



HIL Investigations on Intelligently Tuned PV Integrated DSTATCOM to Enhance Power Quality

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Abstract

Power quality management is a widespread requirement in this renewal energy source (RES) integrated environment. A few of the key challenges faced during power quality management are total harmonic distortion (THD), poor power factor and reactive power compensation. This paper tries to improve these power quality issues using synchronous reference frame (SRF) theory-based distributed static compensator (DSTATCOM). An Adaptive Neuro-Fuzzy Inference System (ANFIS) algorithm has been used to optimize the operation of the DSTATCOM and to obtain maximum power from a PV array. This algorithm optimizes the requirement of compensating current from the PV fed DSTATCOM to make the source current smoother. System dynamic performance is investigated in the presence of balanced/unbalanced nonlinear and reactive loads. The results obtained using ANFIS- and SRF-based methods are compared to other conventional/AI-based methods and found to be superior. The proposed method is validated in real time using Opal-RT on FPGA computation engine to closely emulate actual hardware.

Keywords DSTATCOM · ANFIS · THD · MPP · Photovoltaic array · Power quality

List of Symbols

I_{qs}	Load current of Quasi-square waveform	V_{PV}	PV voltage
I_0	Line current	C_{PV}	Boost converter capacitance
I_{qs1}	Fundamental component of load current	L_{PV}	Boost converter inductance
$I_{DSTATCOM}$	Current rating of DSTATCOM	I_{La}, I_{Lb}, I_{Lc}	Load current
V_p	Phase voltage	V_{La}, V_{Lb}, V_{Lc}	Grid voltage
V_{DC}	DC link voltage	I_d and I_q	Dq0 frame current components
m_a	Modulation index	I_{sa}^*, I_{sb}^* and I_{sc}^*	Park's transform current
C_{DC}	DC link capacitance	I_{spp}	Reference current
ΔE	Change in stored energy	V_{DC}^*	Reference DC link voltage
L_s	Interfacing inductance	V_{DCe}	Error in DC link voltage
I_{crp}	Ripple current	K_p	Proportional constant
f_s	Switching frequency	K_i	Integral constant
V_{IGBT}	Voltage rating of IGBT	E_r	Error signal
V_d	Voltage overshoot	ΔE_r	Variation in error signal
I_{IGBT}	Current rating of IGBT	$\mu(X)$	Membership function
		I_c	Compensating Current
		I_s	Source current
		I_l	Load current
		V_s	Source voltage

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1 Introduction

Harmonic distortions would become extremely important in the future due to widespread usage of power electronic-based gadgets. These distortions result in shorter life of power equipment/power appliance, increased power losses and instability. Further, in this deregulated competitive power market, the customer is inclined to pay/choose for a high-quality power that propels distribution companies to improve the level of power quality. The degradation in power quality calls for proper harmonic mitigation methods. The active power filter (APF) is mostly used as compensating controller due to its small size and flexible tuned setting against passive filters.

The APF is used to mitigate both current-related and voltage-related power quality issues like, dynamic voltage regulator (DVR), distribution static compensator (DSTATCOM) and unified power quality conditioner (UPQC). Singh and Solanki reviewed all possible configurations of APF to minimize total harmonic distortion (THD) and meet out reactive compensation while considering economic and technical aspects [1]. They suggested that by using suitable APF at the load end, consumer can maintain the power quality at acceptable levels even with the nonlinear load.

This paper focuses on current harmonic problems like poor power factor, poor voltage regulation and unbalance current. The shunt type compensating controllers are the most suitable controllers to mitigate these problems. Various types of controllers have been used in the literature to improve the power quality and some of them are briefed here. Li et al. developed a magnetically controlled reactor (MCR) based on single loop voltage control system (SLVCS) to mitigate power demand oscillation by providing required compensating power and improved the voltage profile of power system [2]. Mehmood et al. analyzed magnetically controlled reactors (MCRs) to improve the power quality by provide compensating reactive power and suppress power frequency overvoltage operations [3]. The performance of magnetically controlled reactor can improve with the use of rapid magnetization and demagnetization strategy [4]. Panwar et al. and Dehini et al. used DSTATCOM to minimize THD of source current and supply compensating current to the grid for minimizing voltage sag and swell [5, 6]. Gupta et al. and Latran et al. used various configurations of DSTATCOM for high voltage distribution system and dynamically minimized the power quality problems [7, 8]. Hurkadli and Kulkarni reviewed the various configuration of DSTATCOM for 1-phase and 3-phase systems and proposed a novel control algorithm to increase the compensation capability of DSTATCOM [9]. Jain and Jain improved the power quality by developing

smaller sized and lesser rated DSTATCOM using Star/Delta and Zig/Zag transformers [10]. Singh et al. developed the model of DSTATCOM and battery energy storage system (BESS) using MATLAB/Simulink and analyzed the simulation results with the load variation in power system [11].

The performance of compensating controller, DSTATCOM can be improved significantly by integrating it with renewal energy source (RES). Out of various renewal technology the photovoltaic (PV) technology is preferred due to wider availability of solar irradiation, less moving part, less location dependency and wider commercial availability.

The role of PV technology is not only to improve the performance of compensating controller but also it supplies active power to the grid during peak hours. With the integration of PV systems [12], it provides efficient and carbon emission free operation

The PV integrated system operates in two stages. In first stage, maximum power point (MPP) is tracked and in second stage it provides unbalance current compensation and THD minimization. Kumar and Prabhu developed a fuel cell integrated DSTATCOM to minimize harmonics in source current, balance the load, provide reactive power compensation and support active power during peak load hours [13]. Pulikkal and Rathi simulated a PV integrated DSTATCOM using IcosΦ algorithm and mitigated the source current harmonics under balanced/unbalanced nonlinear loads [14]. They used PI control algorithm to control DC link voltage for smoothing the source current. Ramadan et al. developed PV- DSTATCOM for a distribution network [15]. They analyzed different penetration levels of PV system and optimum location of DSTATCOM for improving the power quality. Maheswari and Gowri developed a RES integrated DSTATCOM for improving the power quality [16]. They integrated solar and wind energy systems as RES and used reactive power theory (IRPT) with hysteresis loss current control algorithm for obtaining MPP. Mishra and Ray developed prototype system of PV supplied DSTATCOM-based sliding mode controller to minimize THD, regulate the voltage level of the grid by supplying required reactive power and satisfy the load demand by supplying required active power to the load [17]. They reduced the capacity of PV systems using LCL filters. Lekouaghet et al. compared different type of multilevel inverter to obtain MPP of PV systems based on modified InC algorithm and found out that 3 level VSI tracked the MPP in a better way with minimum harmonics [18]. Ali and Salimi designed a PV integrated APF based on Fourier transform technique and minimized 33% inverter switching [19]. They used common VSC for both APF and MPP. Mariappan et al. modeled a PI tuned single stage solar inverter for improving the power quality and increased the efficiency of solar inverter from 90.8% to 94% [20]. Hassan et al. designed fuzzy logic-based controller for an off-grid



PV system to minimize the THD as per the standard of IEEE. They have also configured the converter as push-pull boost converter and obtained MPPT accuracy regardless change in irradiance [21]. Dadge et al. compared various types of indirect, direct control and AI-based MPP controls [22]. They concluded that indirect methods are simple and cheaper but are not able to extract MPP perfectly from solar system, direct methods are more suitable with varying load and require less memory as compared to indirect method but are not comfortable to extract the MPP during variation in solar array parameters. The AI-based methods are able to extract MPP with the variation in solar array parameters, supply/load voltage fluctuations and do not require any mathematical modeling, but the algorithms become complex during heavy partially shaded conditions.

Power quality improvement is largely influenced by the control techniques used with compensating controller. PV integrated APF can be modeled and controlled by different types of time and frequency domain controllers to improve power quality. Mehmood et al. used artificial neural network (ANN) to optimize the power generation, managed the power demand oscillations, and improved the voltage profile of power system [23]. Soares et al. developed an APF-based instantaneous active-reactive current (i_d - i_q) technique and improved the steady state and transient performance of distribution system [24]. Mangaraj et al. controlled a DSTATCOM using ANN and improved the power quality in distribution network [25]. They found that ANN-based results are better than PI-based results. Wang and Zhu designed a small sized transformer-isolated multilevel H-bridges DSTATCOM tuned none zero sequence optimal algorithm and

minimized negative sequence load current [26]. Chawda and Shaik developed a DSTATCOM using adaptive linear neural network-based (ADALINE) least mean square (LMS) control algorithm and improved the power quality successfully during multifarious load in weak AC grid [27]. Wang and Fei developed an APF tuned using radial basis function neural network (RBFNN) fuzzy control technique [28]. They used RBFNN to approximate the nonlinearities of the APF model and adaptive fuzzy system to compensate the network errors. Liu et al. proposed a phase-locked loop (PLL) control algorithm to reform the voltage/current signal from unbalanced status to balanced status before any power synchronization [29]. Qasim et al. developed an APF based on phase-locking control technique and minimized THD below 4% while maintaining unity power factor [30]. Amoozegar modeled a DSTATCOM employing Proportional Integral (PI), Fuzzy logic control (FLC) and Fuzzy-PI controller for improving the power quality [31]. They found out that the problems of conventional PI controller like requirement of mathematical modeling and self-tuning can be overcome by FLC. Zahira and Fathima reviewed various control techniques like fixed frequency control, synchronized filtered-X algorithm-based adaptive control, delta modulation, dead-beat current control, neural networks control, fuzzy logic control and wavelet control techniques to compare their performance in improving the power quality [32]. Sakthivel et al. improved dynamic performance of APF using Ant colony Optimized PI control algorithm [33]. Ghamri et al. compared the performance of different controllers like PI controller, backstepping controller and improved backstepping controller in improving the performance of APF and

