Harmonic Mitigation Using D-Statcom and Intelligent Controller with Renewable Energy Sources for Improved Power Quality

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***Abstract*—Power quality (PQ) issues are among the most common challenges faced when integrating renewable energy sources into electrical power networks. This paper addresses the enhancement of PQ in a PV system using a Distribution Static Synchronous Compensator (D-STATCOM). The optimal parameters for the D-STATCOM controller are determined using Particle Swarm Optimization (PSO). To evaluate the performance of the proposed system with D-STATCOM, a comparison with conventional device conducted under various operating conditions particularly harmonic distortion. The proposed method's robustness and effectiveness are demonstrated through extensive simulations. The D-STATCOM system and its controller are implemented and tested using MATLAB/SIMULINK. The proposed system can maintain voltage at suitable levels and elevate voltage during events. Additionally, the system achieves a reduction in total harmonic distortion.**

***Index Terms*—D-Statcom , Harmonics, Particle swarm optimization, Power Quality**

I. INTRODUCTION

In recent years, renewable energy (RE) sources have garnered significant attention from academic institutions, industries, and governments worldwide due to their numerous benefits, including enhanced energy reliability and efficiency, and reduced carbon emissions[1,2]. Wind energy and solar photovoltaic (PV) systems are widely used for power generation at the grid level because they offer environmental sustainability, zero fuel costs, low operational costs, and pollution-free electricity production[3,4]. Solar PV energy, in particular, has advantages over wind energy, such as quieter operation and ease of deployment in residential areas. However, it has the disadvantage of being unavailable during nighttime and its output can vary throughout the day[5].

Integrating RE sources into the utility grid presents technical and economic challenges, including issues related to power quality (PQ), reliability, harmonics, voltage stability, control, and protection. The large-scale incorporation of RE sources can also impact frequency control and reserve allocation [6]. Specifically, the integration of PV systems into the grid can lead to operational challenges due to their intermittent nature, affecting frequency and load control, voltage and current imbalances, and the utility network's ability to follow load demand. These factors contribute to PQ issues, such as poor power factor, voltage disturbances, flicker, and harmonic distortions [7].

Various signal processing techniques, including wavelet transform (WT), Stockwell transform (S-transform), Fourier transform (FT), Hilbert Huang transform (HHT), and short-time Fourier transform (STFT), have been employed to identify power quality (PQ) disturbances in grid-connected PV systems. An overview of different methods for detecting PQ disturbances can be found in [8]. Techniques such as WT and S-transform have been used to detect islanding and identify PQ disturbances in renewable energy (RE) integrated hybrid systems due to load rejection, as reported in [9]. The detection of PQ disturbances in a grid-connected 100 kW PV plant using discrete WT is detailed in [10]. Urbanetz et al. [11] conducted PQ analysis for grid-integrated solar PV systems within the Brazilian utility network. Sinvula et al. [12] studied harmonic analysis in grids with solar PV system integration, observing total harmonic distortion of voltage (THDv) and current (THDi) levels as high as 5.5% and 29.6%, respectively. A method for assessing PQ events associated with grid-connected RE sources, focusing on low computational burden during high RE penetration scenarios in distribution systems, is discussed in [13]. The assessment of PQ issues related to grid-integrated wind power plants is covered in [14]. Active and passive filters are commonly used to improve PQ in utility grids with integrated RE sources. A comprehensive description of various PQ improvement techniques is provided in [15]. The study of PQ enhancement in three-phase grid-tied PV systems using battery energy storage systems (BESS) is introduced in [16].

