Design and Development of a Fuzzy-Based Single-Phase STATCOM Operator for Non-Linear Loads in Standalone PV Systems to Improve Power Quality

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***Abstract*—In the recent decade, environmental preservation has enhanced the usage of renewable energies. The most prevalent renewable energy source is solar. Several papers have shown how to improve power quality with filters. Passive filter is one technique to improve power quality, however it has unset a reactive power compensation, is large if inductors are employed, and loses some signal. Applying these extra compensating devices mitigates power quality concerns and assures voltage sag and swell. The flexible AC transmission has compensating devices. This proposed technique uses a PV farm inverter as a static compensator (STATCOM) to improve power quality for nonlinear loads in standalone PV systems. Two-stage system has a boost DC-DC converter on the primary side. In addition, the boost converter's gradual conductance mechanism assures maximum PV array power. Custom power devices mitigate voltage sag/swell, uneven load voltage, voltage control, etc. by compensating reactive power with shunt current. STATCOM is expected to improve power quality and network stability. A nonlinear and resilient Fuzzy controller is developed for Single phase STATCOM's dc link bus voltage. MATLAB/Simulink simulates a fuzzy STATCOM controller.**

Key Terms: LC filter, Non Linear Load, Fuzzy controller, Power quality, STATCOM, Photovoltaic Cell, PV Inverter, Total Harmonic Distortion (THD), Passive Harmonic Filter.

I. INTRODUCTION

Conventional energy consumption causes global warming. Burning fossil fuels releases toxic gases that destroy living things. SPV (Solar Photovoltaic) power is pollution-free [1]. Once erected, SPV array requires no more expenditure. SPV arrays have no moving parts to extract energy. SPV plant power is cost-effective. Solar power may be used in numerous ways. [2] Discusses sun energy challenges. It has several applications in the kitchen, the bathroom, the garden, and the greenhouse. SPV technology converts solar into electricity. In standalone PV systems, nonlinear loads and power electronics cause harmonic difficulties. 50Hz solar systems certain loads provide 50Hz current and voltage [3]. Power system harmonics are higher-frequency electrical pollution. Harmonics impede equipment or system operation. Electrical systems are encountering increased power quality concerns due to nonlinear loads like power converters. Microelectronics can be damaged by harmonics, inter harmonics, flicker, notches, sags, and swells. Gyugi and Strycula devised active filters in 1976 [4]. Active filters can adapt dynamically to system harmonics and reactive power. The Shunt Active Filter reduces distorted load currents so system currents are in phase with voltages. In industrial settings, problems like those above have a higher impact, but in households and businesses, most loads are nonlinear, causing electrical system and sensitive load disruptions. As scattered power generation increases, low-power renewable energy sources like solar are used more, notably in Portugal. This study suggests injecting energy in a sine wave with the right power factor to preserve single-phase power quality. In single phase STATCOM, PI controllers utilizing linear control algorithms provide dc bus voltage reference values. PI controllers require a linear system model. Parameters are set for a certain place and conditions. STATCOM is controlled by FLCs [5]-[6]. This paper presents a robust Fuzzy Logic controller for single-phase STATCOM dc link voltage regulation. Controllers pick inputs depending on dc link voltage faults and variations. External integrator eliminates steady-state inaccuracy in Fuzzy Controller. To test the proposed controller, MATLAB/Simulink models of the power system, STATCOM, and controller are created. The suggested controller is dynamic, accurate, and robust. Fig. 1 shows a system schematic block. The MPPT is connected in series to the solar panels. The MPPT boosts voltage and links non-linear loads to its secondary circuit. Shunt Active Filter reduces current harmonics and power factor while injecting renewable energy for non-linear loads [7].