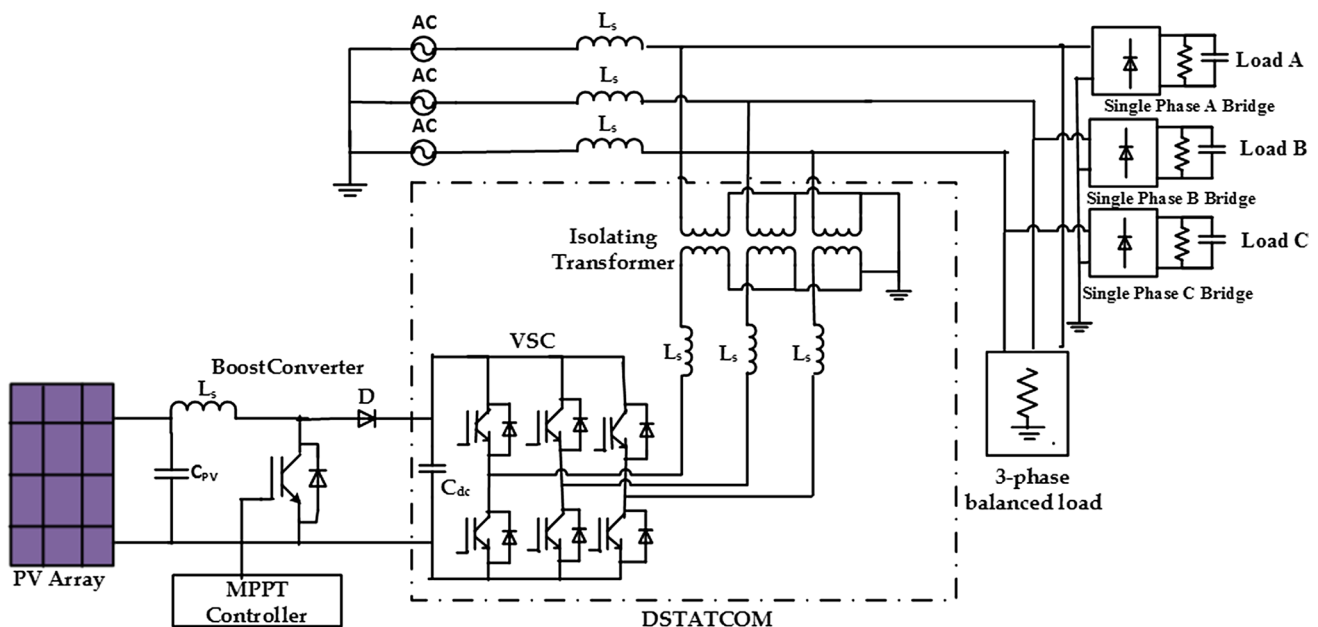


Fig. 1 Configuration of PV fed DSTATCOM



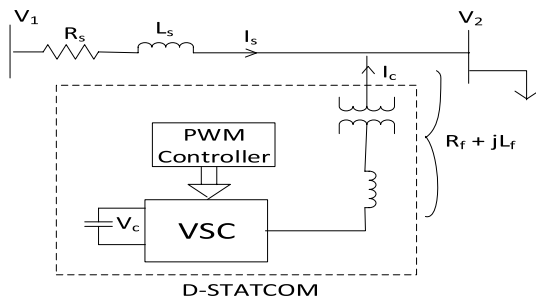


Fig. 2 Schematic of DSTATCOM

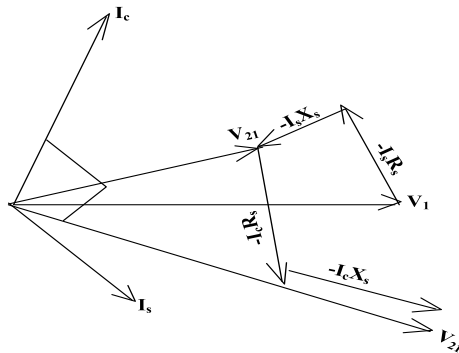


Fig. 3 Phasor Diagram of DSTATCOM

concluded that improved backstepping controllers are suitable when the load is under dynamic regimes and PI controllers are suitable under static regimes [34]. They simulated the proposed model and improved the settling time. Hou and Fei modeled 3-phase APF by using first backstepping controller (BC) then simulate an adaptive fuzzy backstepping controller (AFBC) on MATLAB/Simulink and obtained good steady state and transient performance of APF with an adaptive fuzzy backstepping controller (AFBC) [35]. Jayachandran and Sachithanandam developed the model of DSTATCOM for wire distribution system and used ANN-based one cycle control technique to maintain the voltage across DC link capacitor and compensated the neutral current [36].

From the above literature survey, it can be concluded that for improving power quality the conventional techniques are suitable only for a particular application like static regimes because of the requirement of mathematical modeling and self-tuning. The AI-based techniques overcome these problems and have become popular due to their fast-responding capability, non-requirement of any mathematical model, self-adjusting capability and ability to work in uncertain atmosphere.

Kasa et al. developed RES integrated dynamic APF using Adaptive Neuro-Fuzzy Inference System algorithm (ANFIS) control techniques to improve the power quality

and minimize the use of batteries [37]. Senthilkumar and Raj developed a UPQC and improved the compensation capability by using an adaptive control technique [38]. In the proposed study, model reference adaptive system (MRAS) is used for online self-tuning of the PI controller and ANFIS is used for simulation studies.

Neuro-fuzzy control techniques are very fast, it regulates the reactive power flow to grid more accurately and maintains the grid voltage [39]. Kumar and Bansal analyze the power quality of distribution system by connecting ANFIS tuned PV integrated shunt active power filter [40]. They have compared many control techniques and obtained that the performance of ANFIS is the better for power quality improvement under dynamic loading condition. Abu-Rub et al. used ANFIS control technique to extract MPP from PV systems with fast variation in the irradiation [41]. They found out that ANFIS techniques are very fast responsive and yield very good dynamic response. Rao et al. used ANFIS algorithm to control VSC and minimize THD in inverter output voltage [42]. Reddy and Sreedhar developed a model of DSTATCOM based on combined Least Mean Square-Least Mean Fourth (LMS-LMF) with ANFIS for balanced/unbalanced nonlinear load [43]. They minimized the THD in source current and regulated the grid voltage. Babu et al. found out that DSTATCOM with ANFIS algorithm provides better performance, i.e., increased load ability with improved power quality by comparing the performance of DSTATCOM and static VAR compensator (SVC) controlled using ANFIS algorithm for increasing the load ability of the existing power system [44]. With the literature survey, it is revealed that the hybrid control algorithms are more suitable to track MPP from PV cell and to control the shunt compensator for improving the power quality.

PV integration helps in clean and sustainable energy generation and lesser environmental pollution. In case of grid failure, it can supply essential loads, thus improves the reliability and provides a solution to energy crisis. Further, PV integration with DSTATCOM mitigates harmonics, minimize voltage drops, improve power factor and fulfil the energy demands.

The integration of RES with shunt compensating controller increases the working capability of the existing controllers to supply active/ reactive power to the utility along with improvement in power quality. Therefore, in this paper an AI-based technique, Adaptive Neuro-fuzzy Inference System (ANFIS) algorithm is proposed. This tracks the MPP from solar system efficiently and controls the DSTATCOM. The key contributions of this paper are:

- (a) Mathematical modeling of photovoltaic array and DSTATCOM.

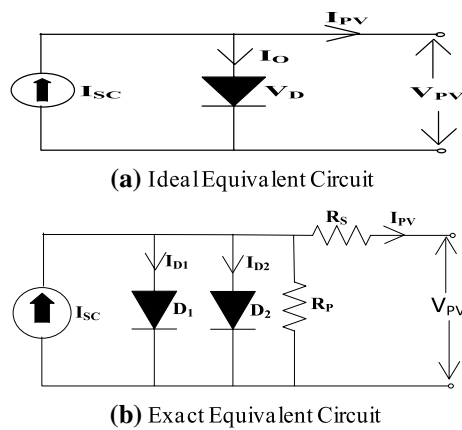


Fig. 4 Ideal and exact equivalent circuit of PV cell

- Design of DSTATCOM and boost converter for high power level operations.
- Development of ANFIS and P- and O-based control algorithm for extraction of maximum power point (MPP) in PV systems.
- Design of ANFIS- and SRF-based controllers to control the DSTATCOM with emphasis on practical issues, such as a combination of balanced/unbalanced, reactive and nonlinear load.
- Evaluation of system performances on MATLAB/ Simulink and validation of results in real time using Opal-RT HIL testing platform.

In this paper, Sect. 2 describes the proposed system configuration, dynamic modeling of DSTATCOM, PV array system and boost converter. Section 3 demonstrates proposed control technique. In Sect. 4, the simulation results obtained from MATLAB/Simulink and HIL system are analyzed. Conclusions drawn from this study are mentioned in Sect. 5.

2 Modeling of PV Fed DSTATCOM

The configuration of PV fed DSTATCOM is shown in Fig. 1. The system is configured using 3-phase, 3-wire DSTATCOM, solar systems and balanced/unbalanced nonlinear load. The components of first part DSTATCOM are VSC, DC link capacitor, interfacing inductor and coupling transformer. Here, VSC is used to exchange reactive power between grid and DC link capacitor and supply active power to the grid, DC link capacitor is used to store energy, interfacing inductor works as a filter to suppress the harmonics and coupling transformer minimizes the size of VSC for higher power ratings. The components of second part solar systems are PV array, boost converter and MPPT controller.