Energy storage technologies have been explored to enhance PV penetration into the grid while addressing power quality (PQ) issues, as noted in [17]. Modern power electronic devices, such as dynamic voltage restorers (DVR), DSTATCOMs, and unified power quality conditioners (UPQC), are increasingly used to improve PQ in hybrid grids incorporating renewable energy (RE) sources [18]. DSTATCOMs offer flexible voltage control at the point of common coupling (PCC) with the grid, aiding in PQ enhancement. When a battery energy storage system (BESS) is integrated in parallel with the DC bus capacitor, DSTATCOMs can manage both active and reactive power exchanges with the grid. The power variations mentioned above can be mitigated by adjusting the amplitude and phase angle of the converter voltage relative to the line's terminal voltage, as discussed in [19]. This approach improves the dynamic performance of systems through voltage regulation and frequency control. BESS further augments DSTATCOM's capabilities, enabling load balancing, reactive power compensation, and harmonic current elimination.In [20], a hybrid grid design incorporating wind energy, solar energy, loads, BESS, and conventional generators was proposed to minimize the effects of grid disturbances. DSTATCOM plays a key role in reducing the variability of power generation caused by the intermittent nature of RE sources. The implementation of DSTATCOM for various applications—such as solar PV generation, wind power generation, water pumping systems, load compensation, and residential low-voltage networks—has been documented in the literature. However, there is limited research focusing specifically on the use of DSTATCOM to improve PQ for grid-integrated PV plants.

The use of a DSTATCOM controlled by an adaptive neural network-based control method for harmonic suppression, load balancing, and voltage regulation in isolated distributed generation systems has been explored in [21]. Shahnia et al. [22] discussed the application of DSTATCOM for managing excess power in medium and low voltage distribution networks interfaced with single-phase renewable power generation systems. Mahela et al. [23] proposed a method to enhance power quality by using DSTATCOM integrated with a battery energy storage system (BESS) in a hybrid utility grid with renewable energy (RE) penetration, demonstrated through simulation studies.

The literature review highlights a research gap that needs to be addressed, particularly for future smart grids with high levels of solar PV plant penetration. A critical review of the existing research reveals that various techniques have been reported for detecting power quality (PQ) events in utility grids connected to RE sources. Additionally, there has been a focus on studying PQ disturbances associated with the design constraints of converters used in grid integration of solar PV panels. While improvements in PQ for isolated operation of solar PV plants have been studied, this paper extends previous research [23] by considering PQ enhancement during operational events in utility grids integrated with solar PV plants.

The paper is organized as follows: Section II harmonic distortions III presents principle of DSTATCOM. Section IV deals with particle swarm optimization Section V PI controller. Section VI provides the simulation setup, and result and discussion of the proposals. Finally, the conclusions are presented in the last section.

II. HARMONICS-DISTORTIONS

One of the notable power quality (PQ) issues is harmonic distortion, which is the periodic deviation of current or voltage waveforms from a smooth sinusoidal shape. This distortion occurs when multiple integer frequencies of the fundamental frequency are present in the waveform of the current or voltage. Harmonics are essentially multiples of fundamental frequency, and total harmonic distortion (THD) is a measure of the extent of these distortions in the waveform.

Harmonic-related problems often arise from nonlinear loads, such as electronic devices and equipment that do not utilize a standard sinusoidal voltage or current waveform. Examples of these include computers, televisions, arc furnaces, arc welders, mercury lamps, battery chargers, variable speed drives, medical diagnostic equipment, and fluorescent lamps. Sources of harmonics can include resonance phenomena, switch mode power supplies, transformer saturation, light dimmers, among others.

Harmonic distortions can cause significant damage to transmission and distribution systems as well as consumer equipment. The most common effects of harmonic distortion include nuisance tripping of circuit breakers, overloading of electric motors, malfunctioning fuses, overheating of transformers and motors, tripping of variable speed drives, and incorrect power measurements, which can lead to failure or damage to electrical equipment such as capacitors and contactors.

To mitigate harmonic distortions, passive filters, active conditioners, and isolation transformers are commonly used. Additionally, electrical devices with built-in power factor correction can help reduce harmonic distortion. FACTS devices such as Static Var Compensators (SVC), Dynamic Voltage Restorers (DVR), and Distribution Static Synchronous Compensators (DSTATCOM) are also employed to reduce THD in electrical power systems.

