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Power Quality Improvement in Fuel Cell based Hybrid Power System using STATCOM

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ABSTRACT: This paper presents the power quality improvement in a microgrid, supplying a nonlinear and unbalanced load using fuzzy logic controller based static synchronous compensator (STATCOM). The microgrid contains a hybrid combination photovoltaic (PV), fuel cell (FC) along with the battery energy storage system (BESS) where a decentralized power sharing algorithm is used to control its power management. Here, STATCOM is used as a compensator for the hybrid system to reduce the harmonics in the voltage and current profile at the point of common coupling (PCC). The current reference is generated taking into account, the active and reactive power to be supplied by the micro-source which is connected to the compensator. Depending on the power requirement of the nonlinear load, the proposed control scheme can change modes of operation without any external communication interfaces. The proposed control scheme can even compensate system unbalance caused by the single-phase micro sources and load changes. The efficacy of the proposed power quality improvement control and method in such a microgrid is validated through simulation in MATLAB/SIMULINK software with detailed dynamic models of the micro-sources and power electronic converters.

KEYWORDS: Photovoltaic; Fuel Cell; WECS; STATCOM; Power Quality; microgrid.

1 Introduction

The ever increasing energy demand, along with the necessity of cost reduction and higher reliability requirements, are driving the modern power systems towards distributed generation (DG) as an alternative to the expansion of the current energy distribution systems [1]. In particular, small DG systems, typically with power levels ranging from 1 kW to 10MW, located near the loads are gaining popularity due to their higher operating efficiencies. Wind turbines, fuel cells (FCs), photovoltaic cells (PVs), batteries, micro-turbines, etc. are nowadays the most available DGs for generation of power mostly in peak times or rural areas [2]. Over the last few decades, there is a growing interest in wind, FC, and PV system for power generation and it has been identified as a suitable solution for distributed generation [3].

Microgrids are systems with clusters of loads and micro-sources. To deliver high quality and reliable power, the microgrid should appear as a single controllable unit that responds to changes in the system [4]. The high penetration of DGs, along with linear and

non-linear loads, always raises concern about coordinated control and power quality issues. In a microgrid, parallel DGs are controlled to deliver the desired active and reactive power to the system while local signals are used as feedback to control the converters. The power sharing among the DGs can be achieved by controlling two independent quantities: frequency and fundamental voltage magnitude. General introduction to microgrid basics, including the architecture, protection and power management is studied in [5]-[6].

A review of ongoing research projects on microgrid is presented in [7]. Different power management strategies and controlling algorithms for a microgrid is proposed in [8]. Refs. [9]-[10] have evaluated the feasibility of the operation of the microgrids during islanding and synchronisation. An algorithm was proposed in [11] and used for evaluation of dynamic analysis for grid connected and autonomous modes of the microgrid. Nonlinear loads (NL) can increase the harmonic level of the network current and voltage, which will increase the loss and reduce the efficiency of the network [12]. On the other hand, a power

electronic converter can mitigate harmonic and unbalanced load or source problems. In [13] a series-shunt compensator is added in a microgrid to achieve an enhancement of both the quality of power within the microgrid and the utility grid. The method proposed and validated in this paper uses STATCOM. In this work, interfacing distributed generation based microgrid system with the conventional power system is considered. It is a challenge for power system engineer to address the power quality issue i.e. to compensate the distorted voltage at PCC to a greater extent. Here STATCOM is being utilized as a compensator to improve the voltage profile at PCC.