In this PV array is used to generate DC power on the behalf of solar irradiation, boost converter is used to increase voltage level of DC power and MPPT controller is used for tracking MPP from PV array. The proposed system is modeled using ANFIS algorithm to improve power quality.

2.1 Design of Proposed DSTATCOM Controller

DSTATCOM is the most suitable custom power device used to improve the current-related power quality problems. Schematic and phasor diagram of DSTATCOM are shown by Figs. 2 and 3. Here, DSTATCOM is connected at distribution end before bus no. 2. Bus no. 1 depicts the start point of distribution line. Phasor diagram depicted the level and phase of the voltage at bus no. 2 in the presence of DSTATCOM.

Here V_{21} and V_{22} refer to the voltage without and with DSTATCOM at bus no.2, respectively. With the presence of DSTATCOM, compensating current injected to grid is given by

$$I_c = I_L - I_s \quad (1)$$

$$\text{where } I_s = \frac{V_{21} - V_1}{R_s + jX_s}$$

Therefore, the required compensating current is

$$I_c = I_L - I_s = I_L - \frac{V_{21} - V_1}{R_s + jX_s} \quad (2)$$

And required compensating power given by

$$Q_c = I_c \times V_{22} \quad (3)$$

The 3-phase instantaneous voltage at PCC given by

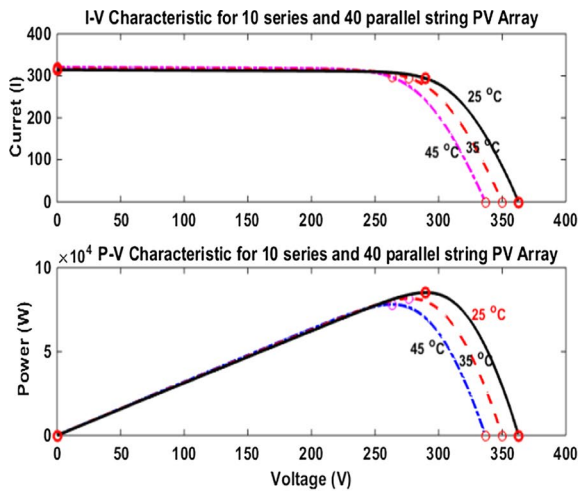
$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} V_s \begin{bmatrix} \sin \omega t \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (4)$$

The 3-phase instantaneous voltage at PCC is given by

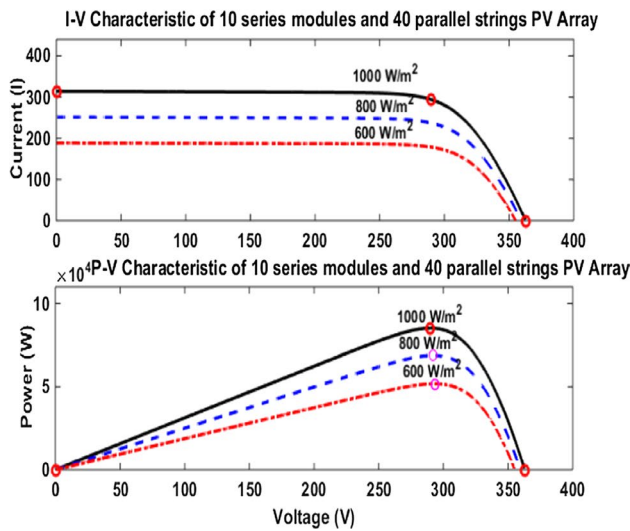
$$\begin{aligned} V_{sa} &= R_f I_{ca} + L_f \frac{dI_{ca}}{dt} + V_{an} \\ V_{sb} &= R_f I_{cb} + L_f \frac{dI_{cb}}{dt} + V_{bn} \\ V_{sc} &= R_f I_{cc} + L_f \frac{dI_{cc}}{dt} + V_{cn} \end{aligned} \quad (5)$$

Here $V_{an} = V_{am} + V_{mn}$, $V_{bn} = V_{bm} + V_{mn}$ and $V_{cn} = V_{cm} + V_{mn}$ are the VSC output voltage at phase a, b and c, respectively. V_{am} , V_{bm} and V_{cm} are VSC output voltage w.r.t. to VSC common point and $V_{mn} = -\frac{1}{3} \sum_{k=a}^c V_{kn}$ is the voltage between VSC common point and neutral. The Eq. (5) is equivalent to





(a) Characteristic at constant temperature



(b) Characteristic at constant irradiance

Fig. 5 I-V and P-V Characteristic of PV Array

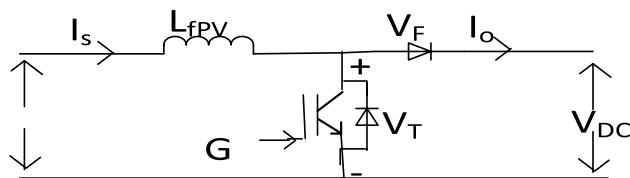


Fig. 6 Equivalent Circuit of Boost Converter

$$\begin{bmatrix} \frac{dI_{ca}}{dt} \\ \frac{dI_{cb}}{dt} \\ \frac{dI_{cc}}{dt} \end{bmatrix} = \frac{1}{L_f} \begin{bmatrix} V_{sa} - V_{am} \\ V_{sb} - V_{bm} \\ V_{sc} - V_{cm} \end{bmatrix} + \begin{bmatrix} -\frac{R_f}{L_f} & 0 & 0 \\ 0 & -\frac{R_f}{L_f} & 0 \\ 0 & 0 & -\frac{R_f}{L_f} \end{bmatrix} \begin{bmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{bmatrix} \quad (6)$$

2.2 Design Dynamic Modeling of PV Array

The solar PV array is used to convert energy of sunlight into electrical energy which is used for various purposes like supplying active power to the load, regulate the voltage of the grid and minimizing the THD. It produces electricity according to quantum-mechanical process known as photo-voltaic effect. The ideal electrical equivalent circuit of solar PV array is shown in Fig. 4a., whereas exact equivalent circuit is shown in Fig. 4b. Here, series resistance (R_s) depicts the resistive losses in series connected cells, parallel resistance depicts the losses due to leakage of current through a resistive path in parallel with the intrinsic devices and diode D_2 shows the non-ohmic current path in depletion region in parallel with the PV cell.

From ideal equivalent circuit of PV cell

$$\text{Diode current is } i_0 = I_0 \left(e^{\frac{V_D}{\eta V_T}} - 1 \right) \quad (6)$$

Where I_0 is the cell saturation current and V_T is the thermal voltage $= \frac{kT_c}{q}$, k is Boltzmann's constant (1.38×10^{-23} J/K), T_c is cell's working temperature, q is electron charge (1.6×10^{-19} C) and η is the ideality factor.

Output current is

$$I_{PV} = I_{SC} - i_0 = I_{SC} - I_0 \left(e^{\frac{V_D}{\eta V_T}} - 1 \right) \quad (7)$$

$$P_{PV} = V_{PV} \times I_{PV} \quad (8)$$

From exact equivalent circuit Eq. (7) showed the PV cell output current (I_{PV}) and Eq. (8) showed output power (P_{PV}).

After considering the $I_{01} = I_{02}$ and $R_P \approx \infty$ the output current is

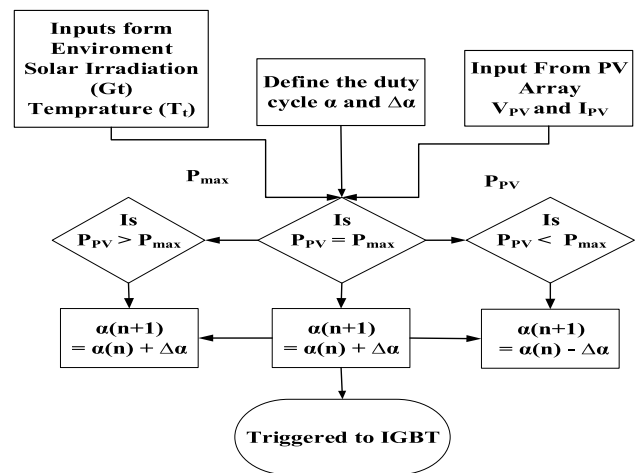


Fig. 7 Schematic Diagram of MPPT Controller

$$I_{PV} = I_{SC} - I_0 \left(e^{\frac{V_{PV} + I_{PV} \times R_s}{\eta V_T}} - 1 \right) \quad (9)$$

The short circuit current (I_{SC}) for given temperature can be written as

$$I_{SC(T)} = I_{SC(T_{ref})} [1 + \alpha(T - T_{ref})] \quad (10)$$

Here α is temperature coefficient, T_{ref} is reference temperature of PV cell in Kelvin (usually 298 K) and $I_{SC(T_{ref})}$ is PV short circuit current at reference temperature taken from data sheets.

The short circuit current (I_{SC}) varies with the intensity of irradiance so it can be written as

$$I_{SC(G)} = I_{SC(G_0)} \times \frac{G}{G_0} \quad (11)$$

Here G_0 refers to the normal value of irradiation and the saturation current can be calculated by considering $I_{PV} = 0$, and the reverse saturation current I_0 at reference temperature becomes

$$I_0 = \frac{I_{SC}}{\left(e^{\frac{V_D}{\eta V_T}} - 1 \right)} \quad (12)$$

The reverse saturation current is temperature dependent so at a given temperature it can be written as

$$I_{o(T)} = I_{o(T_{ref})} \times \left(\frac{T}{T_{ref}} \right)^{\frac{3}{\eta}} \times e^{\frac{qV_{oc}(T_{ref})}{\eta k} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right)} \quad (13)$$

Where $I_{o(T_{ref})} = \frac{I_{SC(T_{ref})}}{\left(e^{\frac{qV_{oc}(T_{ref})}{\eta k T_{ref}}} - 1 \right)}$.

