again which are given to a hysteresis based PWM current controller to generate gate pulses (g1,g2, g3, g4, g5 and g6) for SAF.

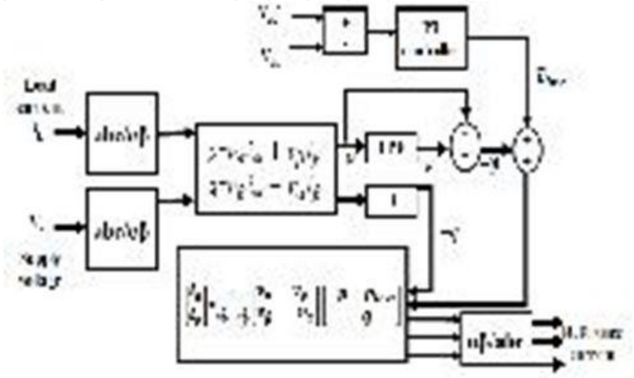

Figure 3: Block diagram of reference current signal generation

In instantaneous reactive power theory [5], the instantaneous quantities three-phase currents and three-phase voltages are calculated and converted into the α–β orthogonal coordinates.
Consider three-phase three-wire system, the three-phase currents can be expressed in terms of harmonic zero sequence, positive sequence, and negative sequence currents. Three-phase conventional instantaneous power is calculated as follows:
Instantaneous real and imaginary powers can be written as (5), (p) and imaginary (q) powers. Since these equations are products of instantaneous currents and voltages in the same axis. In three phase circuits, instantaneous real power is p and its unit is watt. In contrast Iβ and Iα are not instantaneous powers. Since these are products of instantaneous current and voltages in two orthogonal axes, q is not conventional electric unit like W or Var.qis instantaneous imaginary power and its unit is Imaginer Volt Ampere (IVA).
These power quantities given above for an electrical system represented in a–b–c coordinates and have the following physical meaning.
The instantaneous active and reactive power includes ac and dc values and can be expressed as follows:

$$p=\bar{p}+\tilde{p} \quad (9)$$
$$q=\bar{q}+\tilde{q}$$

Equation (6) can be written as Equation (8):
From Equation (8), in order to compensate harmonics and reactive power instantaneous compensating currents (icα and icβ) on α and β coordinates are calculated by using ~ and −q as given below
In order to obtain the reference compensation currents [6] in the a–b–c coordinates the inverse of the transformation given in expression (11) is applied:

b) Generalized Fryze current control - The Generalized Fryze current control theory takes minimum RMS value of source current so that same 3-phase average real power is taken from the source as the original load current.

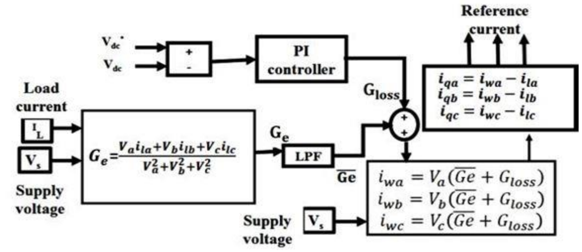

Figure 4: Block diagram of Generalized Fryze current control Theory

The block diagram of this control algorithm is as shown in Fig. The load current and the source voltages are sensed in this controlling algorithm and the active fryze conductance Ge is calculated by using the below equation,

Where,

iLa; iLb; iLc = Load current of phase a, phase b and phase c respectively

Va; Vb; Vc = Source voltage of phase a, phase b and phase c respectively

This Method decreases the ohmic loss in line. Also it shows the linearity between the supply voltage and current [3, 4]. The instantaneous conductance (Ge) is measured from 3-phase instantaneous real power. Moreover RMS aggregate voltage is derived from the instantaneous values of phase voltages. The equivalent conductance (Ge) pass through Butterworth Low Pass Filter (LPF) with cut off frequency 50Hz. The desired reference source current is calculated by the active current after compensation. The active instantaneous currents are calculated as shown below:

Where,

i_{wa}, i_{wb}, i_{wc} = Active instantaneous current of phase a, phase b and phase c respectively

i_{qa}, i_{qb}, i_{qc} = reference current of phase a, phase b and phase c respectively.

