Journal of Scientific & Industrial Research
Vol. 81, February 2022, pp. 180-187

Performance Analysis of ANFIS-PSO based STATCOM in an Isolated Renewable Energy based Micro-Grid

Lavanya M* and Shivakumar R
Department of EEE, Sona College of Technology, Salem, India

Received 05 July 2020; revised 20 January 2022; accepted 20 January 2022

In recent times, the micro-grids have gained more importance owing to the increased need for providing reliable and quality power to the users at remote locations. This work proposes a novel application of Adaptive Neuro-Fuzzy Inference System (ANFIS) in conjunction with Particle Swarm Optimization (PSO)-based controller for static synchronous compensator to improve the performance of a hybrid renewable energy based isolated micro grid environment. Adaptive and robust ANFIS controller combines the features of artificial neural network and fuzzy inference system. The proposed controller provides reactive power compensation and maintains the stability of the system. The functionality of the system is tested in MATLAB/Simulink under varying conditions and results show improvement in power factor and reduction in harmonics. Also, the performance of PSO-ANFIS is superior to conventional PI and ANFIS controller in terms error components.

Keywords: Harmonic reduction, Photo-voltaic, Power quality, Power factor improvement, Reactive power compensation, Wind energy

Introduction

The deficiencies in centralized power system configurations like low flexibility, poor reliability and environmental pollution lead to the concept of distributed generation. However, owing to the problems such as randomness and intermittency, direct connection of distributed generation to the grid has severe impacts. Hence the concept of micro grid was proposed to clear these shortcomings and can act either independently or in grid connected mode.[1] Voltage fluctuation, power flow control, power quality maintenance are the major factors in a power system network. The seriousness of the problem increases with the introduction of renewable energy based micro grids. Since renewable energy sources like solar and wind are highly intermittent, the reliability of the power production is not exactly predictable.[2] Large load changes have serious impact on the same. There are number of challenges like power quality maintenance, voltage regulation, load sharing, frequency regulation, etc., are associated with Microgrid. But very few works have attempted to address the above problems in case of isolated Microgrid. The current work is attributed to solve power quality problem and voltage regulation by introducing a controller.

Conventional LC filter technique utilized for power quality problems brings about resonance with impedance of the system.[3] The Static synchronous Compensator (STATCOM) can be used to absorb or injective reactive power into the network to regulate power flow and improve quality of the power delivered by the system. Wind system-imposed stress can be handled well.[4] Even though conventional Proportional Integral (PI) controllers are robust and have wide range of stability margin, they are very sensitive to variations in system parameter and non-linear behaviour of the system. Also, fine tuning of PI parameters to compute optimal parameters using traditional methods such as Newton Raphson and Ziegler-Nichols is difficult as they depend mainly on initial conditions and solver type. This problem is mainly observed in industrial applications where the system is of higher order and highly non-linear.[5,6]

The performance of PI and fuzzy logic controller in terms of mitigating harmonics when distributed generation is connected to grid were analysed and compared in Zahariah *et al.* (2021).[(6)] Reactive power compensation capability of STATCOM is compared with SVC in Jun Qi *et al.* (2020), where a new

*Author for Correspondence
E-mail: lavanyasenthil2018@gmail.com

coordination between wind generator and STATCOM is introduced for improved reactive power compensation.[7] Dynamic ability of STATCOM in Chandrasekaran *et al*. (2021) and Kulkarni *et al*. (2022) is tested for improving voltage stability in presence of renewable energy sources.[8,9] Flywheel energy system in place of battery energy source is utilized to mitigate power quality problems by compensation.[10] Fuzzy-PID and ANFIS-PID controller for STATCOM are applied to diesel generator wind energy hybrid system and the performance is compared.[11] ANFIS-PID controller supresses the fluctuations in voltage to a greater extent compared to Fuzzy-PID and PID controller.[12] Fuzzy logic control gained importance owing to its simple design and ease of implementation. But tuning the membership functions solely depends on the knowledge and experience of the trainer. On the other hand, Artificial Neural Network (ANN) based controller takes long time to process and converge. Hence adaptive neuro fuzzy inference system which combines the merits and overcomes the shortcomings of both the above methodologies is given more preference these days.[13–18]