The Eqs. (7) and (8) are used to draw the I-V and P-V characteristics of PV array considering variation in temperature and irradiance. The Fig. 5 show the I-V and P-V characteristics obtained using MATLAB/Simulink. Here, Fig. 5a shows the characteristics at constant temperature and Fig. 5b depicts the characteristics at constant irradiance.

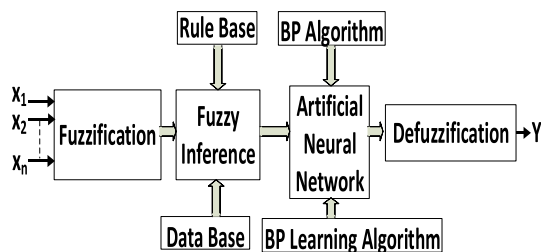


Fig. 8 Schematic diagram of ANFIS

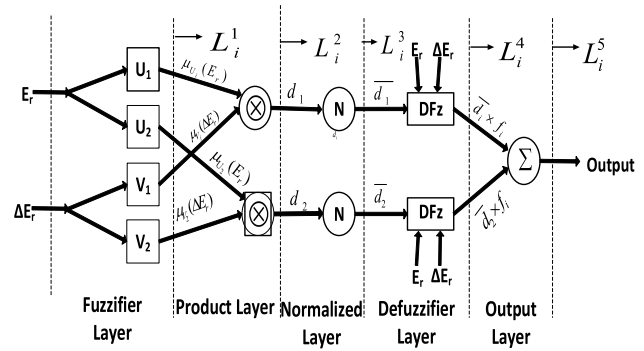


Fig. 9 Five layered architecture of ANFIS

2.3 Dynamic Modeling of Boost Converter

The ideal electrical equivalent circuit of boost converter is shown in Fig. 6. Here inductor L_{fPV} is used to store energy during ON period of IGBT and to boost-up the voltage.

During ON period, voltage across inductor is $V_{PV} = L_{fPV} \frac{I_2 - I_1}{T_{ON}} = L_{fPV} \frac{\Delta I}{T_{ON}}$

$$\therefore T_{ON} = L_{fPV} \frac{\Delta I}{V_{PV}} \quad (14)$$

During OFF period voltage across inductor is $V_{PV} - V_{DC} = -L_{fPV} \frac{\Delta I}{T_{OFF}}$

$$\therefore T_{OFF} = -L_{fPV} \frac{\Delta I}{V_{PV} - V_{DC}} \quad (15)$$

From above equations the peak of ripple current can be defined as

$$\Delta I = T_{ON} \times \frac{V_{PV}}{L_{fPV}} = T_{OFF} \times \frac{V_{DC} - V_{PV}}{L_{fPV}} \quad (16)$$

And average output voltage is

$$V_{DC} = V_{PV} \times \frac{T}{T_{OFF}} = \frac{V_{PV}}{1 - \alpha} \quad (17)$$

For a lossless circuit input power and output power are equal

$$V_{PV} \times I_S = V_{DC} \times I_O = V_{PV} \times \frac{I_O}{1 - \alpha} \quad (18)$$

Therefore, the average input current is equal to $I_S = \frac{I_O}{1 - \alpha}$. Now the switching duration (T) can calculate as

$$T = \frac{1}{f} = T_{ON} + T_{OFF} = L_{fPV} \frac{\Delta I}{V_{PV}} + L_{fPV} \frac{\Delta I}{V_{DC} - V_{PV}} \quad (19)$$



2.4 Design Boost Converter for MPP

The MPP controller is used to regulate the input DC voltage and match the load with PV characteristic for tracking maximum power from PV array. Solar irradiation is time varying non-uniformly distributed over PV array. The (I-V) and (P-V) characteristics of PV array which are nonlinear will change with the change in solar irradiation. Therefore, the operating point of PV array shifts from its MPP point and the efficiency of PV array goes down. For increasing the efficiency and reliability, the tracking of MPP becomes an important issue while solar systems having variable isolation conditions. In this paper DC-DC boost converter with MPPT controller is used for MPP operation. The MPPT controller controls the operation of boost converter according to inputs like PV array parameters (V_{oc} and I_{sc}), environmental parameters (solar Irradiation and temperature) and output like DC link voltage. The schematic diagram of MPPT controller is shown by Fig. 7. In this paper, ANFIS control algorithm is used as MPPT.

3 ANFIS Control Algorithm

Power system continuously faces variable climatic condition (solar irradiation, temperature) and load variations thereby making power quality maintenance is a major challenge. The data of a given system is probable and indefinite. Thus, various types of AI-based soft computing control techniques like FLC, neural network (NN), Genetic Algorithm etc. are used for improving the power quality. FLC is a very high-level technique used for minimization of linear controlling and reasoning problems. It minimizes the power quality problems without an exact model of the power system. In FLC techniques, MF are generated based on learning rules which are very complex and time consuming for nonlinear controlling problems thereby making it less suitable for nonlinear controlling problems. On the other hand, NN is a soft computational technique, used to handle nonlinear controlling problems, but it requires training data to minimize power quality problems. Therefore, no individual technique is sufficient to improve the power quality during uncertain climatic conditions.

ANFIS is a hybrid control technique, called Neuro-Fuzzy hybrid technique formed by the combination of FLC and NN techniques. Therefore, it has the ability of both controllers which are learning abilities, inference mechanisms and parallel data processing. By superimposing, fuzzy interference system on NN, this technique extracts information from a dynamic system and design model for required operation. The main features of this technique are easy implementation capability, quick identification of input data with more accuracy, good generalization skills, easier understanding and

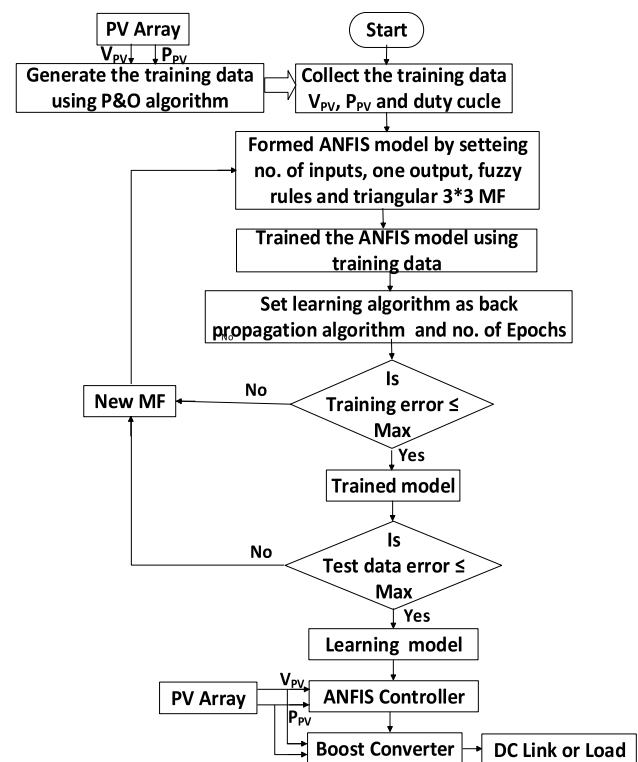


Fig. 10 Flow Chart for MPP using ANFIS Algorithm

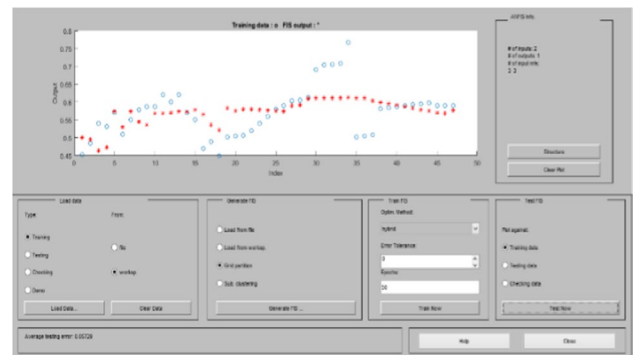


Fig. 11 Graph between actual power output and predicted power output vs training data pair

ability to incorporate both numeric knowledge and linguistic knowledge. The schematic diagram of ANFIS is shown by Fig. 8. In this first information is given into linguistic variables, i.e., MF using fuzzifier, then the degree of membership of MF is computed on the basis of knowledge base (rule base and data base) shown by FIS model. The computed data are applied to NN block which trains the data using back propagation (BP) learning algorithm. The output of NN is then converted to crisp variables from linguistic variables using defuzzifier to generate the output. For better performance of ANFIS, this paper used triangular MF during fuzzification

process due to its less computational burden and Sugeno-type FIS for its good computational efficiency. Out of 3×3, 5×5 and 7×7 MF rules, 3×3 rules base is selected in FIS process for the improvement in power quality.

The ANFIS algorithm is represented by five layered architectures depicted in Fig. 9. These five layers are fuzzifier layer, product layer, normalized layer, defuzzifier layer and output layer.