III. PRINCIPLE OF D-STATCOM

A D-STATCOM (Distribution Static Synchronous Compensator) is a device that provides controlled reactive power, comprising a Voltage Source Converter (VSC) and a DC link capacitor connected in shunt shown in figure 1. It can generate or absorb reactive power. The operating principles of a D-STATCOM are analogous to those of a traditional rotating synchronous compensator. The AC terminals of the VSC connect to the Point of Common Coupling (PCC) via an inductance, which can be either a filter inductance or the leakage inductance of a coupling transformer. The DC side of the converter is linked to a DC capacitor, which serves as the primary reactive energy storage element and handles the converter's input ripple current. This capacitor can be charged by a battery or recharged by the converter itself.

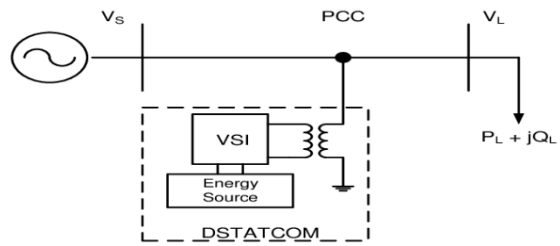

Fig.1.STATCOM

When the VSC output voltage matches the AC terminal voltage, no reactive power is exchanged with the system. If the VSC output voltage exceeds the AC terminal voltage, the D-STATCOM operates in capacitive mode, and if it is lower, it operates in inductive mode. The amount of reactive power flow is determined by the difference between these two voltages. For voltage regulation at the PCC, the D-STATCOM should adjust the supply currents to lead the supply voltages. For power factor correction, the supply currents should be in phase with the supply voltages. This paper explores control strategies to evaluate the performance of a D-STATCOM in achieving power factor correction and harmonic mitigation.

IV. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a population-based optimization technique where each potential solution, represented as a particle, 'flies' through the solution space. The quality of each solution is assessed using a fitness function [16]. As the algorithm progresses, some particles find positions that are better than others, moving towards optimal solutions until a stopping criterion is met. This criterion can be either achieving an optimal state or reaching a predetermined number of iterations. Each particle adjusts its position in the space based on its own best-known position, as well as the best position found by any particle in its neighborhood. Typically, all particles are aware of their own best positions and the best position among all particles. The particle's velocity vector is updated according to a specific equation (1).

$$\overline{v_i}(t+1) = w\overline{v_i}(t) + c_1r_1(\,pbest_i(t) - \overline{x_i}(t)) + c_2r_2(\,gbest_i(t) - \overline{x_i}(t)) \qquad (1)$$

In the PSO algorithm, w represents the inertia weight factor, $\overline{v_i}(t)$is the particle's previous velocity, and $\overline{v_i}(t+1)$is the particle's current velocity. The constants c1c_1c1 and c2c_2c2 are known as acceleration coefficients. The term "pbest" refers to the best solution found by an individual particle, indicating the particle's tendency to repeat its successful past behaviors. "Gbest" denotes the best solution found by any particle in the entire population, reflecting the particles' tendency to emulate the success of others. After updating the velocity, each particle moves to a new position *xi* (*t*+1) from *xi* (*t*), as described by equation (2).

$$\overline{x_i}(t+1) = \overline{x_i}(t) + \overline{v_i}(t+1) \qquad (2)$$

If the goal of optimization is the minimization of the objective functions '*f*' then both $pbest_i$ and $gbest_i$ are updated by equation (3) and (4) respectively.

$$pbest_i(t+1) = \begin{cases} pbest_i(t+1) \text{ if } f\ (pbest_i(t+1) \le f(\overline{x_i}(t+1) \\ \overline{x_i}(t+1) \text{ if } f\ (pbest_i(t+1) > f(\overline{x_i}(t+1) \end{cases} \qquad (3)$$

$$gbest_i(t+1) \in \{pbest_1(t+\ 1) \dots\dots pbest_n(t+1) \qquad (4)$$

$$f(pbest_i(t+1) = min\{f(pbest_1(t+1) \dots\dots f(pbest_n(t+1))$$

The inertia weight can be set according to the following equation (5)

$$w = w_{max} - \frac{w_{max} - w_{mix}}{I_{max}} I \qquad (5)$$

Where $w_{\text{max and}}$ win maximum and minimum weight.