The fuzzy IF-Then rules are encoded into a neural network-based structure in an ANFIS controller and then suitable learning algorithm is applied to train the data set and reduce the error. Also, training fuzzy membership to reduce the error using ANFIS controller remains to be an effective methodology as there is no rule sharing and unity weight is applied for each rule.[19–26] ANFIS controllers are also easy to implement and it possess self-learning and adaptive nature.[27]

In this work, Particle Swarm Optimization (PSO) based learning algorithm for ANFIS controller is applied to static compensator to improve the voltage regulation and reactive power compensation in a renewable energy based micro-grid. Particle swarm optimization is preferred over other methodologies because it is simple to implement, robustness in controlling parameters and high computational efficiency.[28] In the proposed cascaded ANFIS-PSO controller, PSO will tune for optimal value of ANFIS parameters. The performance of this controller for STATCOM was investigated by simulation under load varying conditions. The effectiveness of the proposed controller is compared with the results obtained using PI and ANFIS controllers in the system.

Materials and Methods

Microgrid System – Model

It comprises the RES (solar and WECS system), which provides power to the DC bus and an energy storage system (Battery). These combinations deliver to the AC load-connected to it. In order to regulate the voltage of the proposed topology, STATCOM is implemented (Fig. 1).

Photovoltaic Cell

Photovoltaic cell whose equivalent circuit as shown in Fig. 2 are made of semiconductor materials, makes use of photovoltaic effect and converts incident solar light into charge carriers. If the intensity of the incident photons is large enough to detach covalent electrons from the p-n junction of the semiconductor material, electric current is produced. Irradiance and temperature are the main controlling factors. Equation representing photovoltaic cell characteristics is as given below

$$I = I_L - I_0 \exp\left(\frac{(V+IR_S)}{nV_T} - 1\right) - \frac{V+IR_S}{R_{sh}} \qquad \ldots(1)$$

where I and V represents the current and voltage of solar panel, correspondingly.

$$I_L = N_p I_{L\,cell} \qquad \ldots(2)$$

I_L is the current generated due to photons in a PV module comprising of N_p number of parallel cells.

The system consists of solar panels which can deliver 10 kW. The voltage obtained from these panels is converted into 300 v /50 Hz AC through an inverter. The inverter is switched using 4 KHz, SPWM topology.

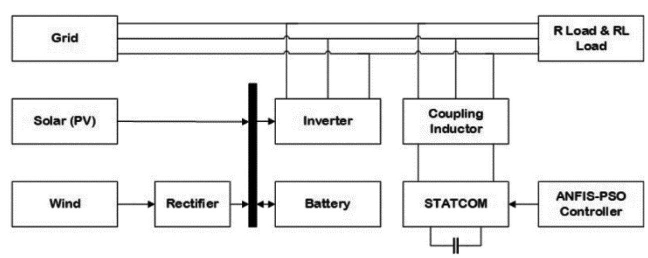

Fig. 1 — Microgrid system block diagram

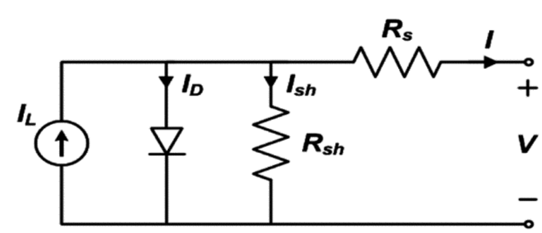

Fig. 2 — Photovoltaic circuit- Equivalent representation

Wind Energy Conversion System

The wind turbine converts the kinetic energy of the wind falling on the blade into mechanical energy which is governed by air density (ρ), Area swept by rotor (A) and wind velocity (V). Permanent magnet Synchronous generator coupled to the shaft of the turbine also rotates and generates electricity. Bernoulli's equation gives relationship between governing factors and the output power (Pw) produced as stated below

$$P_W = \frac{1}{2}\rho A V^3 \qquad \ldots(3)$$

However, it is not practically feasible to retrieve the entire power generated by the wind turbine. Possible power that can be extracted (P_T) depends on the speed and pitch angle of the rotor. C_PC_P (Power coefficient) is generally chosen as 0.593. This is termed commonly as Betz limit.

$$P_T = \frac{1}{2}C_P \rho A V^3 \qquad \ldots(4)$$

where C_P is called power coefficients whose value normally ranges around 0.593. This is generally referred as Betz limit. Value of C_p can be controlled using two factors such as pitch angle of the blades (β) and tip speed ratio (TSR).