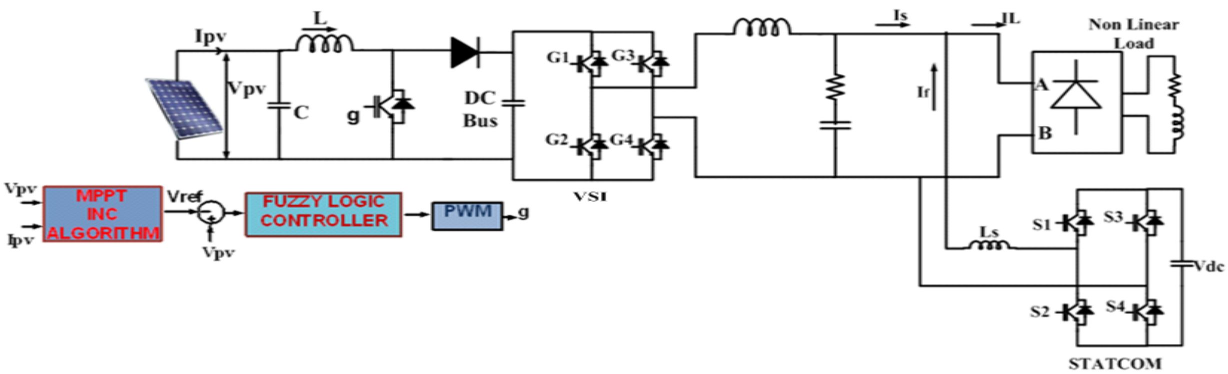

Fig.1 proposed system configuration

The current approach of a PV system employing a passive filter coupled to a full wave bridge rectifier with RL Load was simulated in this research using Matlab/Simulink, as shown in Fig. 2. The simulation is Both a series AC reactor and a series reactor with two single tuned filters to the 3rd and 5th harmonics and a high pass filter to counteract higher order harmonics [8].

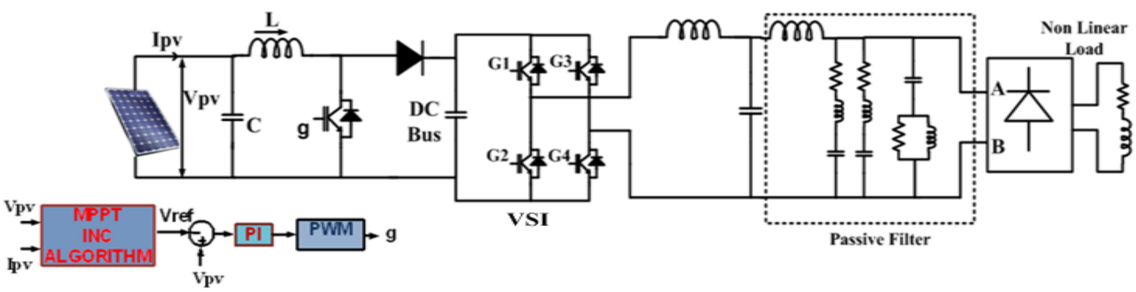

Fig. 2 Passive filter in a stand-alone PV system with a non-linear demand.

An AC reactor in series and composite filters are all studied the voltage and current at the source were analyzed for their harmonic spectra and THD, respectively [9].

II. SYSTEM LAYOUT

Fig. 1 depicts the suggested architecture for a single-phase STATCOM system powered by a freestanding, double-stage solar PV array. In order to establish the rating of a solar PV array, the number of parallel and series modules must be calculated. Other components of the system include a boost converter, a Fuzzy Logic-controlled, voltage source inverter (VSI), AC inductors, an R-C filter, and a non-inductive current controller. In order to regulate the voltage, reactive power compensation using a single-phase STATCOM is possible. When there is a significant voltage imbalance in the supply, STATCOM will switch from reactive power regulation to voltage unbalance correction. For nonlinear loads, STATCOM provides compensation. In most cases, the VSI is connected to the AC inductors and STATCOM compensator. The STATCOM uses a filter to dampen high-frequency switching ripple.

III. CONTROL ALGORITHMS A PHOTOVOLTAIC SYSTEM

The PV cell acts as a diode, with the P-N junction supplying current in proportion to the power of incoming light [10]. A schematic of a PV cell is shown in Fig. 3. Open circuit voltage Voc, short circuit current Isc, maximum peak voltage Vmpp, and maximum peak current Impp are used in the construction of the single-diode PV panel, which is located at the MPP of the I-V curve.