V. PI CONTROLLER

All control systems aim to minimize the error between the actual output and the reference value, ideally bringing it to zero. In a PI controller, the error signal is input to the controller, and the goal is to reduce this input to zero. The error trajectory depends on the initial value, the system's installation properties, and the characteristics of the proportional (Kp) and integral (Ki) parameters in the PI controller. The constants Kp and Ki are crucial in correcting errors and optimizing performance metrics, such as overshoot, transient duration, oscillations, and steady-state error, for a system with a given transfer function. When analyzing a system, Kp and Ki can be selected through trial and error. However, more complex systems with stringent transfer function requirements necessitate specialized tuning methods. Technologies like Particle Swarm Optimization (PSO) can efficiently manage numerous control equations and constraints, identifying optimal solutions. This study demonstrates how PSO can iteratively find the best Kp and Ki values for the PI controller. The primary goal of tuning the PI controller is to achieve acceptable voltage and Total Harmonic Distortion (THD) levels per IEEE standards. The tuning process involves a two-dimensional search for Kp and Ki values.

VI. RESULT AND DISCUSSION

The entire work is done with PSO algorithm initially which is used for navigation of data of DSTATCOM controller coordinately with the help of equations .The simulation is carried out using MATLAB tool box in accordance with the procedure. PSO used here is built on searching the values of appropriate values of impedance and firing angle required for mitigating harmonics. Few modifications are done in range number, technique to control and change in selection criteria technique. Initially the set of impedances, firing angle alpha, change in impedance and firing angle from input variables . At the end of simulation the changes in the electrical parameters is been checked.

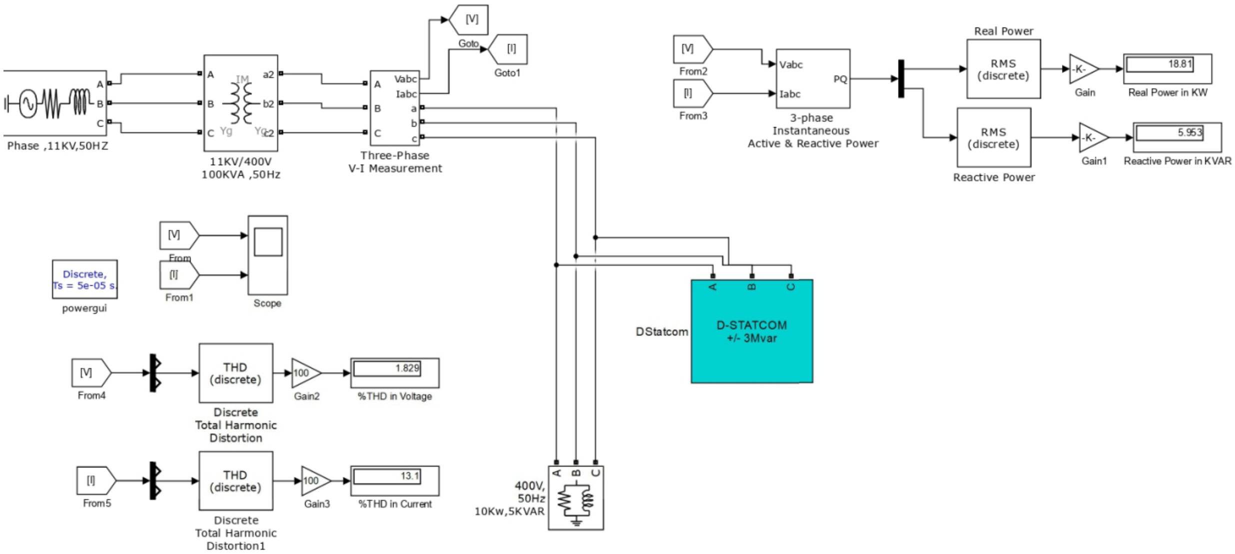

Fig. Single line diagram

In PSO implementation, initially step by step initialization of various function variables were done, then setting of fitness function variable boundary. Combination of different variables sets were generated within the boundary which is equal to the number of population size. In first iteration, required I^{st} variable combination were given to PSO fitness function. After the completion of the fitness function process, as a result it gives return cost value, which in turn related to the required electrical parameters values. At this point input variable combination and return cost is been saved for further process.