Energy storage device

The Battery Energy Storage System (BESS) presented here stores an energy generated by RES. It will be utilized whenever demand at the load side exceeds generated energy or under cloudy days. In the proposed system, the lead-acid batteries are utilised for long-period backup. For safety, the batteries should regularly charge / discharge.

An Overview of STATCOM

Synchronous compensators (Fig. 3(a)) are shunt connected near load which aids in reactive power compensation of the power network. The controller quickly absorbs or injects necessary reactive current and regulates the voltage at the point of coupling. This current controlled device provides superior performance for the networks associated with wide voltage variations and harmonics. By controlling the switching of inverter, phase delay between the source voltage (Vs) and inverter voltage (V_I) is dynamically controlled. When the phase difference is zero there is no reactive power exchange. Capacitive reactive power is generated when V_I is greater than Vs, whereas inductive reactive power is generated when Vs is greater than V_I.

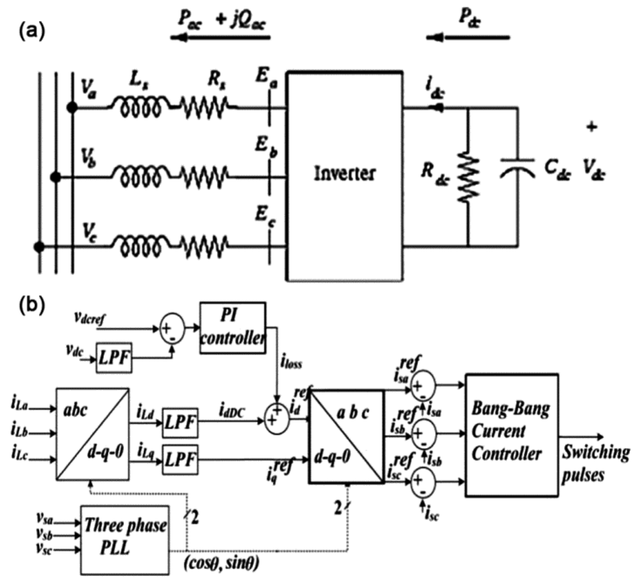

Fig. 3 — Equivalent circuit of (a) a static compensator, (b) d-q transformation

Synchronous Reference Frame Theory

Park's transformation given in Fig. 3(b) transforms the three phase quantities on to a reference frame. Three phase load current is fed to abc to dq0 transformer and the result obtained is passed through a low pass filter to attain reference values and remove the harmonic components of load currents. The sin θ and cos θ terms required for synchronization are provided by the three phase PLL circuit.

Low pass filter is designed using a butter worth filter where the range of cut off frequency is 75 Hz. The harmonic component is subtracted from the output of the voltage controller to discard the steady state error. Q axis and d axis AC Components aids in reactive power compensation and hence elimination of harmonics. In this method the DC voltage regulator determines reference grid current peak value.

STATCOM Controller

ANFIS- Adaptive Neuro Fuzzy Inference System

ANFIS is an intelligent control technique which utilizes fuzzy logic controller to transform input data into desired output over neural network which is greatly interconnected. Learning properties of neural network is utilized to fine tune the parameters of fuzzy logic controller. Different membership functions must be employed for each rule. A two input one output ANFIS structure with some set of rules and five distinct layers is considered.

IF-Then Rules of Takagi-Sugeno Model

Rule 1 : *if* $x1$ *is* A_1 *and* $x2$ *is* $B1$*;*
Then $f1 = a_1x_1 + b_1x_1 + c_1$

Rule 2 : *if* $x1$ *is* A_2 *and* $x2$ *is* $B2$*;*
Then $f2 = a_2x_1 + b_2x_2 + c_2$

where A1, A2, B1, B2 represents the fuzzy sets, x and y are the inputs applied and f1 and f2 gives the output calculated from fuzzy rule and lies inside the fuzzy region.

Layer 1: First layer of the network computes the degree of membership for each input using bell shape membership function. Any other type of membership function can also be employed.

$$\mu_A(x) = gbell(x, a_i, b_i, c_i) = \frac{1}{1+\left|\left(\frac{x_i-c_i}{a_i}\right)^2\right|^{b_i}} \quad \ldots(5)$$

where a_i, b_i a_represents the linguistic labels and x and y are the inputs.