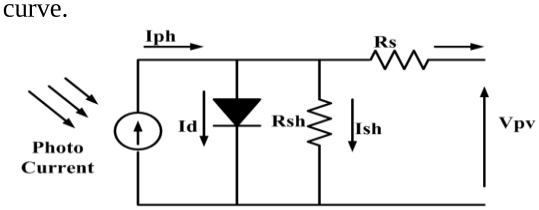

Fig. 3 A solar cell's electrical diagram

The following equation may be used to describe the current produced by the panel, given the circuit:

$$I_{PV} = I_{Ph} - I_d - I_{sh} \quad (1)$$

This is the junction current expressed as a formula:

$$I_d = \frac{I_{sc}+k_1*\Delta T}{\exp\left(\frac{q(v_{Oc})+k_v(\Delta T)}{akT\,N_s}\right)-1} \quad (2)$$

Current through resistor Rsh is equal to:

$$I_{sh} = \left(\frac{V_{Pv}+R_s*I_{PV}}{R_{sh}}\right) \quad (3)$$

- The photo-current, or I_{Ph}
- Id: the reverse saturation current of the diode
- Total number of cells in a series, denoted by Ns
- Current produced by a cell when it is acting as a generator; abbreviated I_{PV}.

- The temperature at which a cell is functioning optimally, expressed in Kelvin as T. (K)
- The voltage across this cell, denoted by V_{PV}.
- Ideality bias K = 1.38e-1023, the Boltzmann constant.
- Electron charge, denoted by q (q = 1,602.1019 C).
- G = w/ m^2 of solar radiation.
- The junction's leakage currents are characterized by a shunt resistance value called R sh.
- The resistance of each link is reflected by Rs, the series resistance.

IV CONSIST OF MPPT DC-DC CONVERTER

The PV panels boost converter, MPPT control, and resistive loads make up the maximum power point tracking system. As shown in Fig. 4, a boost converter regulates the PV panel-to-load current. The MPPT controller's duty ratio output is added to previous results until the system reaches its maximum. Equation (4) ignores internal resistance.

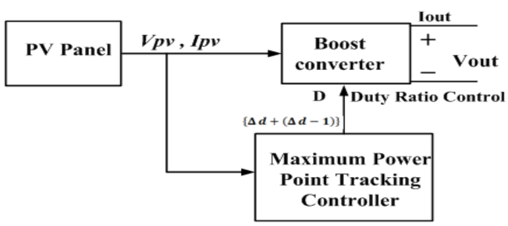

Fig. 4 Diagram Block of MPPT System

$$V_{Out} = \frac{D}{1-D} \quad (4)$$

PV system output power, assuming 100% efficiency from the boost converter and a resistive load:

$$P_{PV} = \left(\frac{D}{1-D}\right)^2 \frac{V_{PV}^2}{R_L} \quad (5)$$

In order to increase PV output power, a DC-DC boost converter was employed to reduce PV voltage (MPPT). Fig. 5 shows the boost converter circuit used to manage maximum PV-to-load power flow.

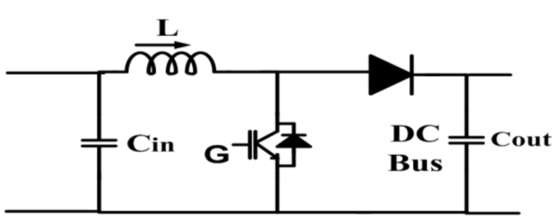

Fig. 5 Boost Converter Circuit

Determine the boost converter's requirements based on the PV. DC-DC boost converter specifications [9]:
The duty cycle equation is as follows:

- Minimum duty cycle

$$\frac{V_0}{V_{in}} = \frac{D}{1-D} \quad (6)$$

- Maximum Duty cycle

$$\frac{V_{0\ max}}{V_{in\ max}} = \frac{D}{1-D} \quad (7)$$

The equation for determining the Boost converter inductance is:

$$\text{Inductor L}= \frac{V_{in}(V_0 * V_{in})}{f_{sw} * \Delta I * V_0} \quad (8)$$

The equation for determining the Boost converter capacitance is:

$$\text{Capacitance C} = \frac{I_o(V_0 * V_{in})}{f_{sw} * \Delta V * V_0} \quad (9)$$

Switching frequency 5KHZs

Current ripple ΔI=5%

Voltage ripple ΔV =1%

A. The "INC" algorithm is an incremental conductance algorithm.

This technique (Fig.6) uses the conductance value and increment to determine the operating point relative to PMP. Increasing conductance reduces duty cycle. Increasing duty cycle if conductance increment is less than opposite. This method is repeated [11].