This process is been repeated with other variables combinational sets. The better cost that is expected ranges of electrical parameter values is been arrived after the completion of all variables. For better values, finding local ranges at its parameter s necessary . Then second set of variable combination sets were generated from last local and global parameters. The entire process must be repeated for remaining iteration. At the end of each and every iteration , finding out local global parameter is very much important from previous global and current local values with its parameters. After the completion of all iteration ,to find global values and its parameter is been used in the functioning of DSTATCOM to minimize the harmonics.

The optimal values for Kp and Ki in the D-STATCOM PI controllers were determined using Particle Swarm Optimization (PSO in a PV system. Following compensation with the adjusted D-STATCOM, the Total Harmonic Distortion (THD) was reduced from 17.02% to 1.24%, as illustrated in fig. 3 to fig.8. This THD level is deemed acceptable according to IEEE standards .

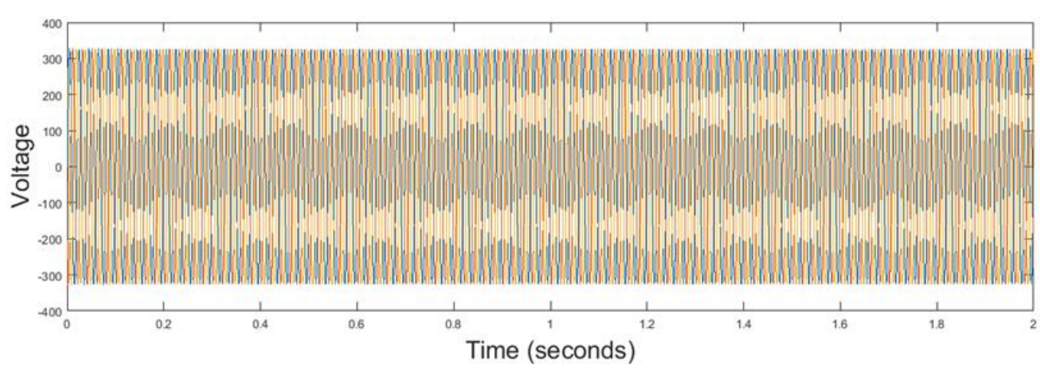

Fig.3.Voltage Magnitude

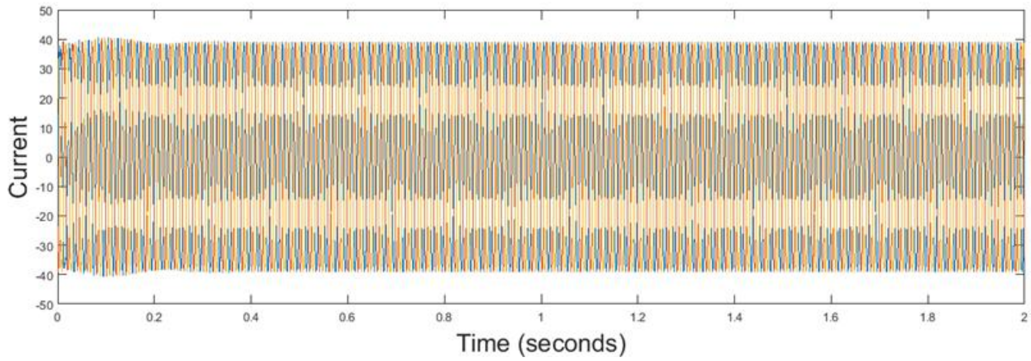

Fig.4. Current Magnitude

In scenarios involving voltage swell, the D-STATCOM effectively reduced the Point of Common Coupling (PCC) voltage. Additionally, after compensation with the D-STATCOM, PCC voltages were balanced and met acceptable standards during various short circuit faults and overload conditions.