Layer 2: In order to fuzzify the inputs AND operator is used in this layer. The output of the layer is firing strength of rules

$$w_i = \mu A_i(x).\mu B_i(y). i = 1,2 \quad \ldots(6)$$

Layer 3: Fixed node performs normalization of the incoming firing strength from 2nd layer.

$$\overline{w_i} = \frac{w_i}{w_1+w_2}, i = 1,2 \quad \ldots(7)$$

Layer 4: Adaptive node calculates the product of polynomials of Sugeno first order with normalized firing strength from previous layer.

$$\overline{w_i}f_i = \overline{w_i}(p_i + q_i y + r_i) \quad \ldots(8)$$

With $p_i, q_i, and\ r_i$ as node parameters.

Layer 5: Incoming signals are added at the rule inference node.

$$\text{Overall output} = \sum_i \overline{w_i} f i = \frac{\sum_i w_i f i}{\sum_i w_i} \quad \ldots(9)$$

Error (e) and change in error (ce) are presented as inputs to the ANFIS controller at the fuzzifier section. Gaussian triangular membership function utilized are categorized into 7 types as presented below: Negative Large (NL); Negative Average (NA); Negative Minor (NM); Zero (ZE); Positive Minor (PM); Positive Average (PA) and Positive Large (PL). The rule base of ANFIS controller is tabulated in Table 1. The defuzzifier section selects the optimal value from the crisp set and outputs the optimal duty ratio (d) to control the STATCOM in this work.

The architecture of ANFIS controller developed in a MATLAB environment is depicted in Fig. 4(a). From the figure each inputs error and change in error are systematically connected to 7 membership functions defined above. The ANFIS controller must be well trained to identify the optimal rule (49 rules) from the available rules in the 2nd and 3rd layers. In the 4th layer best favourable is fired and is subsequently defuzzified at the 5th layer. The duty ratio (d) available at the output is used to switch the converter. The final ANFIS rule base surface view after training is depicted by the Fig. 4(b) as given above.

Particle Swarm Optimization

PSO is a nature stimulated evolutionary algorithm which is robust and stochastic in nature. James kennedy and Russ Eberhart introduced PSO in 1995. The basic inspiration of the algorithm was based on the movement and interaction between individual (particle) in a population (Swarm) of fishes or birds or

Table 1 — Rule base of ANFIS controller

Δe/e	NL	NA	NM	ZE	PM	PA	PL
NL	NL	NL	NL	NA	NA	NM	ZE
NA	NL	NL	NA	NM	NM	ZE	PM
NM	NL	NA	NM	NM	ZE	PM	PA
ZE	NA	NM	NM	ZE	PM	PM	PA
PM	NA	NM	ZE	PM	PM	PA	PL
PA	NM	ZE	PM	PM	PA	PL	PL
PL	ZE	PM	PA	PA	PL	PL	PL

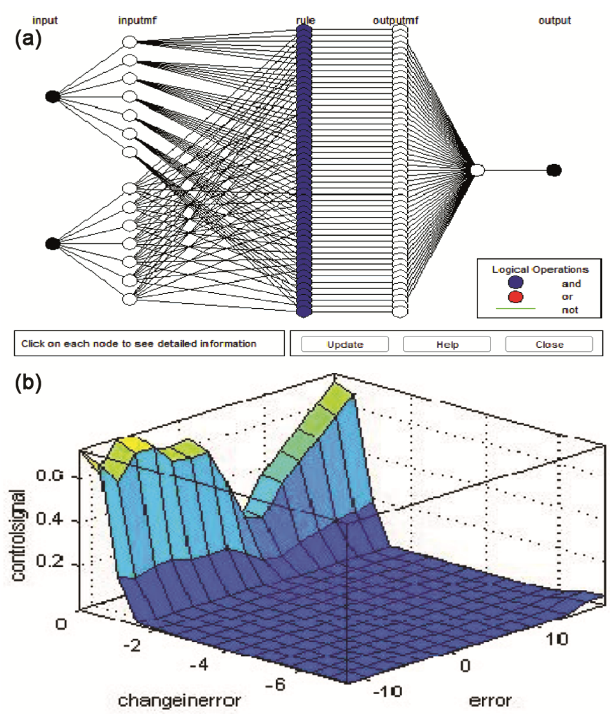

Fig. 4 — ANFIS (a) Structure- MATLAB, (b) Rule base surface view-MATLAB

bees. Initially a search space is identified and the individuals present in the space makes a search in multi dimension to attain an optimal solution. For the given problem each individual is considered as a fitness solution. Each particle updates local best P^{best} and the global best i.e. G^{best} when it moves forward in search of optimal solution. Each particle at any time can signified using three parameters. The current position (X-vector), direction of movement (V-vector) and local best attained do far (P^{best}). X-vector: represents the current location of the individual in the search space.