2 System under study

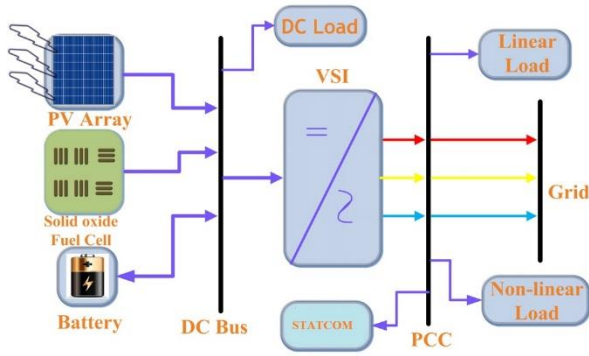


Figure 1: Distribution scheme of a possible micro-grid

The block diagram of the microgrid distribution system under consideration is shown in Fig. 1. The microgrid consists of different DG systems such as FC, PV with BESS and various linear and non-linear loads are connected to the PCC. The distortion in the voltage at PCC is compensated using STATCOM. The voltage source converter (VSC) is controlled based on the fuzzy logic. A power management strategy is adopted to keep the DC bus voltage constant. The parameters of the different components of the hybrid system are in table 1 in the appendix section.

3 System Modelling:

3.1 Solid oxide fuel cell model (SOFC):

The model of an SOFC power plant used in this study is based on the dynamic SOFC stack model developed and validated in [7]. The FC model used in this study is realized in Matlab / Simulink. The following equations (1-7) models the voltage of the FC stack.

$$V_{fc} = N_0 \left(E_0 + \frac{RT}{2F} \ln \left(\left(\frac{P_{H_2} P_{O_2}}{P_{H_2O}} \right)^{0.5} \right) \right) - r I_{fc} \quad (1)$$

With P_{H_2} , P_{H_2O} , P_{O_2} determined by the following differential equations:

$$P_{(H_2)} = -1/t_{(H_2)} (P_{(H_2)} + 1/K_{(H_2)} (q_{H_2}^{in} - 2K_r I_{fc})) \quad (2)$$

$$P_{H_2O} = -\frac{1}{P_{H_2O}} \left(P_{H_2O} + \frac{2}{K_{H_2O}} K_r I_{fc} \right) \quad (3)$$

$$P_{O_2} = -\frac{1}{t_{O_2}} \left(P_{O_2} + \frac{1}{K_{O_2}} q_{O_2}^{in} - 2K_r I_{fc} \right) \quad (4)$$

Where N_0 is the number of series FCs in the stack; E_0 is the standard no-load voltage (V); R is the universal gas constant; T is the absolute temperature (K); I_{fc} is the current of the FC stack (A); F is Faraday's constant; K_{H_2} , K_{H_2O} , K_{O_2} are the molar constants of the hydrogen, water, and oxygen valves, respectively; K_r is the modeling constant; P_{H_2} , P_{H_2O} , P_{O_2} are the partial pressure of hydrogen, water and oxygen, respectively; $q_{H_2}^{in}$ is the hydrogen input flow $q_{O_2}^{in}$ is the oxygen input flow; r is the FC internal resistance (Ω); t_{H_2} , t_{O_2} and t_{H_2O} are the hydrogen, oxygen and water time constants (s), respectively. The K_r constant is defined by the relationship between the rate of reactant hydrogen and the FC current:

$$q_{H_2}^r = \frac{N_0 I}{2F} = 2K_r I \quad (5)$$

Where $q_{H_2}^r$ is the hydrogen flow that reacts. Another important operating variable is the reactant utilization, U_f , referred to as the fraction of the total fuel (or oxidant) introduced into an FC that reacts electrochemically:

$$U_f = \frac{q_{H_2}^{in} - q_{H_2}^{out}}{q_{H_2}^{in}} = \frac{q_{H_2}^r}{q_{H_2}^{in}} \quad (6)$$

Where $q_{H_2}^{out}$ is the hydrogen output flow. A high utilization is considered desirable because it minimizes the required fuel and oxidant flow, for a minimum fuel cost and compressor load and size. Moreover, a simple model of reformer that generates hydrogen through methane has been considered. The model is second-order transfer function. The mathematical form of the model can be written as follows:

$$\frac{q_{H_2}}{q_{methane}} = \frac{CV}{\tau_1 \tau_2 s^2 + \tau_1 + \tau_2 s + 1} \quad (7)$$