In cases of sudden heavy load addition, the D-STATCOM successfully increased the voltage magnitude. Compared to other FACTS devices, the D-STATCOM is considered one of the most effective, offering rapid voltage control. It can maintain full compensation current even at low line voltages and manage output power through self-generation or reactive power absorption, providing effective power oscillatory damping.

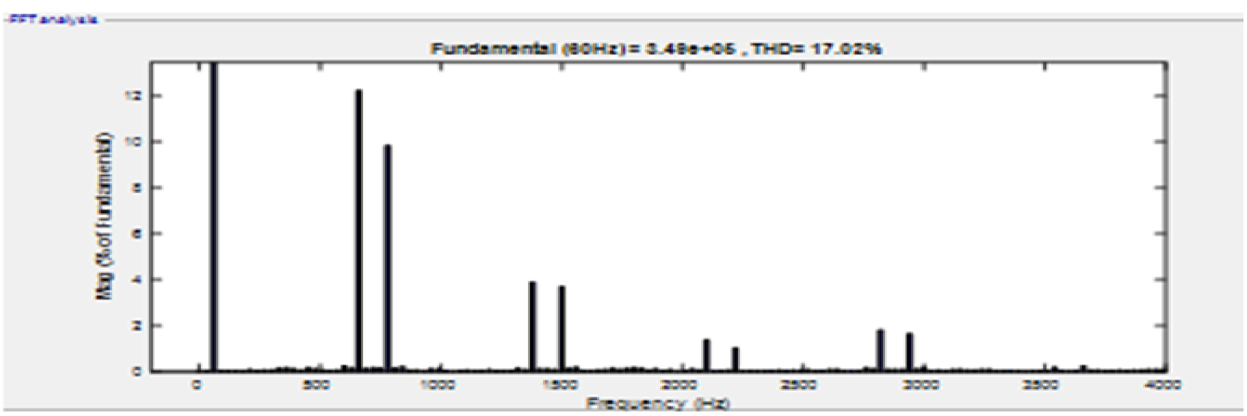

Fig.5 The Voltage THD without DSTATCOM

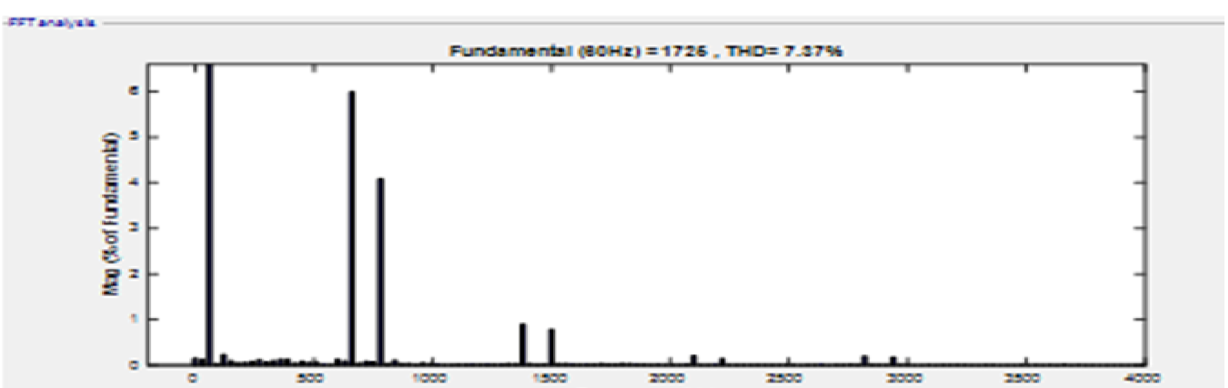

Fig.6 The Current THD without DSTATCOM

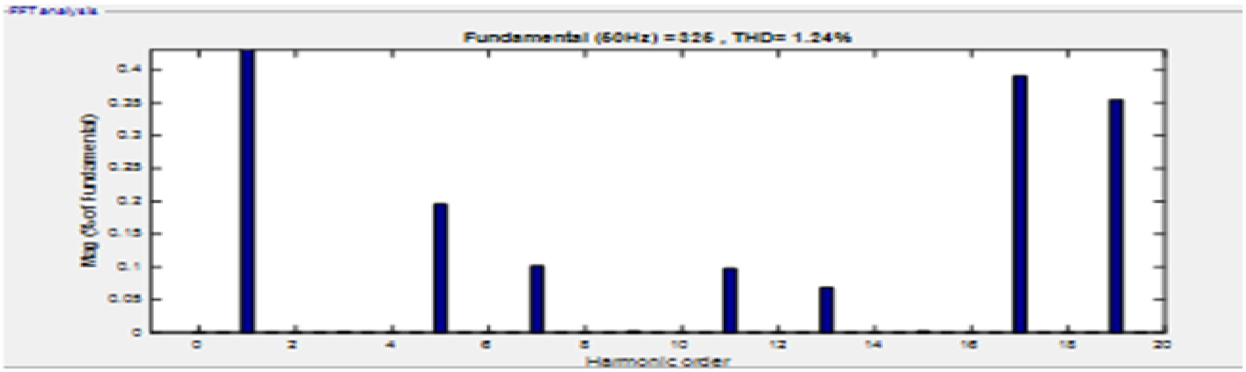

Fig.7 The Voltage THD with DSTATCOM

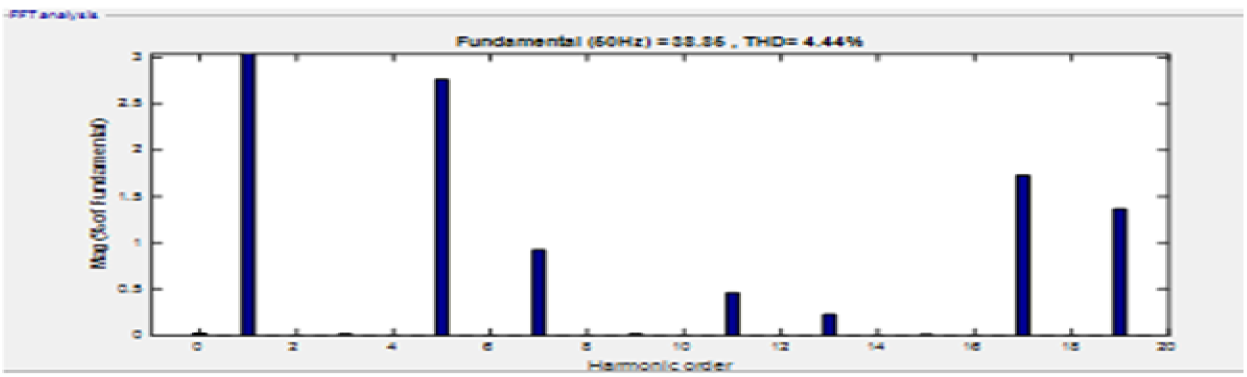

Fig.8 The Current THD with DSTATCOM

VII. CONCLUSION

This paper presents the modeling and simulation of a D-STATCOM integrated with a PV system using MATLAB/SIMULINK software. The D-STATCOM is employed to mitigate harmonic distortion, with its PI controller tuned using Particle Swarm Optimization (PSO) techniques. Additionally, the D-STATCOM is utilized to address voltage profile improvement resulting from sudden heavy loads and short circuit. Simulation results indicate that the D-STATCOM effectively mitigates harmonic distortion, voltage sag, and voltage swell. It demonstrates superior voltage recovery performance compared to the SVC. Specifically, the total harmonic distortion (THD) with the D-STATCOM reduced with the conventional controller.

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