$$V_i^{t+1} = \omega\, X\, V_i^{(t)} + C_1\, X\, r_1 X \left(P_i^{best} - X_i^{(t)}\right) + C_2\, X\, r_2\, X(G^{best} - X_i^{(t)}) \quad ...(10)$$

The current velocity of the particle is updated every time using the Eq. 10. V_i^{t+1} gives the current velocity of the i^{th} particle where $V_i^{(t)}$ is the old velocity, ω is the particle inertia weight, C_1 and C_2 are acceleration coefficient, r_2 and r_1 are random numbers and $x_i^{(t)}$ is the existent position of the individual i at t^{th} iteration. The ideal range for acceleration coefficient varies between 0 and 4 and 0.9 to 0.4 in case of inertial weight. The value of inertial weight is decided depending on the necessary amount of damping. The value of random number is opted between 0 and 1. The formula to calculate inertial weight with initial weight (ω_{min}) and final weight (ω_{max}) is as below.

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} \times iter \quad ...(11)$$

$$X_i^{(t+1)} = X_i^{(t)} + V_i^{(t+1)} \quad ...(12)$$

In Eq. 12 the current position of individual with respect to the updated velocity is updated. This equation drives the particle towards the best fitness value as it depends on both local and global best. The algorithm terminates after a specified number of epochs or when a best fitness value is attained whichever is earlier.

Proposed PSO- ANFIS

In PSO- ANFIS, ANFIS is represented as one particle which yields a potential solution. The variables which influence the function of the ANFIS are taken as particle dimension. Thus, the flowchart representation of proposed control strategy is depicted in Fig. 5.

Based on Fig. 5, the procedure of PSO- ANFIS is as follows

Step 1. For each particle with velocity V generate initial particles P of population size = N. ANFIS consequent parameters, linguistic borders and optimal normalization rule elements are allotted with random integer values ranging 0 or 1. Minimum and maximum values from dataset form the elements of membership parameter.

Step 2. For each particle put on a local search based on adaptive neuro fuzzy inference system (ANFIS) and obtain preliminary fitness function.

IF x is A_1 AND y is B_1 THEN $f_1=p_1x+q_1x+r_1$

IF x is A_2 AND y is B_2 THEN $f_2=p_2x+q_2x+r_2$

Step 3. Identify Personal best (P^{best}) for each particle.

Step 4. Analyse P^{best} results and obtain global best (G^{best}) which in turn is the candidate solution.

Step 5. Check the objective function.

Objective function**:** $ITAE = 1000 \int_0^t \Delta v\, t.dt$

If stop criterion is reached, go the solution else continue to the next step.

Step 6. Repeat main procedure of PSO- ANFIS.

Thus, the parameter settings of a PSO- ANFIS process are described in Table 2.

Simulation Results and Discussion

Solar PV and Wind energy are connected to the medium level Microgrid along with a battery. Owing to the intermittent nature of the renewable sources power quality problems increase in the system.

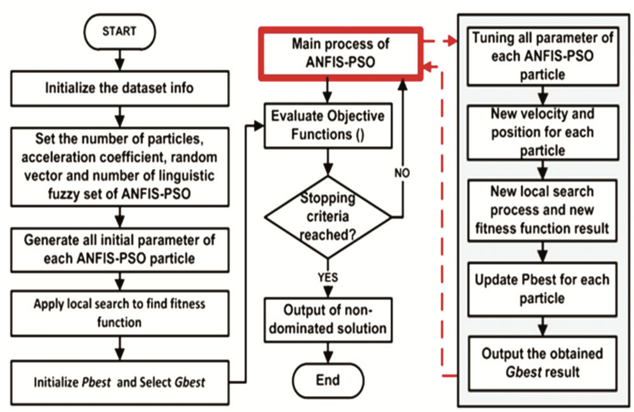

Fig. 5 — Flow chart of proposed control strategy

Table 2 — Specification of parameter used in PSO-ANFIS controller

Parameters	Value
Population	100
Number of linguistic fuzzy set	3
Type of membership function	Gaussian function
Number of iterations	1000
Acceleration coefficient	c1 = 0.5; c2 = 1
Random vector r1 and r2	r1=r2=1.2

Various problems like harmonics, voltage variations either slow or quick and frequency variations may arise in the system increasing power quality issues. Voltage variation and harmonics are major problems which can be mitigated through reactive power compensation by implementing STATCOM.

