FC/PV Fed SAF with Fuzzy Logic Control for Power Quality Enhancement

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ABSTRACT

In this paper, a Fuel cell (FC)/Photovoltaic cell (PV)/Battery operated three-phase Shunt Active power Filter (SAF) is proposed for improving the power quality at the utility side. Fuzzy based instantaneous p-q theory control is proposed for SAF. This SAF consists of Voltage Source PWM Converter (VSC) and a DC link capacitor supplied by a FC/PV/Battery. The filter provides harmonic mitigation with reactive power compensation and neutral compensation for loads at the Point of Common Coupling (PCC). A Single switch boost DC-DC converter connects the FC/PV/Battery with the VSC to maintain the load. The performance of the proposed SAF is tested in MATLAB/SIMULINK environment with Fuzzy logic controller (FLC). The controller maintains the DC link voltage based on the current reference generated by the p-q theory. The Hysteresis PWM current controller is employed to generate the gating pulses to the switches in VSC. The simulation results of the proposed SAF validate the effectiveness of FLC in power quality enhancement.

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1. INTRODUCTION

The increasing energy demands as well as the environmental pollutions have significantly promoted the usage of renewable energy systems for all applications. Many researches have been carried out in utilizing the renewable systems like Photovoltaic (PV) cell or Fuel cell (FC), wind power to meet out the requirements of the growing energy demands [1]. From the above renewable energies, the low voltage sources are the PV and Fuel cell. This can be connected in series to get the required voltage according to the applications The generated DC voltage from the PV/FC is boosted by using the DC/DC boost converter before connecting to the DC link side.

Many of the loads in the industries and commercial work places are nonlinear loads such as personal computers, electronic ballasts, variable and adjustable speed drives and electronic house hold appliances. It creates power quality problems like utility current distortion due to harmonics, high currents in neural, unbalanced loads and high reactive power compensation, etc. The problems created by the inclusion of nonlinear loads in the distribution systems are solved by many compensators like Shunt Active power Filter (SAF), Dynamic Voltage Restorer (DVR) and Unified Power Quality Conditioner (UPQC), etc. [2]. All these systems are well known for its merits, but it suffers by its own drawbacks like usage of slow response, more passive elements, increase in size of the system and more losses etc. But the SAF shows faster response with good mitigation of harmonics. There are a lot of control techniques available in the literature for controlling the SAF [3], to provide the source current harmonics reduction, reactive power compensation and load balancing [4]. Out of those techniques, instantaneous p-q theory [5] is most suitable control for compensating the problems due to nonlinear loads.

The objective of this work is to maintain the DC link voltage of the VSC to provide continuous compensation. The IGBT (Insulated Gate Bipolar Transistor) based boost converter fed by PV/FC/battery uses Pulse Width Modulation (PWM) technique for maintaining the DC link voltage. The compensation is provided continuously in day and night time by PV/FC/battery. During the excess power condition, the battery is charged. The maximum power point tracking algorithm is not discussed in this paper.

2. PROPOSED SAF

Referring to Figure 1, at the Point of Common Coupling (PCC), the boost converter fed VSC is connected with nonlinear loads. The VSC [6] includes IGBT, inductors and a DC link capacitor. The formula for calculating the voltage across the DC link capacitor (V_{dc}) [4], [6], is as follows,

$$V_{dc} = \frac{2\sqrt{2}V_L}{\sqrt{3}}\left(\frac{1}{M_a}\right) \tag{1}$$

M_a is the modulation index and V_L is the source voltage.

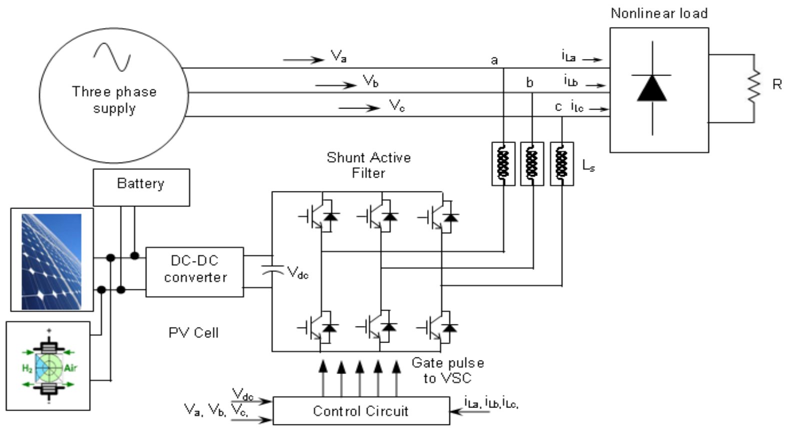

Figure 1. PV/FC/Battery fed three phase SAF

The value of capacitor is determined by using the formula as follows,

$$C = \frac{6V_{ph}(\alpha I_{ph})T}{\left(V_{ref}^{\ 2} - V_{o1}^{\ 2}\right)} \tag{2}$$