The role of each layer is given as follows:

- i. Fuzzifier layer- It is the first layer of the ANFIS architecture which converts input physical variables into the linguistic variables using Sugeno fuzzy rule. Each node labeled ((U and V) at this layer has adaptive nature, showing that the parameter of individual node is affected by other node. In this paper, there are two input variables, i.e., error voltage (E_r) and change in error voltage (ΔE_r) represented as e_1 and e_2 . The output of this layer given by

$$L_i^1 = \mu_{V_2}(E_r) \text{ and } L_j^1 = \mu_{V_2}(\Delta E_r) \quad (20)$$

Here E_r and ΔE_r =input variables, U_i & V_j =Linguistic variable of the corresponding node, μ_{U_i} & μ_{V_j} =MF corresponding to linguistic variables, i and j are the nodes at which input variables E_r & ΔE_r applied,

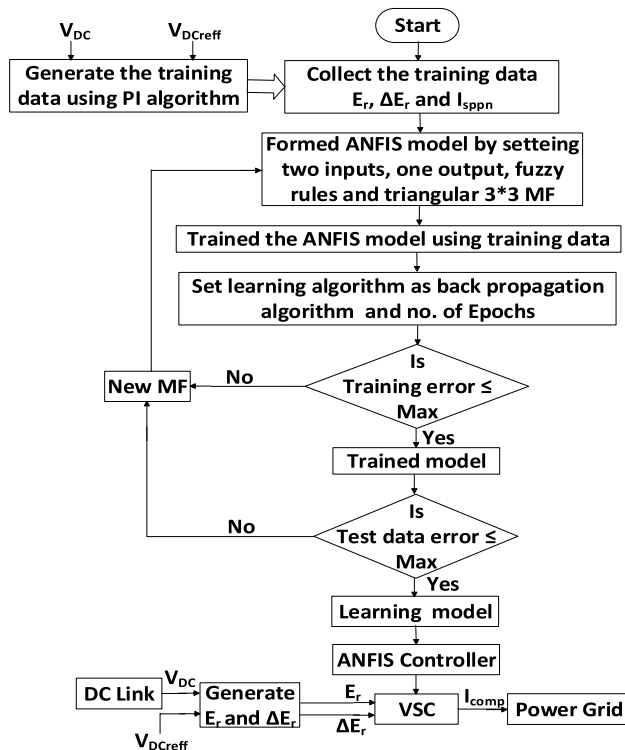


Fig. 12 Flow chart for tuning of DSTATCOM using ANFIS

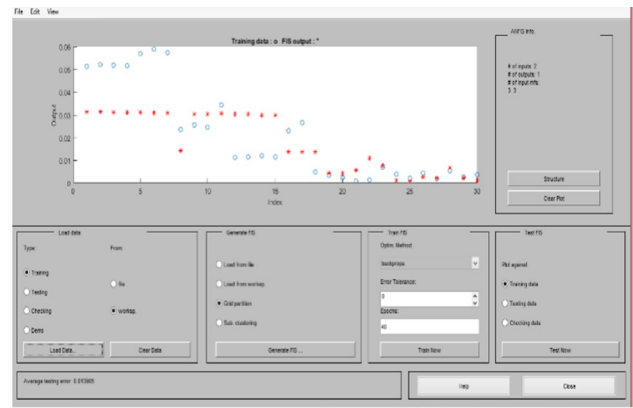


Fig. 13 Graph between test data output vs training data pair

- respectively. The value of i is 1 and 2 and value of j is 1 and 2 shows input nodes.
 - ii. Product Layer- This is the second layer of the ANFIS architecture. Output of each node in this layer {labeled ($\otimes$)} is obtained by multiplying the inputs (MF's) at the corresponding node. Each node in this layer has fixed type nature. This layer is mainly used to calculate the degree of applied fuzzy rule. The output of this layer is given by
- $$L_i^2 = d_i = \mu_{U_i}(E_r) \times \mu_{V_i}(\Delta E_r) \quad (21)$$
- iii. Normalized layer- It is the third layer of ANFIS architecture. Each node of this layer {labeled (N)} is the fixed nature type. This layer is used to normalize the input degree of the fuzzy rule and complete IF part of the fuzzy rule. The output of this layer is given by
- $$L_i^3 = \bar{d}_i = \frac{d_i}{\sum_{k=1}^2 d_k} \quad (22)$$
- iv. Defuzzifier layer- This is the fourth layer of ANFIS architecture, who's each node is square shaped and

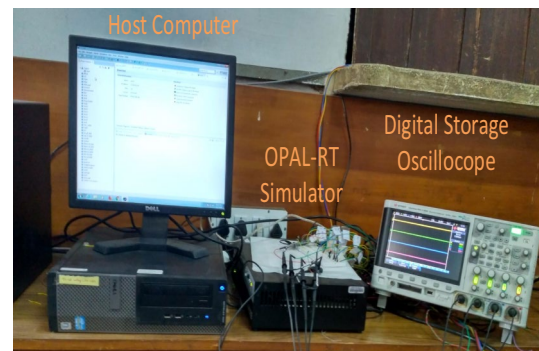
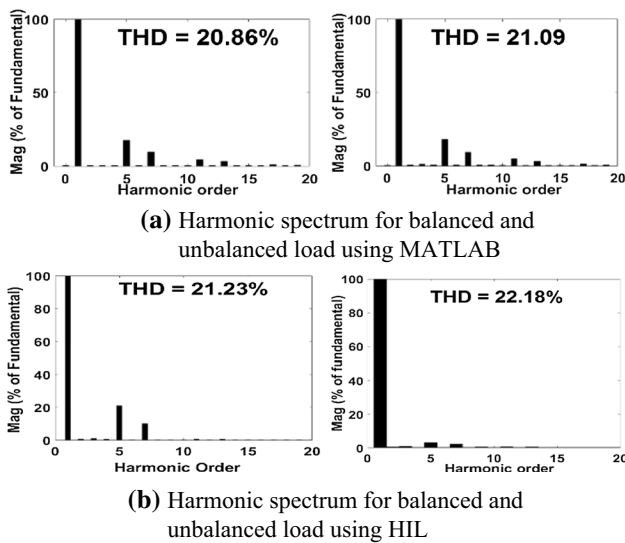


Fig. 14 Test bench set-up

Table 1 Designed parameters of PV fed DSTACOM

Component	Formula	Value
Current rating of the DSTATCOM	$I_{DSTATCOM} = \sqrt{I_S^2 - I_{S1}^2}$	67.89 A
Power rating of DSTATCOM	$S = 3 \times V_p \times I_{DSTATCOM}$	48.88 KVA
DC link voltage (V_{DC}) of DSTATCOM	$V_{DC} = \frac{2\sqrt{2} \times V_p}{m_a}$	800 V
DC link capacitance	$C_{DC} = \frac{2 \times 3 \times V_p \times \alpha \times I_{DSTATCOM} \times \Delta t}{(V_{DC}^2 - V_{DC1}^2)}$	3000 μ F
Interfacing inductor	$L_S = \frac{\sqrt{3} \times m_i \times V_{DC}}{12 \times \alpha \times f_s \times I_{crp}}$	2 mH
Voltage rating of the IGBT	$V_{IGBT} = V_{DC} + V_d$	880 V
Current rating of IGBT	$I_{IGBT} = 1.25(I_{crp} + I_{peak})$	124.25 A
Boost converter capacitor	$C_{PV} = \frac{0.6 \times V_{PV}}{4 \times f_s^2 \times \Delta L_{PV} \times \Delta C_{PV}}$	375 μ F
Boost converter inductor	$L_{PV} = \frac{V_{PV}(V_{DC} - V_{PV})}{4 \times f_s^2 \times \Delta L_{PV} \times \Delta C_{PV}}$	3.084 mH

**Fig. 15** Harmonic spectrum of source current without compensation

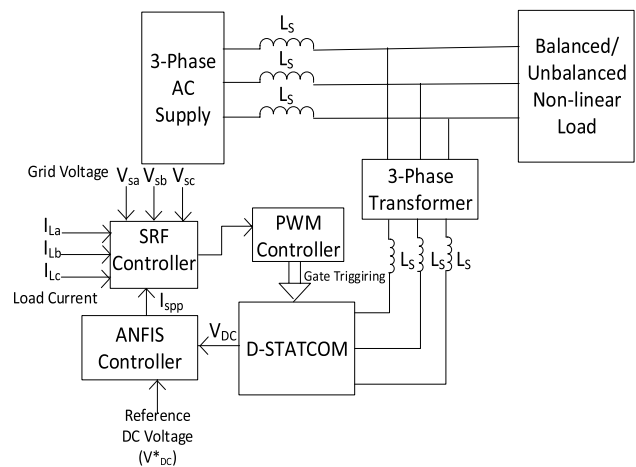
adaptive nature type. Each node in this layer generates MF output based on learning rules. The output of this layer given by

$$L_i^4 = d_2 \times f_i = \bar{d}_i \times (x_i \times E_r + y_i \times \Delta E_r + z_i) \quad (23)$$

Here $\{x_i, y_i, z_i\}$ is a set of linear parameters.

- v. Output layer- This is the fifth and last layer of the ANFIS architecture which consist of only one node. In this layer, the exit node is fixed nature type and labeled by summation sign. The output of this last part of fuzzy rule given by

$$L_i^5 = \sum_i (\bar{d}_i \times f) = \frac{\sum_i (d_i \times f_i)}{\sum d_i} = \text{Output} \quad (24)$$

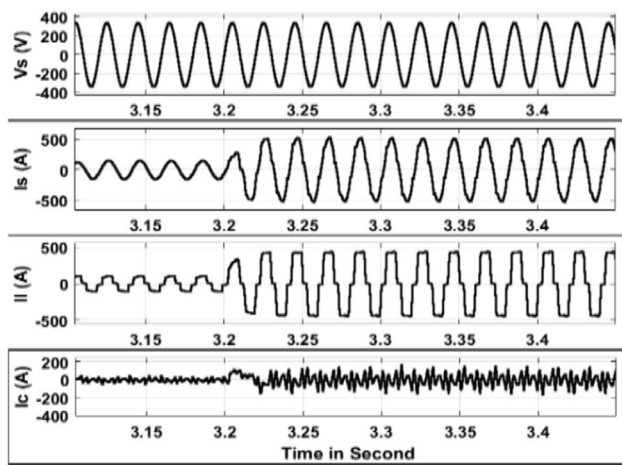
**Fig. 16** Proposed model of ANFIS tuned DSTATCOM

Here L_i^5 is the final output of the controller used to control the boost converter during MPP operation and VSC for improvement in power quality.