This calculated compensated current is compared by measured compensated current and the generated error signal is given to the voltage source inverter which is generated triggering pulses and is fed to the gate of the inverter.

c) Synchronous Reference Frame Method - The Block Diagram of Synchronous Reference Frame Method is shown in fig. 5

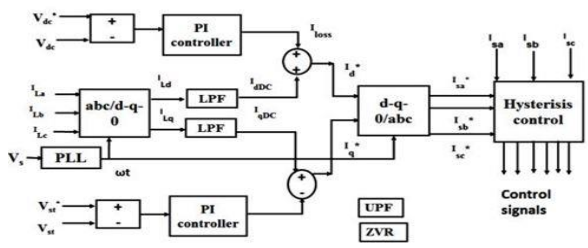

Figure 5: Block diagram of Synchronous Reference Frame Method

In this control strategy the SRF-based SAPF control technique is used to generate gate pulses for controlling of SAPF. Here from the control strategy is designed with abc frame to d-q frame conversion block, PLL block, LPF, PI controller, DQ to ABC conversion block and hysteresis controller.

A 3-phase Phase Locked Loop (PLL) is chosen for synchronization of PCC voltages with current signal. 3-phase load currents are converted into two phase using Park’s transformation as per equation (12)

In abc frame to d-q frame conversion block is used to convert three phase load current parameters (Iabc) to dq0 parameters frame by using parks transformation. Firstly, the current components from block in d–q co-ordinates are generated. Iabc phases can then be transformed into d–q coordinates.

This method is classified in two modes 1. Unity power factor (UPF) and 2. Zero voltage regulation modes

i). Unity Power Factor Mode: This control strategy is used to compensate reactive power in UPF mode. The source has to supply the (active current) component of ild current component. The output of PI controller is considered as the current iloss for meeting switching losses of IGBT. Output obtained from addition of and iloss is shown in equation (14). The reference source current is obtained by the following reverse Park’s transformation shown as in Equation (15) and id∗and io∗are zero and isa* , isb*, isc* are reference currents.

ii). Zero voltage Regulation Mode: The comparison of quadrature-axis current of the load and the different of reference voltage of PCC and actual voltage and it is given to PI controller which is denoted as used for regulating the voltage at PCC for Voltage Regulation. At PCC, the AC terminal voltage (amplitude is controlled to its reference voltage (∗) is peak value of PCC voltage (586 Volts). The amplitude of the AC voltage (Vs) at PCC is calculated by AC voltages (Vsa,Vsb,Vsc) in equation (16). The reference supply quadrature-axis current in equation (17)

V. HYSTERESIS CURRENT CONTROL TECHNIQUE

The generated reference current signal ∗ is taken as the reference of the active power filter and actual source currents are. The hysteresis band current controller compares the current signals and deiced to generate the switching pulses for active power filter. The logic of switching is formulated as follows:

If < (∗ −) upper switch is OFF and lower switch is ON for leg-a (SA = 1).

If < (∗ +) upper switch is ON and lower switch is OFF for leg –a (SA = 0).

The switching functions of SB and SC for leg ―”b” and ―”c” are determined similarly, using corresponding reference and measured currents and hysteresis bandwidth (HB).

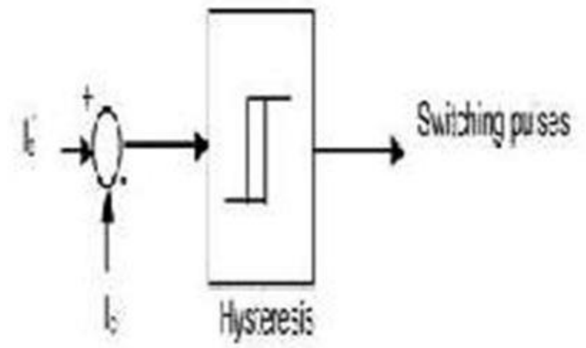

Figure 6: Generation of switching of pulses

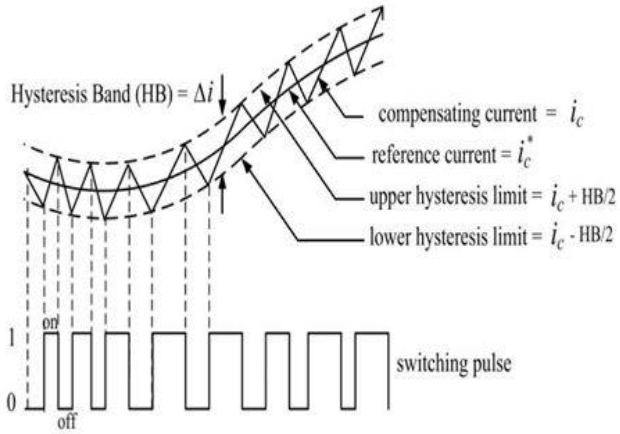

Figure 7: Block diagram of hysteresis band current controller

VI. SIMULATION RESULTS

Simulation block diagram of SAF is shown in figure connected parallel to nonlinear load at point of common coupling (PCC).SAF injects the compensating currents at PCC and protects the source current. The simulation model of shunt active power filter is shown in figure