Where V_{ref} and $V_{o1}$is the reference DC voltage and the minimum voltage level of DC bus respectively, α is the overloading factor, V_{ph} is the phase voltage, I_{ph} is the phase current, and T is the time by which the DC bus voltage is to be recovered. The star/delta transformer is utilized for connecting the VSC to the three phase lines at the Point of Common Coupling (PCC). The single switch DC-DC boost converter is connected to VSC. The reference current adoption for VSC is derived from the p-q theory. This current reference wave shape the utility current to near sinusoidal.

3. MODELING OF PV AND FC

A PV cell works on the photo voltaic effect and it should be cascaded to meet out the required voltage and current [7]. The PV cell voltage depends on the solar irradiation level and temperature with respect to the weather conditions. Table 1 gives the data's of SHARP ND-Q250F7 PV panel with the illumination of 1 kW/m^2 and solar irradiance at a cell temperature of 25°C.

Table 1. Electrical Characteristics of SHARP ND-Q250F7 solar panel

Maximum power (Pmax)*	250W
Tolerance of P_{max}	+5%/-0%
Type of the cell	Polycrystalline Silicon
Cell Configuration	60 in Series
Open circuit Voltage(V_{oc})	38.3V
Maximum Power Voltage(V_{pm})	29.8V
Short Circuit Current(I_{sc})	8.90A
Maximum Power Current (I_{pm})	8.4A
Module Efficiency(%)	15.3%
Temperature Coefficient(P_{max})	-0.485%/◦C
Temperature Coefficient (V_{oc})	-0.36%/◦C
Temperature Coefficient (I_{sc})	0.053%/◦C

The FC generates the voltage with the help of hydrogen and air. Proton Exchange Membrane (PEM) type [8] of fuel cell is the most popularly used and the Table 2 gives the parameters of PEM type FC.

Table 2. Parameters of PEM Fuel cell

Fuel cell nominal parameters	
Stack power	Nominal=5998.5V Maximal=8325 W
Fuel Cell Resistance	0.07833 ohms
Nerst voltage of one cell[En]	1.1288V
Nominal utilization	Hydrogen(H2)=99.56% Oxidant (O2)=59.3%
Normal consumption	Fuel =60.38slpm Air =143.7slpm
Exchange current (i0)	0.29197A
Exchange Coefficient(alpha)	0.60645
Fuel cell signal variation parameters	
Fuel composition (x_H2)	99.95%
Oxidant composition (y_O2)	21%
Fuel flow rate [Fuelfr] at nominal hydrogen utilization	Nominal=50.06lpm Maximum=84.5lpm
Air flow rate(AirFr) at nominal oxidant utilization	Nominal=300lpm Maximum=506.4lpm
System temperature[T]	338 Kelvin
Fuel supply pressure[Pfuel]	1.5bar
Air pressure[PAir]	1bar

There are three modes of operation for PV/FC/Battery based VSC viz,

Mode1: Compensation by PV/FC in day time, in this mode the voltage is fed to VSC from PV/FC through the single switch boost DC-DC converter to compensate the source current as well as it charges the battery (48V).

Mode2: Continuous Compensation by PV/FC, in this mode continuous source current compensation is provided by PV/FC without any interruption, even if one source is not capable of supplying the voltage.

Mode3: Compensation in night time, in this mode battery/FC supplies VSC through the boost converter to provide compensation.

4. DC - DC CONVERTER AND ITS CONTROL

Figure 2 shows the basic boost converter is used to increase the input voltage to get the required output voltage [9]. The input to the boost converter is fed from PV/FC/Battery. There are two modes of operation in boost converterand it is given as follows: [10], [11]. Mode 1, when the switch(S) is in Turned ON, the input current (I) charges the inductor (L) upto a period of T_{ON} Mode 2, when S is Turned OFF, the inductor discharges. The inductor dicharging voltage adds with the supply voltage to give increased output voltage.