3.2 DC/DC Converter Modelling

To connect PV/FC to an external power system, it is necessary to boost the PV/FC voltage or to increase the number of cells. The role of the DC/DC boost converter is to increase the PV/FC voltage, to control the PV/FC power, and to regulate the voltage. Fig. 2 shows the DC/DC converter model. This boost converter is described by the following two nonlinear state space averaged equations

$$\frac{dX_1}{dt} = \frac{1-d}{L} X_2 + \frac{d}{L} U \quad (8)$$

$$\frac{dX_2}{dt} = \frac{-1-d}{C} X_1 - \frac{X_2}{RC} \quad (9)$$

where d is the duty cycle of the switching device; U is the input voltage (V); X_1 is the inductor current (A); X_2 is the capacitor voltage (V).

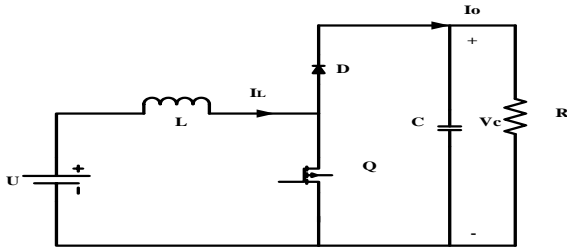


Figure 2: Boost dc/dc converter model

3.3 DC/AC converter modelling:

To interface various energy sources with AC grid and the utility loads, a VSC is used. A pulse width modulation (PWM) is widely used to interface hybrid system to the grid and the utility load. To reduce the harmonics, filters are connected between the converter and the grid. In Fig. 3, V_{abc} is the grid voltage taken as a reference signal to generate the pulses of the inverter. abc to dq theory is adopted for this purpose.

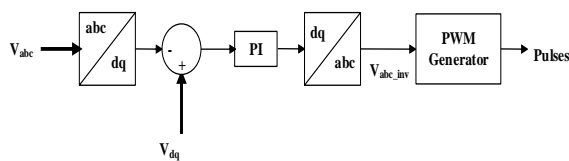


Figure 3: Inverter control strategy

3.4 STATCOM Modelling

STATCOM is a popular device for power quality improvement [14, 15]. The equivalent circuit of the STATCOM is shown in Fig. 4. In this modelling, the resistance R_s in series with the voltage source inverter represents the sum of the transformer winding resistance losses and the inverter conduction losses. The inductance L_s represents the leakage inductance of the transformer. The resistance R_C in shunt with the capacitor C represents the sum of the switching losses of the inverter and the power losses in the capacitor. In Fig. 4, V_{as} , V_{bs} and V_{cs} are the three-phase STATCOM output voltages; V_{al} , V_{bl} and V_{cl} are the three-phase bus voltages.

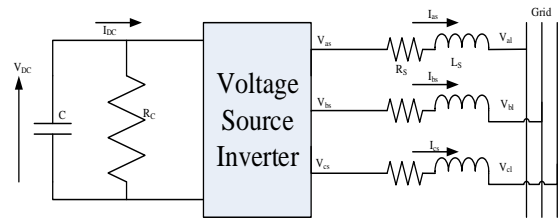


Figure 4: STATCOM Circuit

4 CONTROL STRATEGIES:

4.1 Control of STATCOM Using FUZZY Logic:

Fuzzy logic (FL) control is a new addition to control theory. Its design philosophy deviates from all the previous methods by accommodating expert knowledge in controller design. Fuzzy logic control for STATCOM is described in [16].