Voltage Profile Improvement

Voltage profile of the Microgrid at the bus without STATCOM and with STATCOM are depicted in Fig. 6 (a and b) respectively. The voltage profile at Fig. 6(a) shows ± 10% variations in voltage from time to time without STATCOM whereas Fig. 6(b) depicts the voltage profile after including controllers. The proposed controller has reduced overshoot and fluctuations much better than PI and ANFIS. The superiority of the controller is proved in terms of performance indices.

From Table 3, it can be seen that the performance of PSO-ANFIS is superior to the performance of other controllers. Low value IAE represents less sustained oscillations, whereas low ISE indicates the capability to produce fast response and quick elimination of large errors. Utilizing ITAE tuning method helps the system quicker compared to other two above mentioned errors.

Table 3 — Error comparison between controllers

Controllers	IAE	ISE	ITAE
PI	108.25	6.32	2.245
ANFIS	91.36	5.89	1.9745
PSO-ANFIS	90.45	5.82	1.931

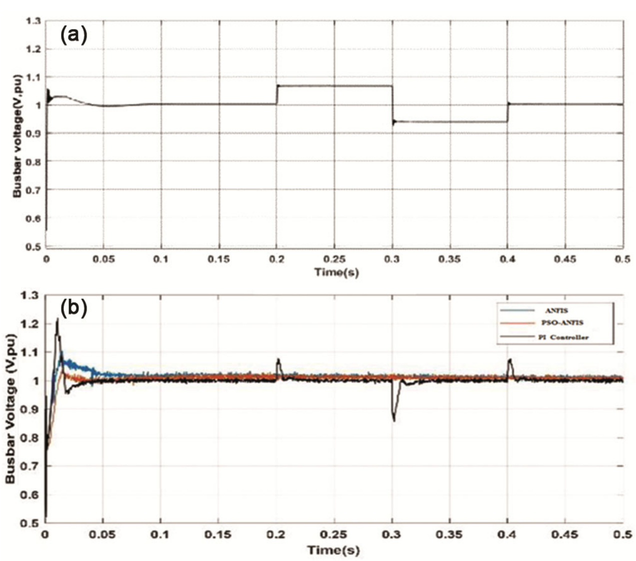

Fig. 6 — Bus bar voltage profile (in p.u.) (a) Without STATCOM, (b) Comparison for controllers (PI, ANFIS, PSO tuned ANFIS)

Harmonic Reduction and Reactive Power Compensation

The current waveform of the system source which is not linear is shown in Fig. 7(a). The reactive power compensation provided by the STATCOM to overcome the above non-linearity is presented in Fig. 7(b). The current output after compensation is presented in Fig. 7(c) and the waveform is highly linear. The harmonic level in the system which is at 6.5 % is reduced to 4.8 % when conventional PI controller is installed (Fig. 7(d)). The harmonic developed in the system gets reduced further with the