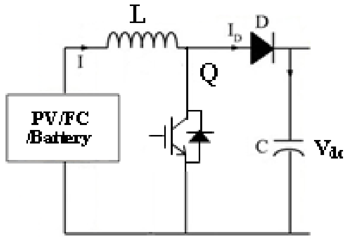

Figure 2. Basic Boost converter

The input voltage is 48V and the output voltage from the boost converter is 670V. The switching frequency used is 25 kHz and the value of the inductor (L) and capacitor(C) are chosen as 0.0171 mH and 3000μF.

5. CONTROL ALGORITHM OF SAF

The Instantaneous reactive power theory (p–q theory) [5], [15], is chosen for controlling the DC link voltage of the VSC [12]-[13] and its control block is shown in Figure 3. The reference current is derived based on the p-q theory and the equations are as follows,

By applying the Clarke matrices, voltages (v_{Sa}, v_{Sb}, v_{Sc}) and the load currents (i_{La}, i_{Lb}, i_{Lc}) are sensed and converted to *α-β-0* reference frame. The compensating reference current is calculated by of active ($\tilde{p}$) and reactive power ($\tilde{q}$) components and is given in the Equation (3),

$$\begin{bmatrix} i_{ref,C\_\alpha} \\ i_{ref,C\_\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\alpha \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -(\bar{q} + \tilde{q}) \end{bmatrix} \tag{3}$$

$$i_{ref,C\_0} = i_{L0} \frac{1}{\sqrt{3}} \left[i_{La} + i_{Lb} + i_{Lc} \right] \tag{4}$$

The a-b-c coordinates (i_{ref_a}, i_{ref_b}, i_{ref_c}) are determined by taking the inverse Clarke transformation to the currents in the α-β-0 coordinates and the reference compensation currents are expressed in the Eqnuation (5)

$$\begin{bmatrix} i_{ref,C\_a} \\ i_{ref,C\_b} \\ i_{ref,C\_c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ref,C\_0} \\ i_{ref,C\_\alpha} \\ i_{ref,C\_\beta} \end{bmatrix} \tag{5}$$

The power components regulate the capacitor voltage [14] in the DC side of SAF and it done by Fuzzy logic controller. The triangular membership function variables are used as the input and output variables. The error voltage (e) and change in error voltage (ce) are the two inputs of fuzzy controller. The Fuzzification is done by using continuous universe of discourse, Implication using the “min” operator and Defuzzification using the “centroid” method. The linguistic variables for error voltage and changing error voltage are Negative Big (NB), Negative Small (NS), Zero (Z), Positive Big (PB), and Positive Small (PS). The output variable is ΔP_{dc} and Table 3 shows the fuzzy rules framed to control the harmonics using the proposed SAF.

Table 3. Fuzzy Rule Table

		e				
		NB	NS	Z	PS	PB
ce	NB	NB	NB	NB	NS	Z
	NS	NB	NS	NS	Z	PS
	Z	NB	NS	Z	PS	PB
	PS	NS	Z	PS	PS	PB
	PB	Z	PS	PB	PB	PB

The hysteresis current controller is employed to generate the switching patterns. It forces a bang – bang instantaneous control to draw the sinusoidal current which follows the reference current derived by p-q theory within a certain band limits.

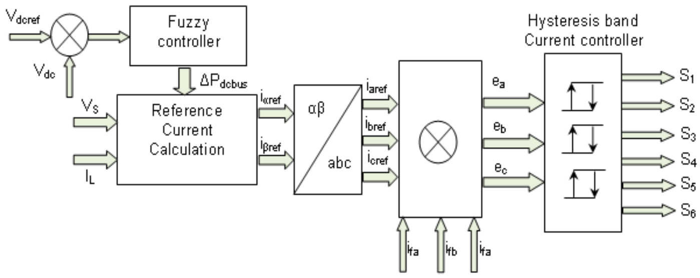

Figure 3. Control Structure for PV/FC fed VSC

The firing pulses to the VSC are derived from the error difference (e_a, e_b, e_c) generated between the actual current (i_{fa}, i_{fb}, i_{fc}) and the reference current (i_{aref}, i_{bref}, i_{cref}). This error is subjected to a hysteresis controller to generate the gating pulse as shown in Figure 3.

6. RESULTS AND DISCUSSION

The majority of the non linear loads are the powering units by using diode bridge rectifier. These loads in the distribution system, distorts the source current and degrades the power quality. The MATLAB/SIMULINK software is used for modeling the proposed SAF with PV/FC/Battery. Figure 4 illustrates the distorted source current waveform observed without the connection of SAF. The FFT analysis for the distorted phase current A is shown in Figure 5. The signals are observed for the simulation time interval between 0 to 0.4s. Similarly, the THD obtained for Phase currents A, B, C are 19.84%, 20.98% and19.82% respectively.