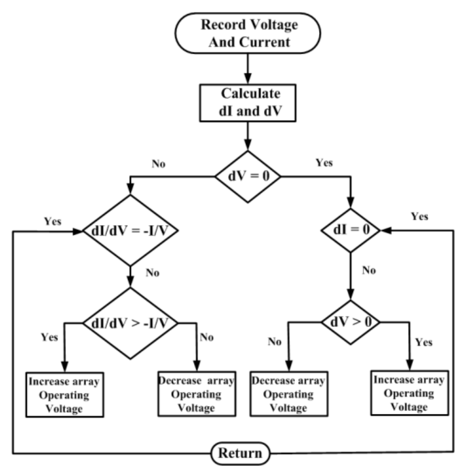

Fig. 6 'INC' algorithm flow chart

$$V_s = V_m \sin(\omega t) \quad (10)$$

$$I_{Load} = I_m \sin(\omega t + \phi) \quad (11)$$

Reactive component = $I_m \sin(\omega t + \phi) * \cos(\omega t)$ (12)

Where $\cos(\omega t)$ from PLL

From this trigonometry formula,

$$\sin A \cos B = \frac{1}{2}[\sin(A+B) + \sin(A-B)] \quad (13)$$

From equation (13) reactive component is

Reactive component = $\frac{I_m}{2}[\sin(\phi) + \sin(2\omega t - \phi)]$ (14)

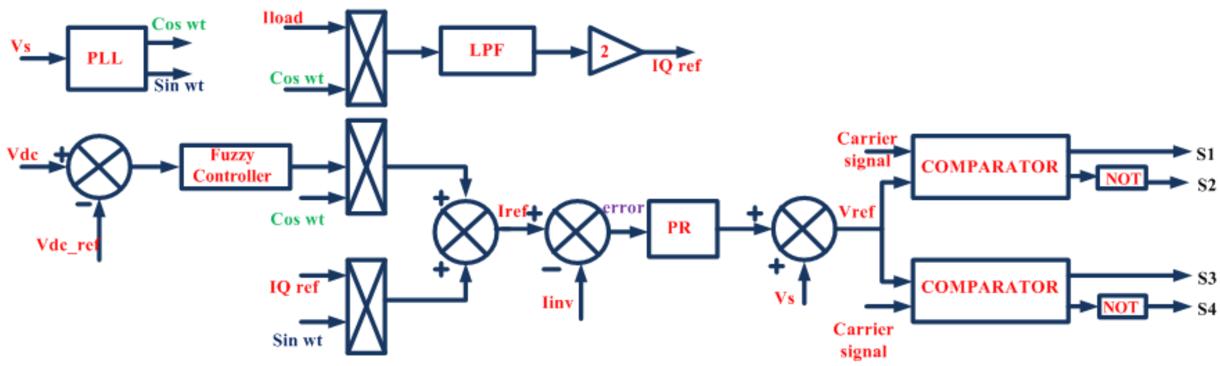

Fig .7 Control Design for STATCOM

$\sin(2\omega t - \phi)$ is high frequency term

Reactive component = $\frac{I_m}{2}(\sin(\phi)) * 2$ (15)

Then we get reactive component is $I_m \sin(\phi)$ as shown in fig.7

B. Design STATCOM inductor:

Maximum permissible voltage drop is

$V = IX_L$

$V = I * 2\pi f * L$ (16)