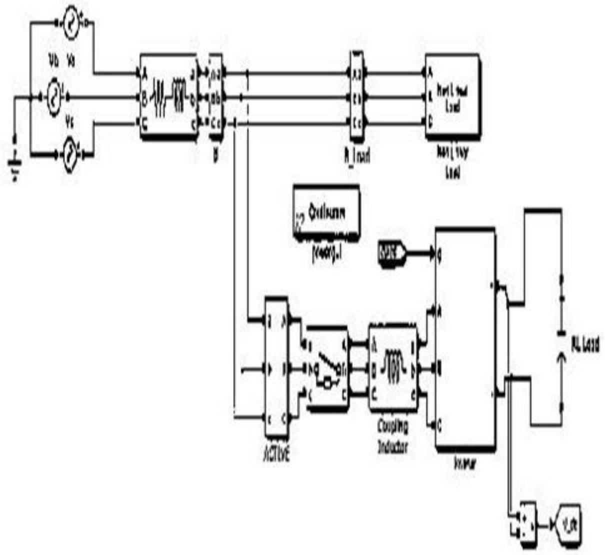

Figure 8: Proposed system Matlab model of Shunt Active Power Filter

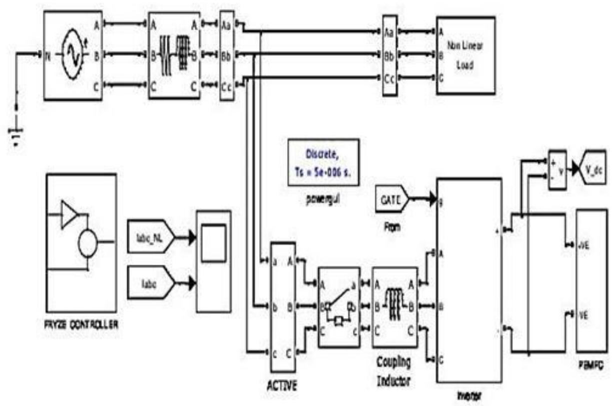

Figure 9: Matlab model of grid connected Fuel cell

Case A: Balanced Supply Voltage - In this case considered three different types of loads and observe the performance analysis for (i) R=60 Ω (ii) R=100 Ω, L=25mH and (iii) R=10 Ω,
L=1000mH with all three control techniques. In each control strategy Load current and source current waveform are shown in fig. and calculated their THD in each condition for all three control strategies.

i). Proposed System Waveforms:

a) Constant Instantaneous Power Theory:

R=60Ω

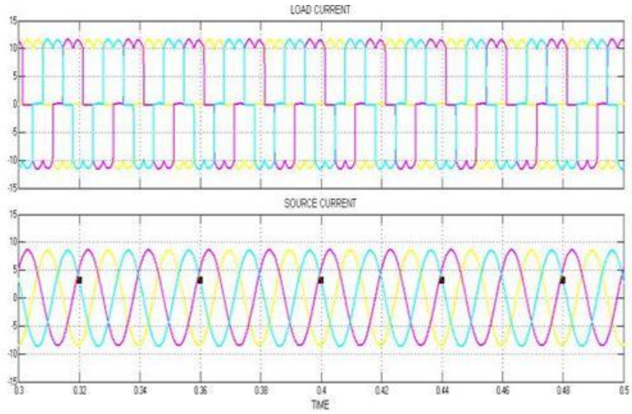

Figure 10: Load current and Source current

R=100 Ω, L=25mH

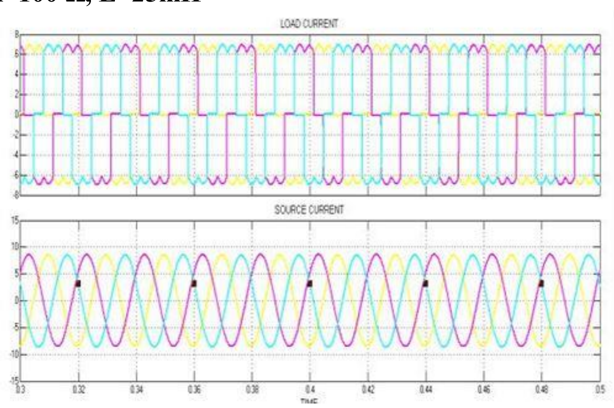

Figure 11: Load current and Source current

R=10Ω, L=1000mH

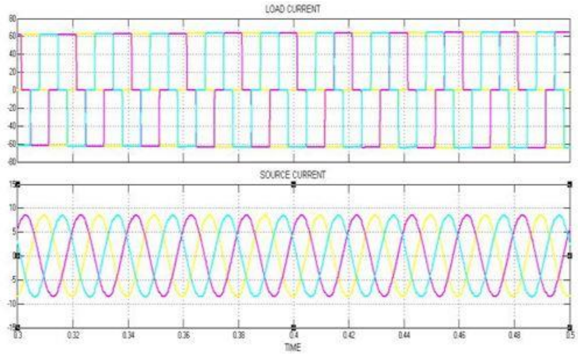

Figure 12: Load current and Source current

b) Generalised Fryze Current Control Method:

R=60Ω

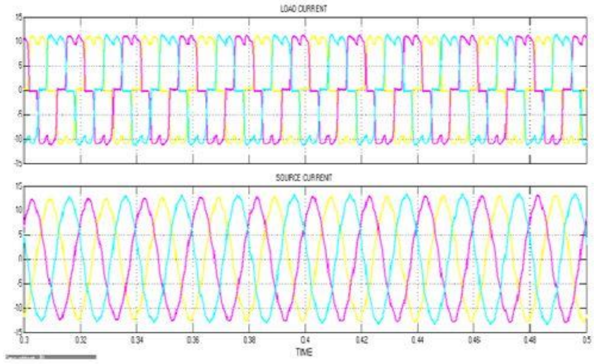

Figure 13: Load current and Source current

R=100 Ω L=25mH

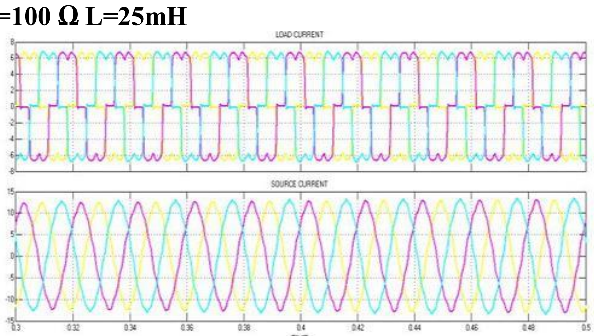

Figure 14: Load current and Source current

R=10Ω, L=1000mH

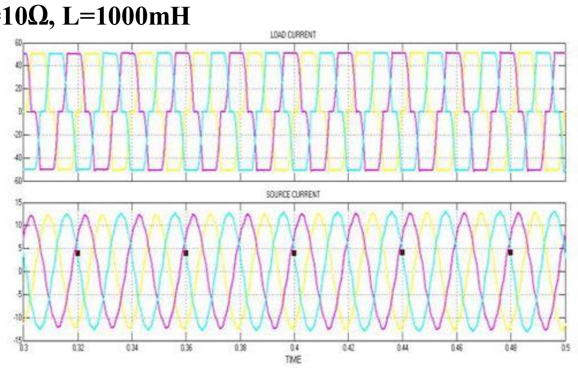

Figure 15: Load current and Source current

c) Synchronous Reference Frame Method:

1. Unity Power Factor:

R=60Ω

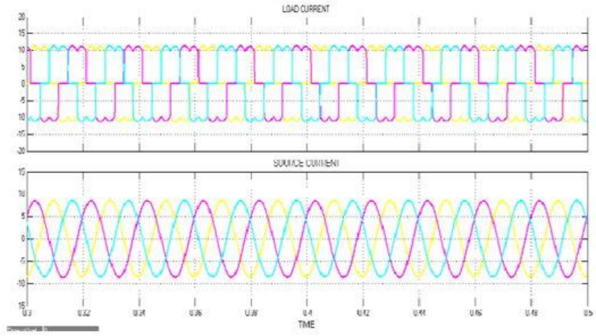

Figure 16: Load current and Source current

R=100 Ω , L=25mH

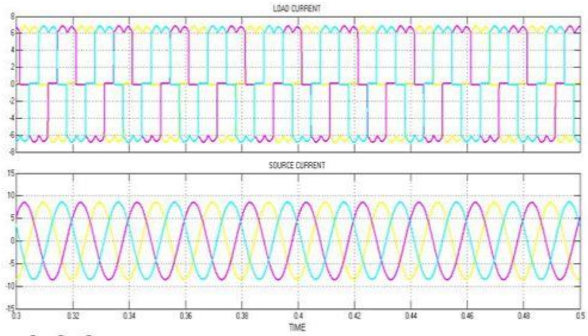

Figure 17: Load current and Source current

R=10 Ω L=1000mH

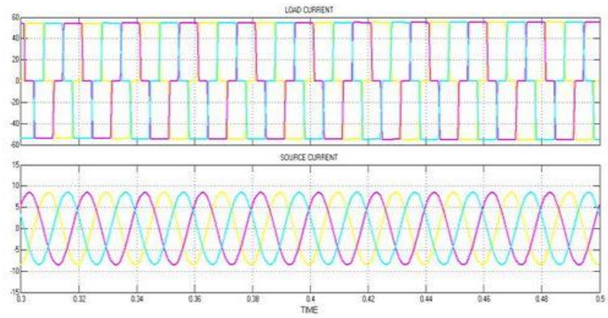

Figure 18: Load current and Source current

2. Zero Voltage Regulation:

R=60Ω

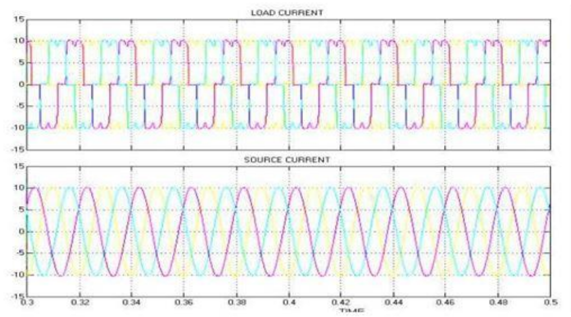

Figure 19: Load current and Source current

R=100 Ω , L=25mH

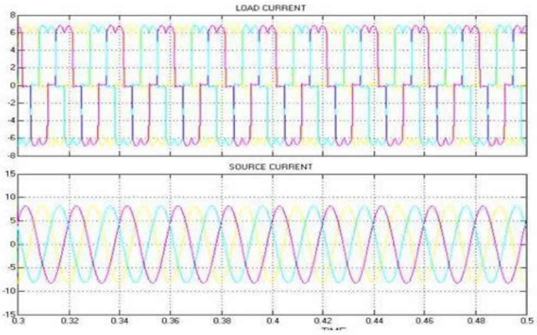

Figure 20: Load current and Source current

R=10 Ω L=1000mH

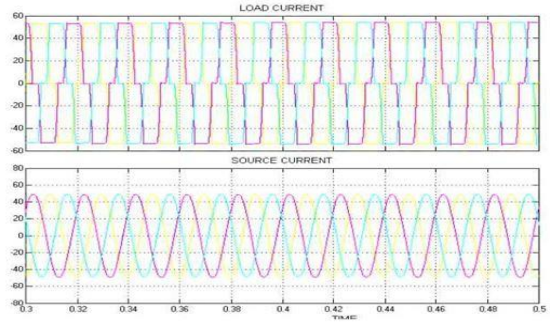

Figure 21: Load current and Source current

ii). Grid Connected Fuel Cell Waveforms -

a) Constant Instantaneous Power Theory:

R=60Ω

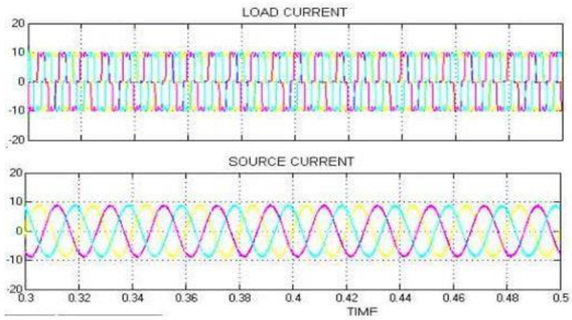

Figure 22: Load current and source current waveforms

R=100 Ω , L=25mH

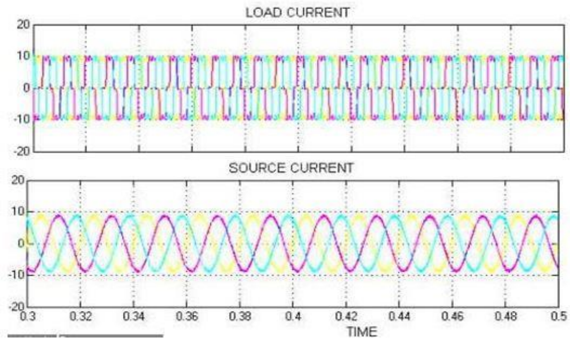

Figure 23: Load current and source current waveforms

R=10 Ω L=1000mH

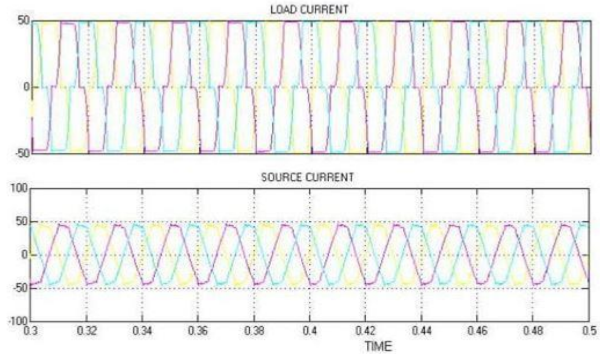

Figure 24: Load current and source current waveforms

b) Generalised Fryze Current Control Method:

R=60Ω

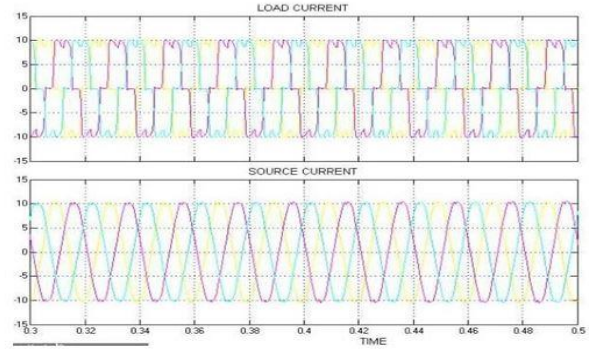

Figure 25: Load current and source current waveforms

R=100 Ω , L=25mH

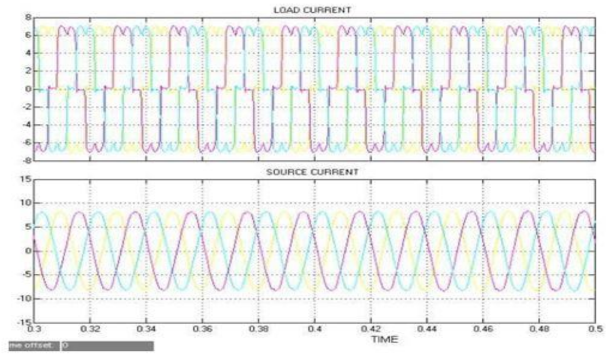

Figure 26: Load current and source current waveforms

R=100 Ω , L=25mH

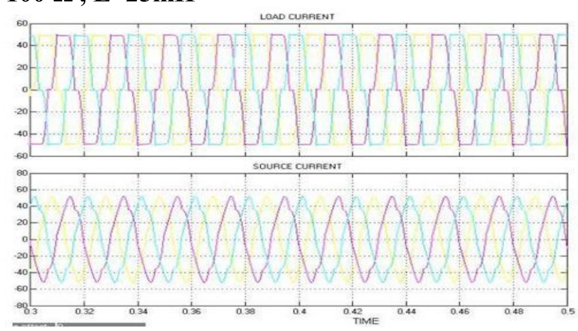

Figure 27: Load current and source current waveforms

c) Synchronous Reference Frame Method:

1. Unity Power Factor:

R=60Ω

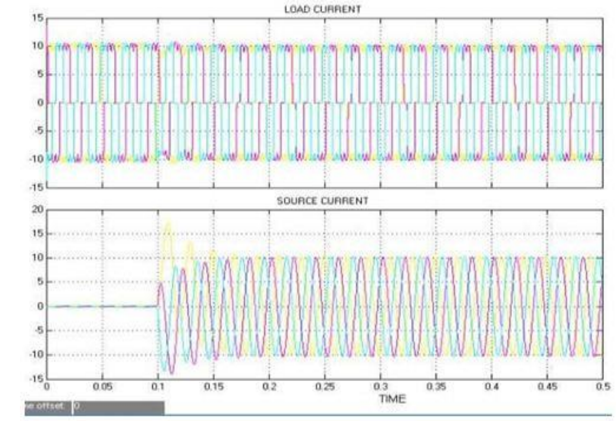

Figure 28: Load current and source current waveforms

R=100 Ω , L=25mH

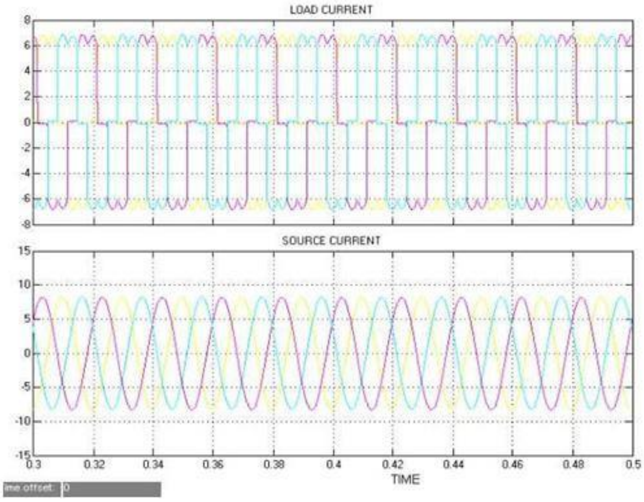

Figure 29: Load current and source current waveforms

R=100 Ω , L=25mH

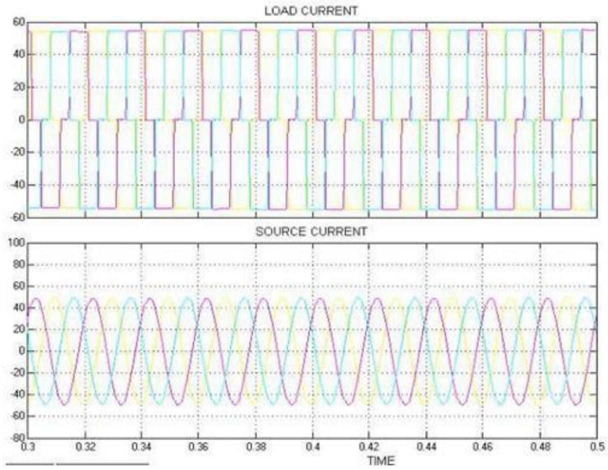

Figure 30: Load current and source current waveforms

2. Zero Voltage Regulation:

R=60Ω

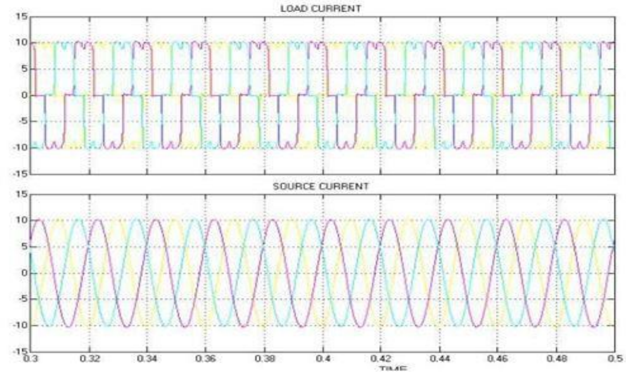

Figure 31: Load current and source current waveforms

R=100 Ω L=25mH

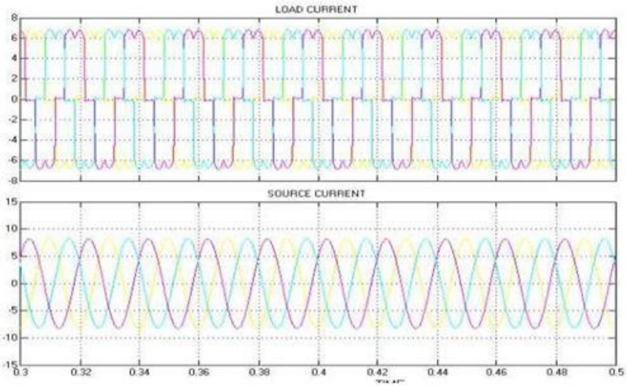

Figure 32: Load current and source current waveforms

R=10 Ω L=1000mH

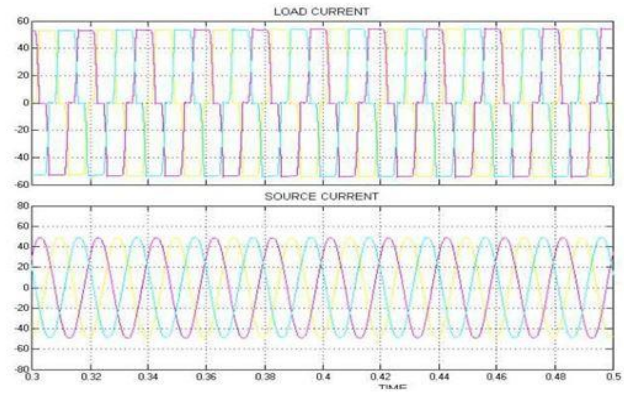

Figure 33: Load current and source current waveforms

Case B: Unbalanced Supply Voltage - In this case considered unbalanced supply voltage magnitudes and phase angles condition are (I) 10%, 20%, 30% in magnitude, (II) 10%, 20%, 30% in phase angle and (III) 20% in magnitude and 20% in phase angle. All conditions are observed with resistive load (R=60 Ω). All these conditions are simulated with all three control techniques. . In each control strategy Load current and source current waveform are shown in fig. and calculated their THD in each condition for all three control strategies.

The THD (%) Results obtained with different techniques and different operating conditions are summarized as below.

Table I THD (%) of Source current for different control condition of proposed system

	% THD			
Operating condition	*Constant Power*	*FRYZE*	*UPF*	*ZVR*
R=60 Ω	3.98	2.55	3.85	3.88
R=100 Ω, L=25 mH	5.26	2.96	5.19	5.18
R=10 Ω, L=1000 mH	5.70	5.46	5.43	5.49