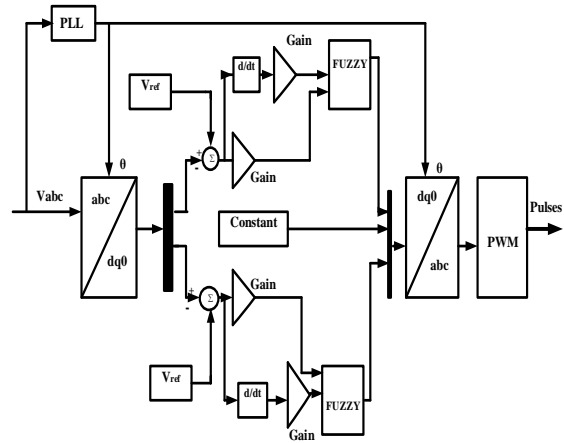


Figure 5: Block diagram for fuzzy controller (voltage regulator)

FL controllers are an attractive choice when precise mathematical formulations are not possible. Other advantages of FL controller are: 1) it can work with less precise inputs; 2) it doesn't need fast processors; 3) it needs less data storage in the form of membership functions and rules than conventional look-up table for non-linear controllers and 4) it is more robust than other non-linear controllers. The FL controller is used as a substitute for the conventional PI compensator. The block diagram of the STATCOM control based on FL controller is similar to the system of Fig. 5, where instead of PI, FL controllers are used.

The voltage error and its derivative are the FL controller crisp input values. The reference voltages for the PWM generator are the FL controller crisp output commands. When an FL controller is used, the tracking error and transient overshoots of PWM can be considerably reduced. This is because, in contrast to the conventional PI compensator-the control surface of the FL controller can be shaped to define appropriate sensitivity for each operating point. The FL controller can easily be implemented as an off-line pre-calculated three-dimensional lookup table consisting of the control surface. For a PI controller, the control parameter is normally fixed so when the operation point of the converter has changed the parameter of the PI are re-designed again. Here the voltage component V_d and its derivative are considered as the inputs of the first FL controller and the voltage component V_q and its derivative are the inputs of the second FL controller. The reference voltages for the voltage regulator are the voltages V_{dref} and V_{qref} . The membership functions are triangular shaped, with 50% overlap for a soft and progressive control adjustment as shown in Fig.6. Each variable has nine membership functions labeled from negative large (NL) to positive large (PL). All variables have the same partition and membership functions.

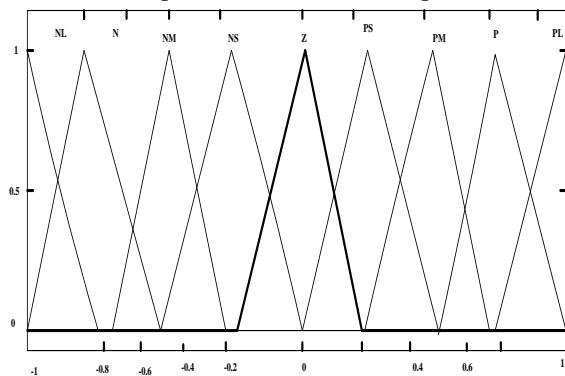


Figure 6: Membership functions

A rule base of 81 rules as shown in fig. Seven is selected to establish the fuzzy controller. With the use of Mandani's implication and with de-fuzzification by a centroid method, the FL controller provides the state of the switching function. Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. The triangular carrier modulation method is used for deciding the appropriate switching patterns for the converter legs. Thus, the gating patterns of the PWM generator can be correctly decided.

e Δe	NL	N	NM	NS	Z	PS	PM	P	PL
NL	NL	NL	NL	NL	NL	NL	N	N	NM
N	NL	NL	NL	NL	N	N	NM	NS	NS
NM	NL	NL	NL	N	N	N	NM	NS	NS
NS	NL	N	NM	NM	NM	NM	NS	NS	NS
Z	N	NM	NS	NS	Z	PS	PS	PM	P
PS	PS	PS	PS	PM	PM	PM	PM	P	PL
PM	PS	PS	PM	P	P	P	PL	PL	PL
P	PS	PS	PM	P	P	PL	PL	PL	PL
PL	PM	P	P	PL	PL	PL	PL	PL	PL