When the proposed three phase SAF fed PV/FC/Battery is connected to the power system during transient operation, the source current is made to follow the sinusoidal template of the reference current. This work is done by fuzzy based p-q theory. Figure 6 presents the waveforms of current after compensation by the SAF. The harmonics of the phase A is mitigated from 19.84% to 1.53% and it is shown in Figure 7. The THD for other two Phases B and C is reduced from 20.98% to 1.55% and 19.82% to 1.50%. Table 4 gives the compensation provided by the proposed SAF with fuzzy controller. The merits of this SAF system is, continuous compensation is provided with the use of FC/PV/Battery, even if one of the sources is affected, the other source will continue in connection with SAF. Thus, the harmonic mitigation is continuously done without any interruption.

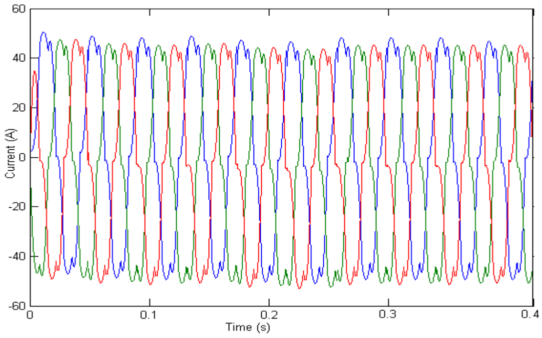

Figure 4. Source current waveform before inclusion of SAF

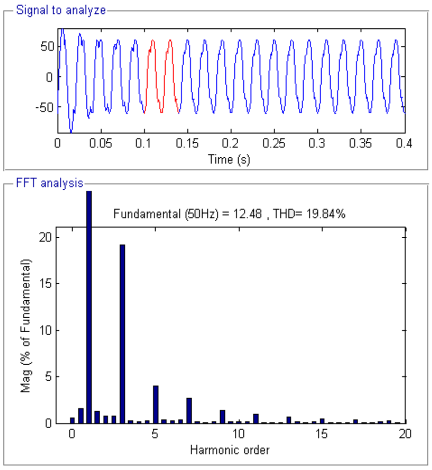

Figure 5. Current waveform taken before compensation (Phase A)

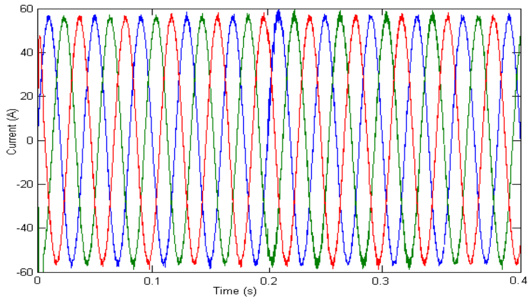

Figure 6. Sinusoidal Source current waveform observed after compensation of SAF

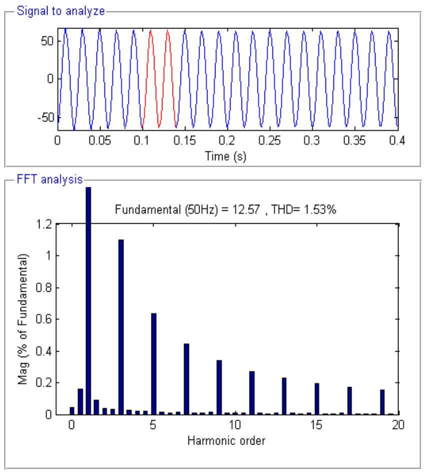

Figure 7. THD measurement of phase A after compensation of SAF

Table 3 Observed Total Harmonic Distortion before and after compensation of SAF with Fuzzy control

Source current THD	Without compensation	With compensation
Phase A	19.84	1.53
Phase B	20.98	1.55
Phase C	19.82	1.50

7. CONCLUSION

A three phase SAF fed with PV/FC/Battery has been simulated in MATLAB/SIMULINK software and results are presented. A satisfactory performance has been achieved by using fuzzy controller with instantaneous p-q theory. based control for having effective source harmonic reduction and reactive power compensation has been presented in this paper. The single switch boost converter is used to step up the voltage in order to maintain the DC link voltage of the shunt active filter. The comparison is made between the PI controller and fuzzy controller at the DC bus. It shows that p-q with fuzzy controller has reduced source current THD. The observed source current THD of the phase A without compensation is 20.98 % and after compensation it is reduced to 1.53%.

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