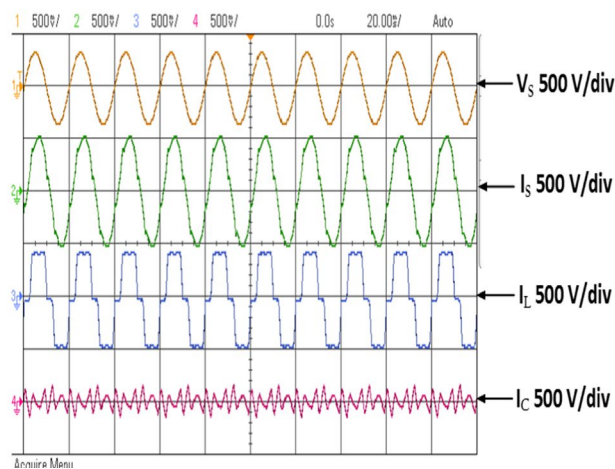
3.1 Training of ANFIS controller for MPPT

The ANFIS algorithm completes the MPP tracking after considering skilled knowledge and human being information. The flow chart for MPP operation using ANFIS algorithm is given by Fig. 10.

Here, in first step training, data are collected to train the ANFIS model using P and O algorithm. The P and O algorithm generates the training data by varying temperature and irradiance with help of MATLAB workspace. In second step ANFIS model is formed with two input variables (PV power and PV voltage), one output variable (duty cycle), Sugeno fuzzy rules and MF. Here, triangular linear type 3*3 MF is used to derive the ANFIS model. In third step,



(a) Waveform on MATLAB



(b) Waveform on HIL

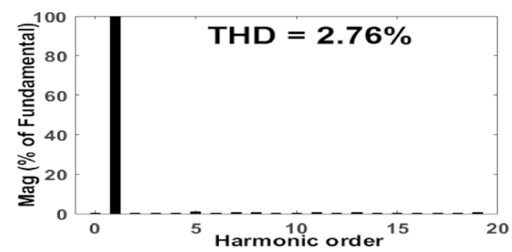
Fig. 17 Waveform for Nonlinear Balanced load

the collected training data (50 data pairs) trains the formed ANFIS model using back propagation learning algorithm to minimize mapping error and optimize MF and its parameters. Finally output from ANFIS is obtained by converting the ANFIS fuzzified variable to crisp variable which is applied to boost converter to track maximum power tracking from PV system.

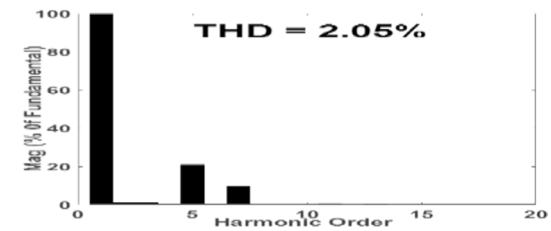
In MPP control operation while training ANFIS, Fig. 11 shows the graph of predicted power output and test data with respect to training data. Here, red stars show the graph of predicted output and blue circle shows the graph of test data with the showing of epoch and training data error.

3.2 Training of ANFIS Controller to Control

ANFIS algorithm used to control DSTATCOM controller for improving the power quality. For this, the first step is to collect training data for ANFIS using PI algorithm. The

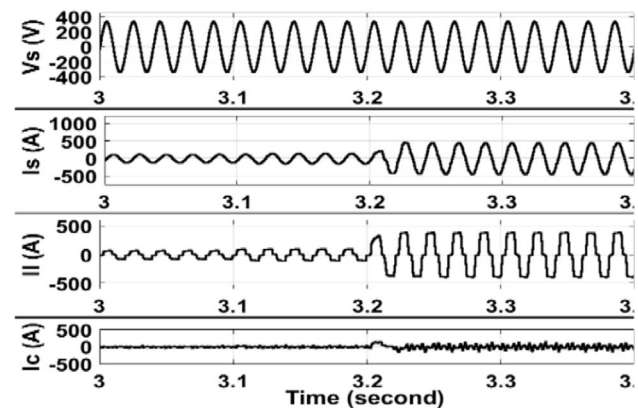


(a) Harmonic spectrum of source current using MATLAB

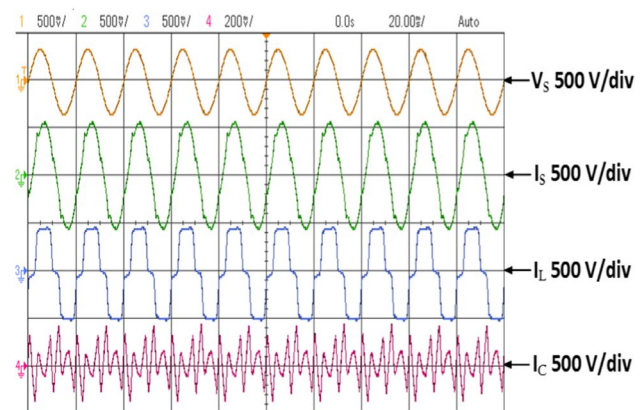


(b) Harmonic spectrum of source current using HIL

Fig. 18 Harmonic spectrum with ANFIS tuned DSTATCOM



(a) Waveform on MATLAB



(b) Waveform on HIL

Fig. 19 Waveform for Nonlinear Unbalanced load



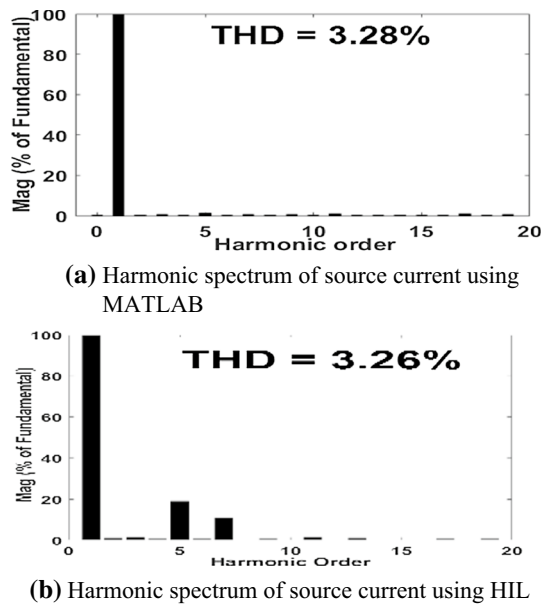


Fig. 20 Harmonic spectrum with ANFIS tuned DSTATCOM

PI algorithm generates the training data when connected with DSTATCOM controller to improve power quality and collects data using MATLAB workspace while applying varying load. In second step ANFIS model is formed with two input variables (error and change in error), one output variable (active current component), Sugeno fuzzy rules and MFs. In this triangular linear type, 3*3 MF are used to

derive the ANFIS model. In third step, the collected training data (30 data pair) is used to train the ANFIS model-based learning algorithm which is back propagation algorithm. The training is continued till the error between target data and ANFIS output minimizes. Finally output from ANFIS is obtained by converting ANFIS fuzzified variable to crisp variable which is applied to DSTATCOM controller to minimize THD and improve the power quality. The flow chart for power quality improvement-based tuning of DSTATCOM using ANFIS algorithm is given by Fig. 12.

In DSTATCOM control operation while training of ANFIS, Fig. 13 shows the graph of predicted outputs and test data w.r.t. training data. Here, red stars show the graph of predicted output and blue circle shows the graph of test data with the showing of epoch and training data error.

3.3 Real time on HIL Testing Platform

The simulation results obtained for different control algorithm on MATLAB/ Simulink need to be verified in real time. The experimental verification of simulation results obtained on MATLAB/ Simulink is not feasible for high power system. The hardware in loop testing (HIL) platform is developed to verify such simulation results. It saves testing time, minimizes testing cost, provide test functionalities at all possible scenarios and also provides flexibility to modify test system. The set-up of HIL simulator is shown by Fig. 14. It includes host computer, digital storage oscilloscope and Opal-RT 4510 simulator. It is a DSP-based fully digital real