Figure 7: LOOK UP DECISION TABLE

4.2 Power management strategies

Power flow control strategy is decided by mainly charge level of the battery bank also known as the state of charge (SOC). The main objective of this control strategy is to provide a constant voltage to the DC bus. The battery storage capacity should not get deteriorated after repeated charging and discharging cycles. As Power generated by the fuel cell, the solar cell is summed up because of it, if PV is unable to supply power during charging time due to partial shading or inadequate availability of sunlight, fuel cell contributes power, so the cumulative power of these two systems provides redundant power. Thus, the flow of power is decided by finding the battery state of charge, and the minimum and maximum charge levels are defined. Subsequently, it is compared to predefined level of SOC and accordingly charge will flow as shown in the flowchart below (Fig. 9). According to the three cases depicted in flowchart, charging and discharging of battery can be done. In the first and third case charging and discharging of battery occurs respectively. In the

second case where SOC lies between the SOC_{min} and SOC_{max} level, the charging and discharging phenomena depends on the generated power and power consumption.

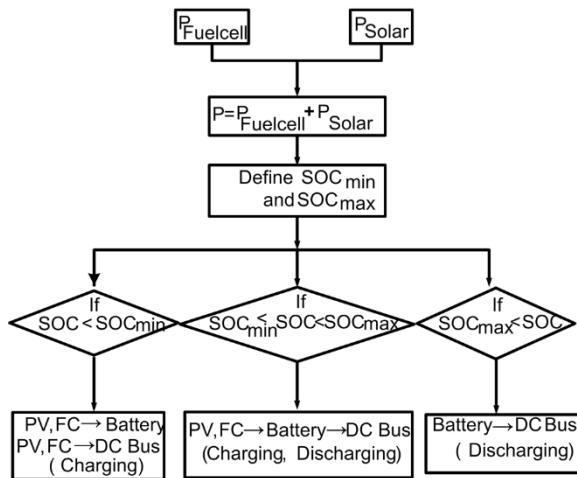


Figure 8: Flow chart of the power management strategies

5 Simulation Results and Analysis

To validate the proposed control strategies, the hybrid system is simulated in Matlab/Simulink. STATCOM is incorporated in PCC to improve the power quality. All the technical data used in simulation process are given in the appendix section in Table I.

Fig 9 shows the DC link voltage of the hybrid system. Due to the sluggish response of fuel cell, DC link voltage maintaining a constant value after 0.5 second BESS with the proper power management scheme helps to maintain DC link voltage constant.

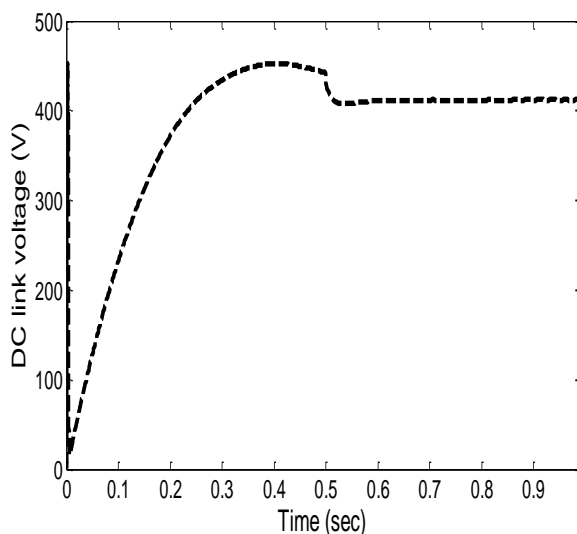


Figure 9: DC link voltage

In this analysis power, quality improvement is also studied. Fig. 10-12 exhibits the power quality improvement with the incorporation of STATCOM at PCC.

A comparative assessment is made of load current with STATCOM and without STATCOM in Fig. 10 with the incorporation of NL balanced load. Fig. 11 provides a clear picture of power quality improvement, where an unbalanced NL load is considered. Thus, the improvement in the current profile at PCC is obvious with the incorporation of STATCOM. Fig. 12 suggests the voltage and current of phase 'A' are about in the same phase, and thus power factor is near to unity (0.95).