Mag. 10% unbalanced	8.02	5.64	3.88	3.92
Mag. 20% unbalanced	15.08	10.56	3.98	4.23
Mag. 30% unbalanced	22.73	15.66	4.21	4.60
Phase 10% unbalanced	15.03	4.87	4.25	4.46
Phase 20% unbalanced	29.04	6.52	5.39	6.15
Phase 30% unbalanced	44.82	8.34	7.14	8.36
Phase 20%, Magnitude 20% unbalance	34.89	15.45	5.17	6.30

Table II THD (%) of Source current for different control condition of grid connected fuel cell

	% THD			
Operating condition	*Constant Power*	*FRYZE*	*UPF*	*ZVR*
R=60 Ω	3.78	2.25	3.54	3.58
R=100 Ω, L=25 mH	5.06	2.70	4.95	4.93
R=10 Ω, L=1000 mH	5.55	5.32	5.29	5.42
Mag. 10% unbalanced	7.65	5.85	3.59	3.63
Mag. 20% unbalanced	13.78	8.72	3.78	4.03
Mag. 30% unbalanced	17.12	13.87	4.12	4.39
Phase 10% unbalanced	13.27	4.21	4.16	4.26
Phase 20% unbalanced	23.28	5.79	4.87	5.94
Phase 30% unbalanced	37.66	7.42	6.58	7.90
Phase 20%, Magnitude 20% unbalance	29.04	13.91	4.39	6.13

VII. CONCLUSION

In this paper, various control techniques used for Shunt Active Power Filter with fuel cell are modeled and discussed. Simulation for Constant Power Technique, Fryze Current Control technique and SRF Method has been developed in Matlab/Simulink tool. Simulation results for balanced supply conditions shows that Fryze Current Control technique gives better performance compare to remaining control methods of Constant Power technique and SRF Method. Like that, for unbalanced supply conditions SRF Method gives better performance compare to remaining control methods of Constant Power technique and Fryze Current Control technique.

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