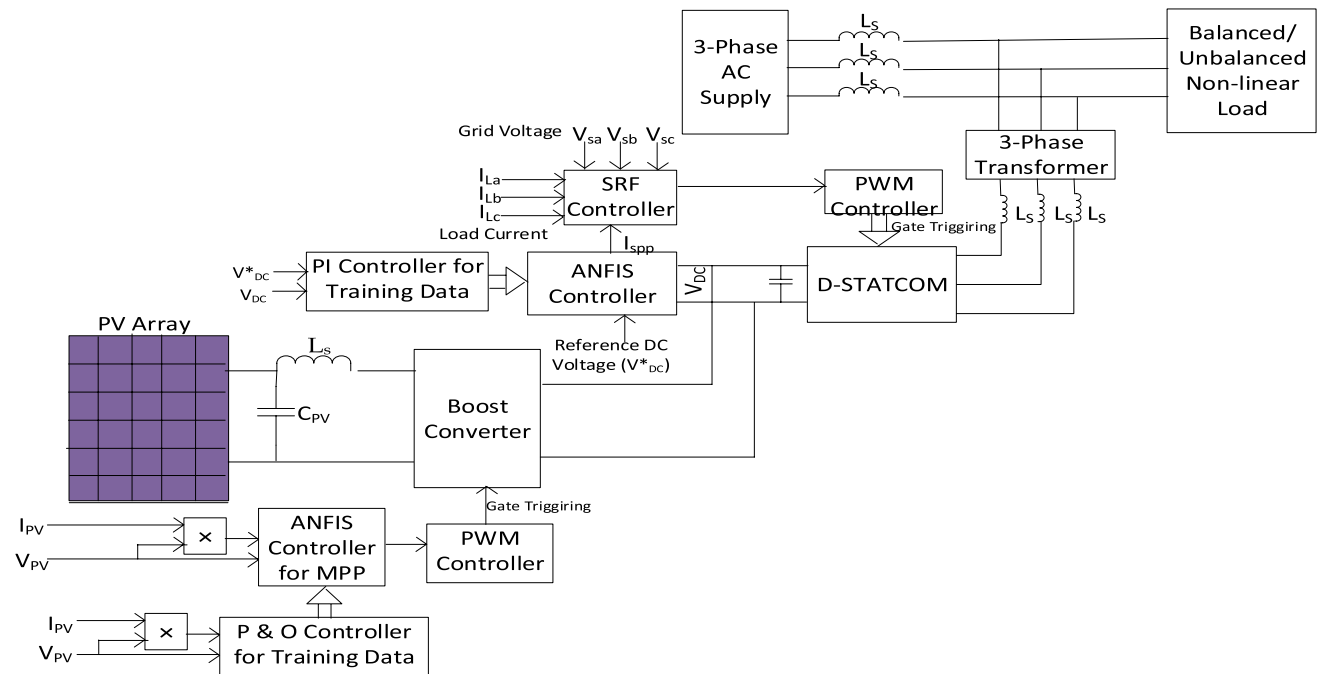


Fig. 21 Proposed model of ANFIS tuned PV integrated DSTATCOM



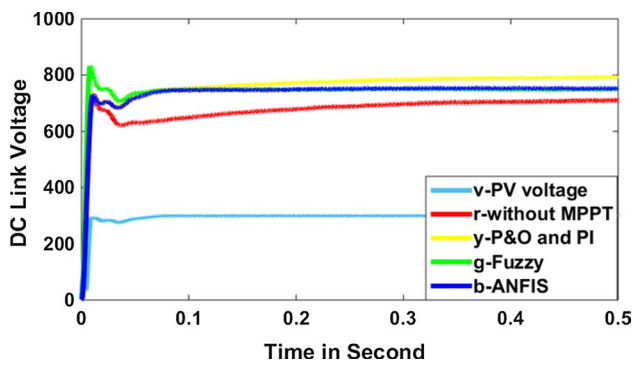


Fig. 22 DC Link voltage with various control algorithms

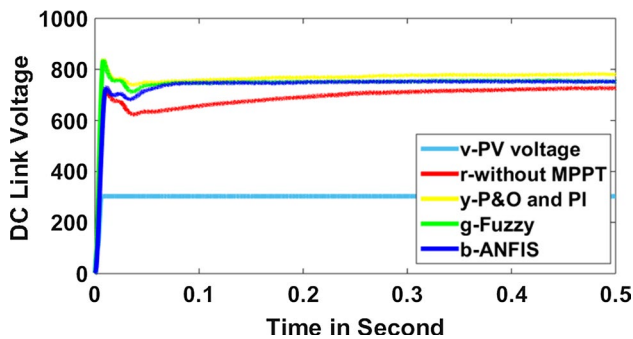


Fig. 23 DC Link voltage with various control algorithms

time simulator and used fixed step solver to run Simulink in real time. It uses MATLAB/Simulink as frontend for editing and viewing the graphical model in block diagram format from which code is automatically generated, manipulated and downloaded for real time simulation.

4 Simulation and HIL-based Results

This section comments on the compensation capability of proposed model, DSTATCOM without and with PV integration-based ANFIS algorithm for balanced/unbalanced nonlinear loads combinations on MATLAB/ Simulink and HIL testing platform. The proposed model is designed for 3-phase power grid having line voltage 415 V, line current 250 A and 50 Hz frequency with the nonlinear balanced (active load 10 kW and reactive load 6kVAR for each phase) or nonlinear unbalanced load (active loads 9kW, 10 kW & 11 kW and reactive loads 5.5kVAR, 6.0 KVAR & 6.6 KVAR

Table 2 Settling time of DC link voltage with different control algorithms

Control algorithm (PV fed STATCOM)	Balance load				Unbalanced load			
	Without MPPT	P&O-PI	Fuzzy-Fuzzy	ANFIS-ANFIS	Without MPPT	P&O-PI	Fuzzy-Fuzzy	ANFIS-ANFIS
Settling time (sec.)	0.52	0.24	0.09	0.08	0.61	0.3	0.14	0.09

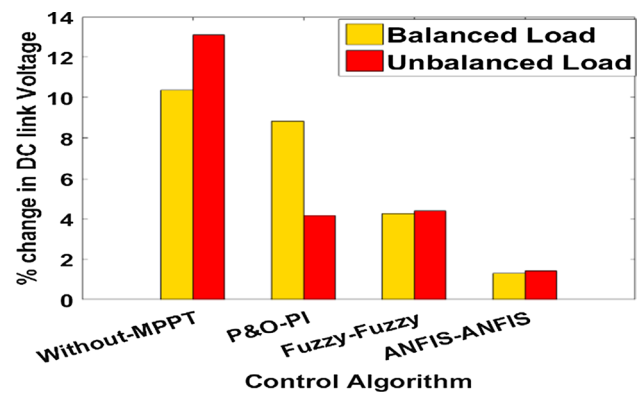


Fig. 24 DC link Voltage with Dynamic loading

phase wise, respectively). The design parameters of PV fed DSTATCOM are tabulated in Table 1.

Figure 15 shows the THD source current (when DSTATCOM is in off condition). This section discusses about the compensation capability of without and with PV fed proposed model.

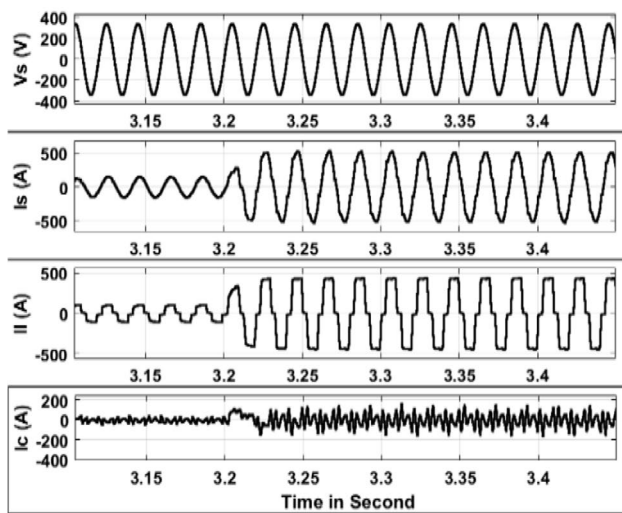
4.1 Results using ANFIS and SRF Tuned DSTATCOM

Figure 16 shows the proposed model of ANFIS tuned DSTATCOM. In this first, ANFIS controller is trained using training data obtained from PI controller and learned using BP algorithm. The ANFIS trained model has: 35 nodes, 27 linear parameters, 18 nonlinear parameters (45 total parameters 45), 50 training data pairs, and fuzzy rules. The performance of ANFIS tuned system for balanced/unbalanced nonlinear load is discussed in following sections.

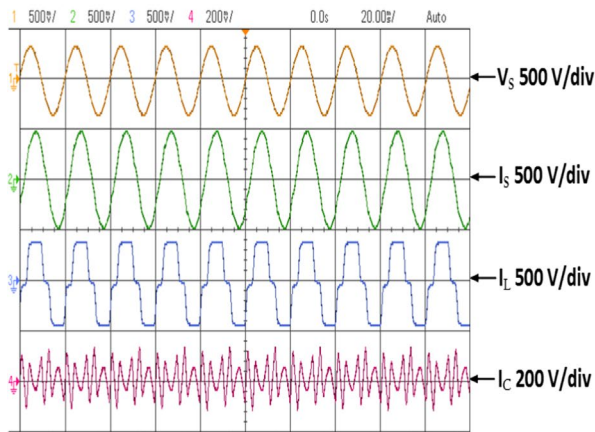
4.1.1 Balanced Nonlinear Load

The performance results for balanced nonlinear load using ANFIS tuned DSTATCOM are shown in Figs. 17 and 18. Figure 17 provides the details regarding source voltage, source current, load current and compensating current obtained from MATLAB and HIL system. Figure 18 depicts the THD obtained from MATLAB and HIL systems.





(a) Waveform on MATLAB



(b) Waveform on HIL

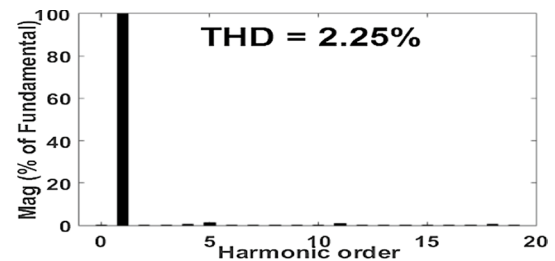
Fig. 25 Waveform for Nonlinear Balanced load

4.1.2 Unbalanced Nonlinear Load

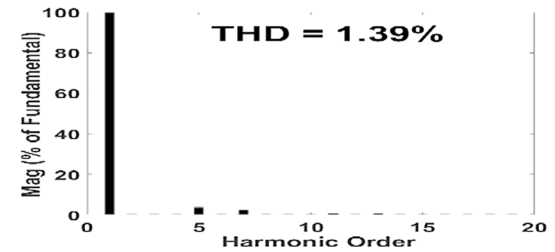
The performance results for unbalanced nonlinear load using ANFIS tuned DSTATCOM are shown in Fig. 19 and 20. Figure 19 provides the details of source voltage, source current, load current and compensating current obtained from MATLAB and HIL system. Figure 20 depicts the THD obtained from MATLAB and HIL systems.