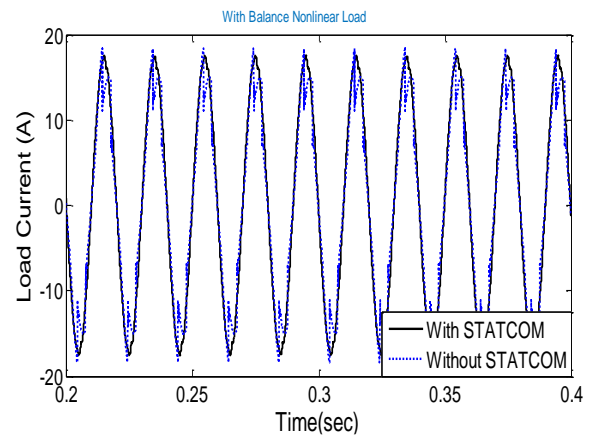


Figure 10: Load Current of phase 'A', with and without STATCOM

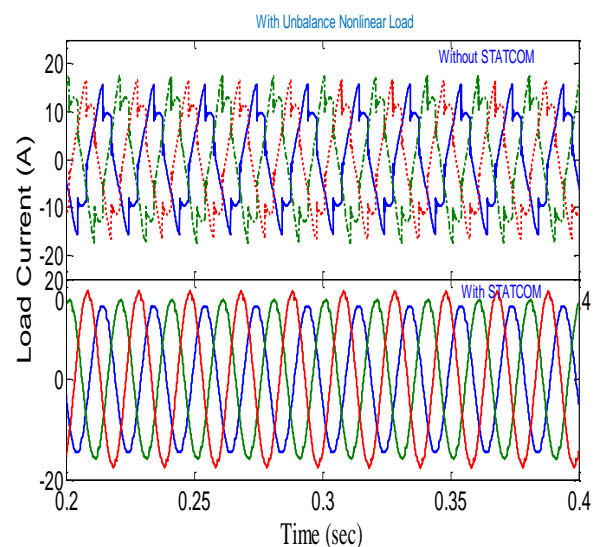


Figure 11: Load Current with the unbalanced non-linear load.

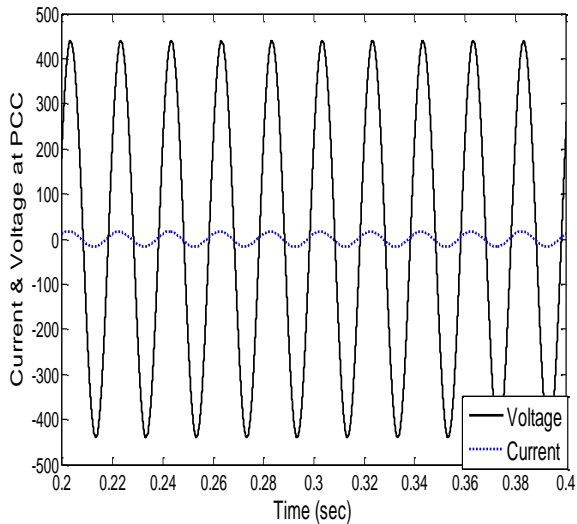


Figure 12: Current and Voltage of phase A at PCC with STATCOM

The FFT analysis for THD of load current (phase 'A') without and with STATCOM is presented in Fig. 13 & 14 respectively. A close observation suggests an appreciable difference in the level of THDs obtained with the incorporation of STATCOM. It is worth to note that even for unbalanced load conditions with STATCOM, the THD level has remained low, and power factor remained high.