Voltage drop across inductor = 5% of V_s

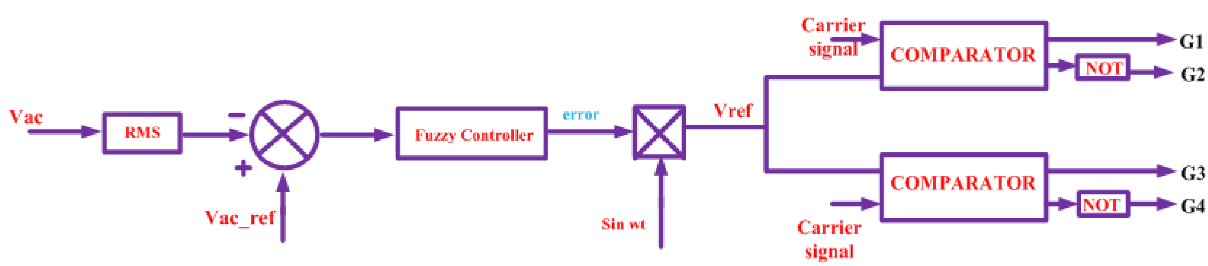

Fig. 8 Control design for VSI

C. Voltage Reference Accuracy Prediction Using Fuzzy Logic Controllers

Due to its flexibility, accuracy, and ability to handle nonlinearities, fuzzy logic controllers have seen widespread application in the past decade. In Fig. 9, we see how the membership function connects the scores of all linguistic factors (represented by circles). Depending on controller precision, the number of membership functions can be anything from 5 to 7 [12]. For the sake of this investigation, we will refer to NB (Negative Big), NS (Negative Small), Z (Zero), PS (Positive Small), and PB (Positive Big) as the fuzzy memberships (Positive Big). the values of a, b, and c are dependent on the range of the input variable (number).

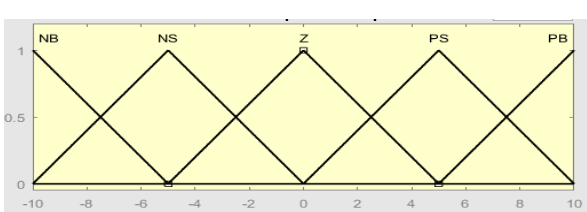

Fig. 9 Fuzzy membership function

Defuzzification is the next-to-last stage of the fuzzy logic controller. Using the membership function, the linguistic outcome is converted to a numeric value. Several methods exist for assigning a numerical value to a verbal one. At the centre of things, popularity. DC voltage and current from the solar array were measured with STATCOM and VSI to calculate the error. Fuzzy logic controllers take in data in the form of error and error drift. The maximum power reference voltage (V ref) is reached by employing the aforementioned fuzzy logic controller and providing the appropriate constant for each error, change of error, and output.

TABLE I. RULE BASE

e|ê	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

V. RESULTS AND DISCUSSION

Matlab/Simulink is used to model a stand-alone PV system consisting of a passive filter, full-wave bridge rectifier, and RL load. A series AC reactor is modelled on its own, as well as with third- and fifth-harmonic single-tuned filters and a high-pass filter for correcting higher-order harmonics. Without a filter, with an AC reactor in series, and with composite filters, we examine the harmonic spectra and total harmonic distortion (THD) of the source voltage and current. Fig. 10. Current and voltage waveforms at the source, before filtering. THD for the source current and load current is shown to be 20.51% and 14.58% for the source voltage in Fig. 11.

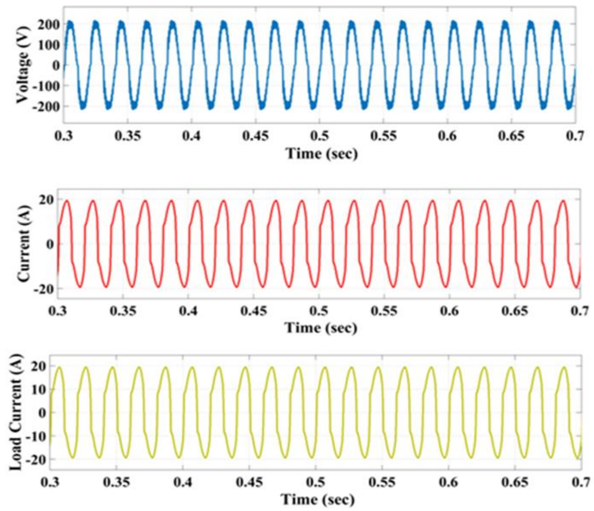

Fig. 10 Currents at the source and at the load, as well as the voltage at the source, prior to any passive filtering.