4.2 Results using ANFIS and SRF tuned PV fed DSTATCOM

Figure 21 shows the proposed model of ANFIS tuned PV fed DSTATCOM. In this, first ANFIS controller connected with DSTATCOM is trained using training data obtained from PI controller and learned using BP algorithm. ANFIS controller used for MPPT is trained using training data

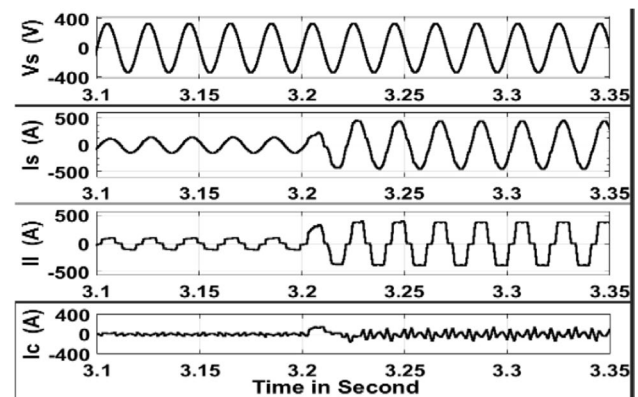


(a) Harmonic spectrum of source current using MATLAB

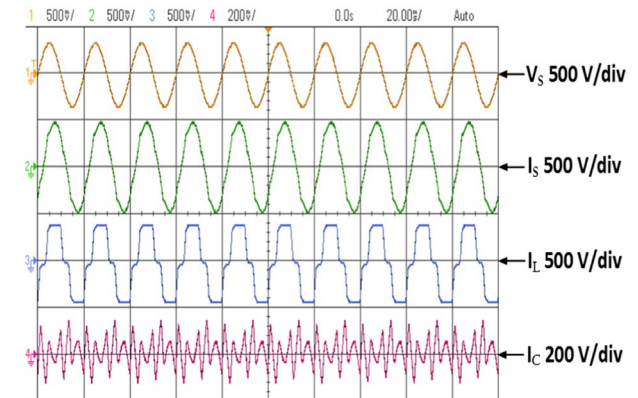


(b) Harmonic spectrum of source current using HIL

Fig. 26 Harmonic spectrum with ANFIS tuned PV integrated DSTATCOM

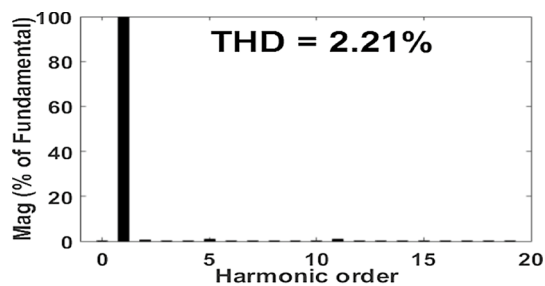


(a) Waveform on MATLAB

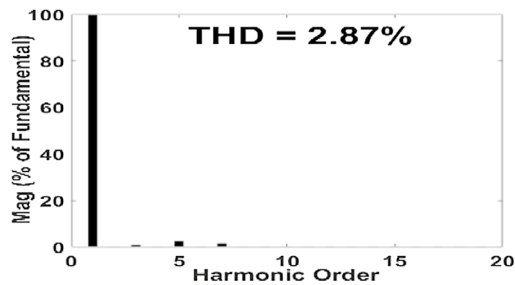


(b) Waveform on HIL

Fig. 27 Waveform for Nonlinear Unbalanced load



(a) Harmonic spectrum of source current using MATLAB



(b) Harmonic spectrum of source current using HIL

Fig. 28 Harmonic spectrum with ANFIS tuned PV integrated DSTATCOM

obtained from P and O controller and learned using BP algorithm. Here, the MPPT-based ANFIS trained model having following specifications: Number of nodes: 35, Number of linear parameters: 09, Number of nonlinear parameters: 18, Total number of parameters: 27, Number of training data pairs: 47. Number of checking data pairs: 0 and Number of fuzzy rules: 9. In this section, the transient response of DC link voltage and THD of source current is validated using results obtained on MATLAB/Simulink. Performance of ANFIS-based system for balanced/unbalanced nonlinear load is discussed in subsequent sections.

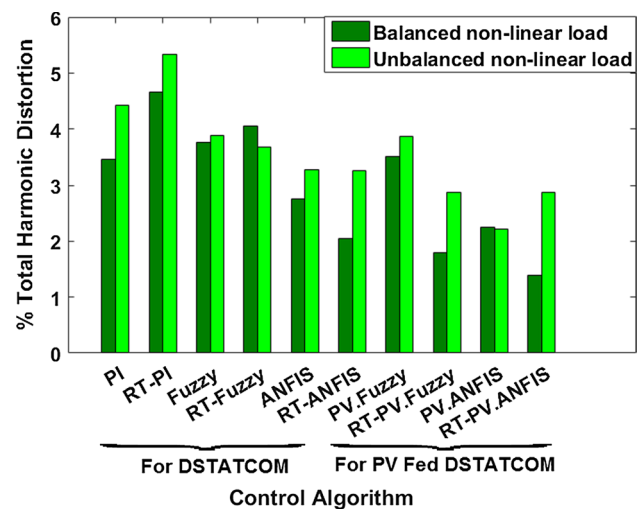


Fig. 29 Performance results based on different control algorithms

4.2.1 DC Link Voltage with Control Algorithms

DC link voltage simulated with PV integrated DSTATCOM for balanced load while applying various control algorithms is given by Fig. 22 and by Fig. 23 for unbalanced load. The simulation is completed keeping temperature at 25°C and irradiance at 1000 W/m². The Table 2 shows the settling time of DC link voltage with different control algorithms. From Fig. 22 and Fig. 23 it can be concluded that the DC link voltage characteristic for ANFIS algorithm-based system has minimum overshoot and settling time. The settling time with ANFIS algorithm is 0.083 s for balanced nonlinear load and 0.0929 s for unbalanced nonlinear load which are least compared to other control algorithms. The percentage change in DC link voltage under dynamic loading under various control algorithms is shown by fig. 24.

Table 3 THD in source current using different methods

Proposed systems and controller	Percentage total Harmonic distortion (THD) in source current			
	With nonlinear balanced load		With nonlinear unbalanced load	
	MATLAB	Opal-RT	MATLAB	Opal-RT
Without Compensation	20.86	21.23	21.09	22.18
PTI controlled DSTATCOM	3.47	4.66	4.42	5.34
FL Controlled DSTATCOM	3.77	4.05	3.88	3.69
FL controlled PV fed DSTATCOM	3.52	1.79	3.86	2.87
ANFIS controlled DSTATCOM	2.76	2.05	3.28	3.26
ANFIS controlled PV fed DSTATCOM	2.85	1.39	2.21	2.87



4.2.2 Balanced Nonlinear Load

The performance results for balanced nonlinear load using ANFIS tuned PV integrated DSTATCOM are shown in Figs. 25 and 26. Figure 25 provides the details of source voltage, source current, load current and compensating current obtained from MATLAB and HIL system. Fig. 26 depicts the THD obtained from MATLAB and HIL systems.

4.2.3 Unbalanced Nonlinear Load

The performance results for unbalanced nonlinear load using ANFIS tuned PV integrated TATCOM are shown by Figs. 27 and 28. Figure 27 provides the details of source voltage, source current, load current and compensating current obtained from MATLAB and HIL system. Figure 28 depicts the THD obtained from MATLAB and HIL systems.

The performance results for proposed compensator DSTATCOM with/without PV-based and using various control techniques are shown by Table 3 and Fig. 29. The results in Table 3 clearly depicts that the ANFIS tuned PV fed DSTATCOM has highest performance and reduces the THD from 20.86 to 2.25% as per result from MATLAB/Simulink and 21.23% to 1.39% as per results obtained from HIL for balanced nonlinear loading conditions. For unbalanced nonlinear loading conditions, the THD is reduced from 21.09% to 2.21% as per result from MATLAB/Simulink and from 22.18% to 2.87% as per results obtained from HIL

5 Conclusion

In this paper, a PV fed DSTATCOM tuned with various control scheme is modeled in MATLAB/ Simulink and the results obtained are validated in real time using hardware in loop (HIL) testing platform. The DSTATCOM used here with/without PV integration has mitigated the source currents harmonics effectively and has improved the power quality while maintaining DC link voltage for balance/unbalance nonlinear loads.

The control strategies like, P and O, Fuzzy and ANFIS are employed here to extract MPP from a PV array. Further, SRF-based DSTATCOM is tuned using PI, Fuzzy and ANFIS-based algorithms. The settling time for DC link voltage is mentioned in Table 2 and the content of THD in source current is mentioned in Table 3 for varying load conditions using various control strategies. The proposed ANFIS tuned control scheme has reduced the settling time of DC link voltage from 0.52 s. to 0.08 s for nonlinear balanced load and 0.61 s. to 0.09 s for nonlinear unbalanced load. Further, ANFIS tuned PV fed DSTATCOM has reduced the

THD of source current to 1.39% for balanced nonlinear load and 2.87% unbalanced nonlinear load. The ANFIS-based method successfully resolves the trade-off between MPP tracking speed and steady state oscillations. It is concluded that the scheme built around ANFIS provides superior performance.

The value of THD of source current obtained from various control techniques are in the limit (less than 5%) as per requirement of IEEE standard 519–1992.

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