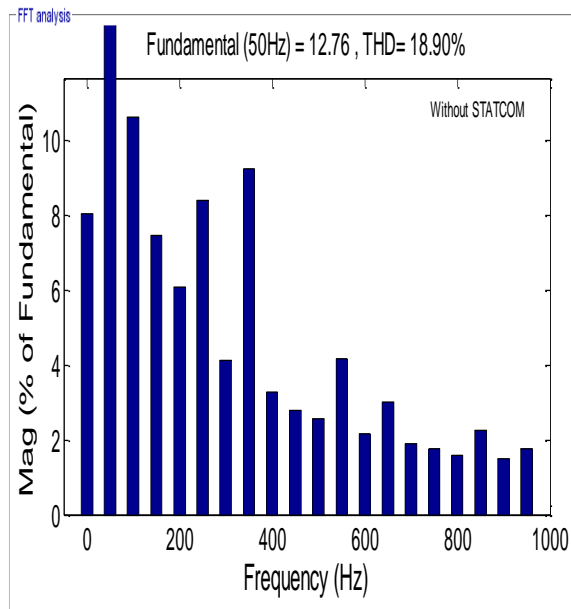


Figure 13: THD of load current without STATCOM.

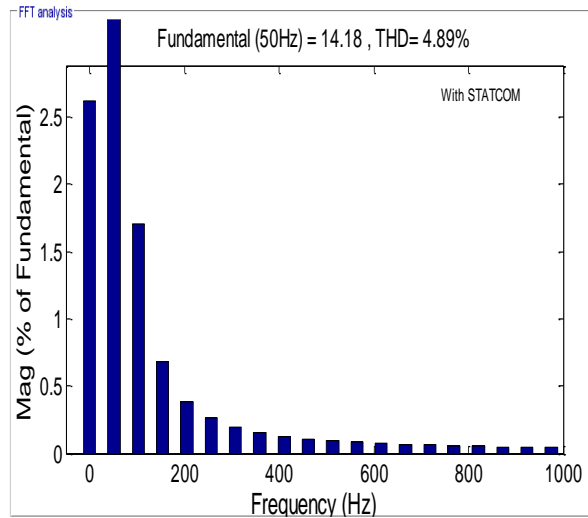


Figure 14: THD of load current with STATCOM.

6 Conclusion

In a grid-connected hybrid system power, quality enhancement is carried out by the suitable design of STATCOM. Different case studies are carried out through series of simulation results to demonstrate the superiority of its design for compensation of distorted signal retrieved at PCC in the presence of various types of a load connected to it. The THD obtained in the presence of STATCOM is less than 5 %, which satisfies the IEEE 519 standard.

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8 Appendix

Grid and Load Types	
Grid Voltage	415 V L-L RMS
Grid Frequency	50 Hz
Grid impedance	R=0.02W,L=0.001H(between each load)
DC load	R=15Ω,L=20mH
Linear load	R=15Ω,L=20mH in each phase
Non linear load	R = 30 Ω, L = 20 mH with uncontrolled rectifier
PV Boost Chopper, Converter and Controller	
Diode ideality factor, A	1.3
Temperature coefficient, CT	0.00023 A/K
Series resistance of cell, Rs	0.0064 Ω
Parallel resistance of cell, Rsh	1573 Ω
Band Energy gap, Eg	1.173 eV
Reference cell temperature, Tref	298 K
Reference Photo current, Iph.ref	3.75 A
Reference solar irradiance, Sref	1000W/m ²
No. of PV cells in series	10
No. of PV cells in parallel	2
Output voltage of Chopper	70 V
Boost Chopper Parameters	L=60mH,C=240μF,fsw =10 kHz
Fuel Cell, Boost Chopper, Converter and Controller	
Fuel cell rated power	10kW
Boost Chopper Parameters	L =1mH, C =1 mF, fsw =10 kHz
Boost Chopper Controller	Open loop control, Switch duty cycle=10%
Converter Structure	3-Phase Voltage Source Inverter
Controller	SVPWM
BESS	
No. of battery units in series	10
No. of battery units in parallel	2

Table 1: Technical Data and Parameters