Waveforms of the source current, source voltage, and load current following a shunt passive filter and a series inductor are shown in Fig.12. Harmonic source current and combined load current are shown in Fig. 13. Combining passive filters improves source and load current THD to 1.26% and 18.75%, and reduces supply voltage to 2.14%.

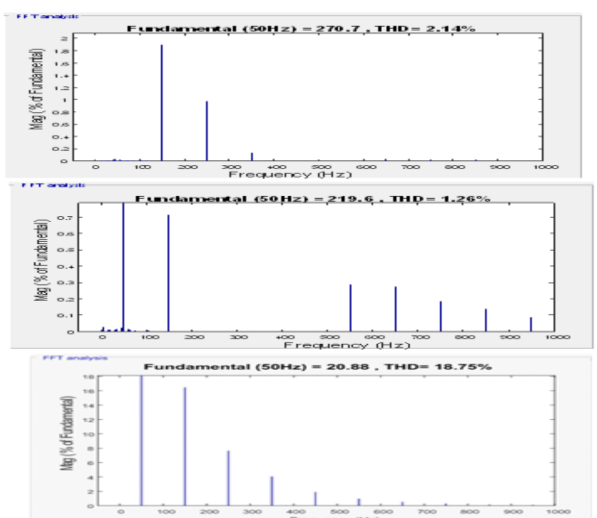

Fig.11 Harmonic Spectrum before passive filtering.

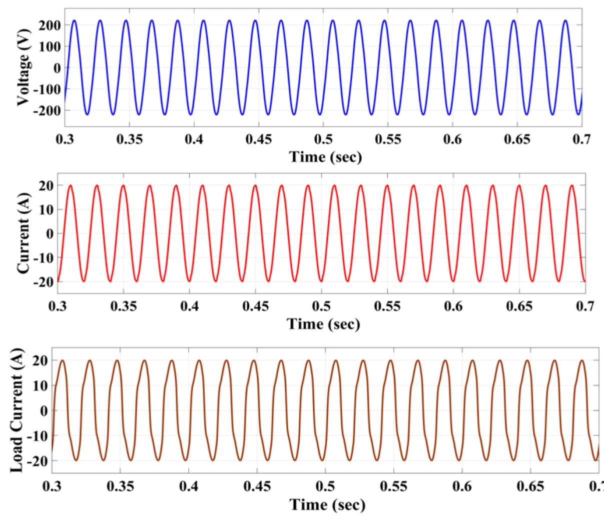

Fig. 12 Source current, source voltage and load current after passive filtering

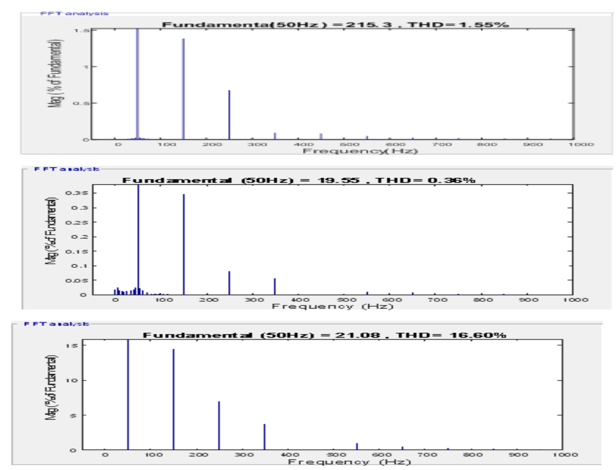

Fig. 13 Harmonic Spectrum after passive filtering

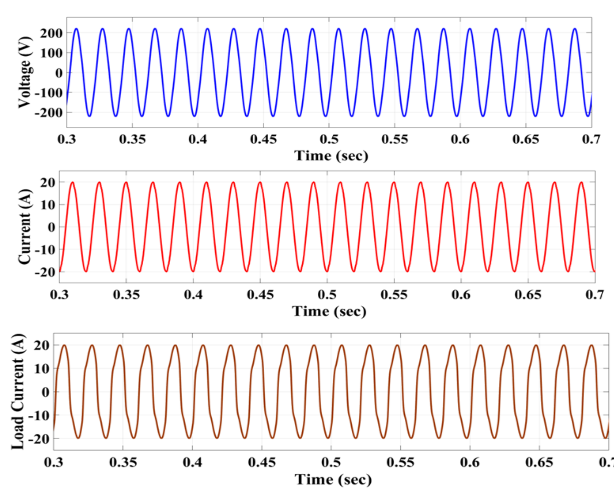

Fig. 14 Source current, source voltage and load current with proposed STATCOM

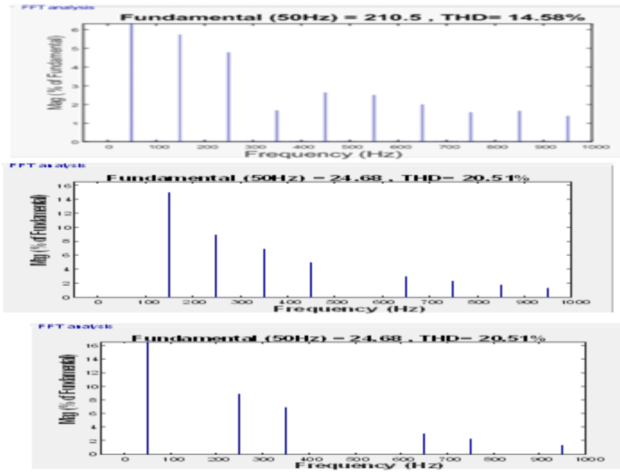

Fig. 15 Harmonic Spectrum with proposed STATCOM.

This study suggests employing STATCOM to improve power quality in a 220V 50Hz single-phase PV system with nonlinear loads. Independent, single-phase PV setup with a nonlinear RL load. In a system with a passive filter and a power factor observer that follows the source and not the load, the power factor is measured after the fact. Fig. 10 shows source side voltage without STATCOM attached. Current source profile shows improvement. Load changes source current power factor and waveform. After connecting STATCOM, system power quality and power factor increased. Simulate system with MATLAB and get results. Fig. 14 shows source side current waveform with STATCOM attached, maintaining unity power factor. This waveform's load can vary, but source current profile cannot. Fig.13 and Fig.15 illustrate FFT analysis without and with STATCOM. In this figure, overall harmonic distortion of the source current is 0.36 percent with STATCOM and 1.26 percent without it.

TABLE II. PARAMETERS USED FOR SIMULATION

LC filter	Lc = 2.25mH, Cc = 4.7 μF
PV source	V_{DC}_Bus=400V, Vs=220V, f =50Hz
Load	RL=10Ω, L_L =25mH
STATCOM	Ls=4.2mH, Cs=3000 μF, Vdc=200V
Boost Converter	Cin=1000 μF, L=1.45mH, Cout=3227 μF

VI CONCLUSION

In this study, a fuzzy logic-based single-phase STATCOM is employed to enhance power quality in a standalone PV system for non-linear loads. The model is simulated in Matlab/Simulink, and the controller performance is assessed using fuzzy logic control for nonlinear and resilient structure and Single phase STATCOM's dc link bus voltage and VSI. This work presents a harmonic mitigation research in a standalone system employing three types of passive filters: single tuned and high pass filters. This passive filter cannot increase reactive power, and other compensating devices are needed to reduce power quality issues and assure voltage sag and swell. The suggested technique can correct for reactive power and harmonics within the power converters' current limits. By employing the suggested Fuzzy-based Single-phase STATCOM control method, the harmonic profile of the compensated source current is maintained even when the converters reach their current limitations.

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