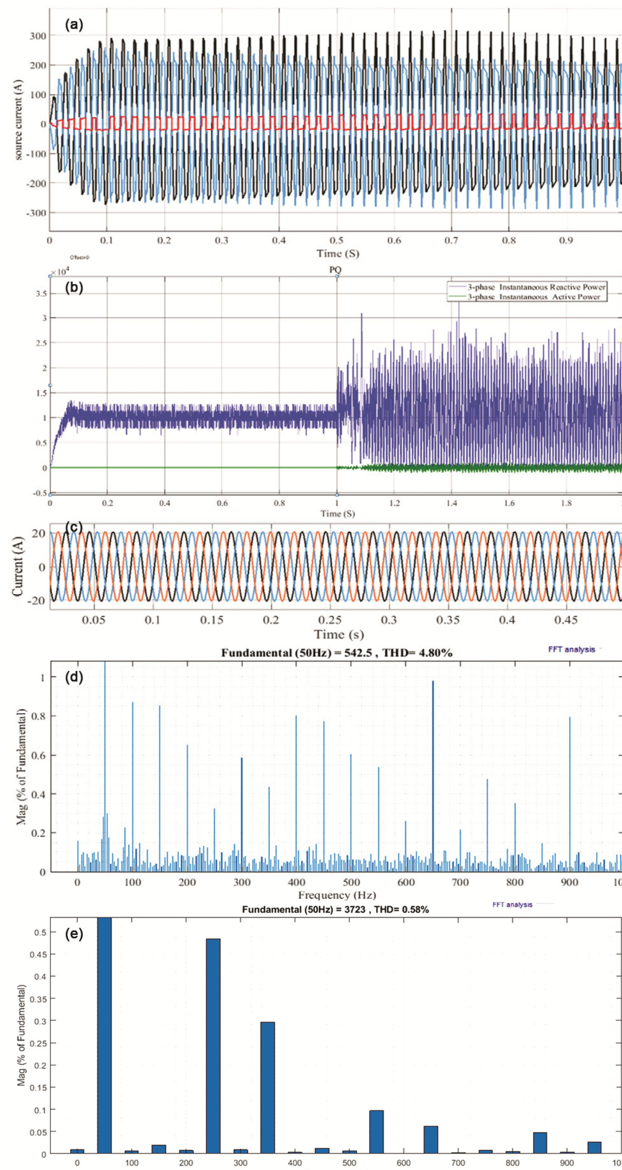

Fig. 7 — (a) Current waveform of the system, (b) Compensation current – STATCOM, (c) Current waveform after compensation, (d) THD of the system with PI controller based STATCOM, (e) THD of the system with PSO tuned ANFIS controller based STATCOM

Table 4 — Comparison of THD values

Controller	THD
Without any controller	6.5
PI Controller	4.8
ANFIS	1.5
PSO tuned ANFIS	0.58

Table 5 — THD comparison

Harmonic Order	Magnitude percentage of frequency (Before Compensation)	Magnitude percentage of frequency (After Compensation)
1	4.65	0.25
3	1.23	0.19
5	1.79	0.23
7	2.31	0.19
9	1.26	0.11

Table 6 — Power factor at different loads

	Loads	Active power	Reactive power	Power factor
Without STATCOM	Linear load (R Load)	9.2e+04	−42.1	0.86
	Nonlinear Load	−1.2e+06	4.95e+05	0.84
With STATCOM	Linear load (R Load)	−5.6e+06	−1.7e+06	0.98
	Nonlinear Load	−4.62e+06	−1.45e+06	0.92

introduction of ANFIS and PSO tuned ANFIS Controllers. The total harmonic distortion in the system is at 0.58% with PSO tuned ANFIS controller.

From the Table 4, it can be clearly observed that the proposed controller with the STATCOM reduces the harmonics about 4.6% of the system against the conventional PI controller coupled with STATCOM. Similarly, Table 5 depicts the magnitude of individual frequency before and after compensation.

Performance Analysis of the Micro Grid Subjected to Variation in Loading Conditions

The performance of proposed system with linear and non-linear loads is tested with and without STATCOM. The features of the controller are compared in terms of active power and reactive power produced and the power factor attained as mentioned below in Table 6. STATOM inclusion boosts the system power factor to a greater extent.

Conclusions

PSO tune ANFIS controller was designed for STATCOM controller which aided the system in improving voltage stability and power factor improvement. The test system is simulated in MATLAB / Simulink environment and the results are tabulated. The dominance of the designed controller is proved under various indices like harmonic reduction, power factor improvement and voltage profile improvement. The results confirm that the ANFIS tuned PSO controller is best suited for remote micro grids consisting of intermittent renewable energy sources. But the only limitation is that the STATCOM controller is not applicable to low voltage grids.

References

1 Acharya D P, Nayak N & Choudhury S, Active power management in an AC microgrid using artificial neural network and DSTATCOM, in APSIT (Siksha O Anusandhan deemed, Bhubaneswar) 8–10 Octobern 2021.

2 Mariam M & Kenjrawy H, Improving electrical power quality in distributed networks using a unified power quality conditioner controlled by an adaptive hysteresis band, *JMSEAT*, **23** (2021) 91–109.

3 Aiwa F, Al-Hayat M T & Suliman M Y, Power Quality improvement in Mosul city using shunt active power filter, NTU-JET, **1** (2021) 19–24.

4 Datar P V & Kulkarni D B, A XGBOOST-MRFO control scheme for power quality improvement in grid integrated hybrid renewable energy sources using STATCOM, *Int Trans Electr*, (2021).

5 Sadiq R, Wang Z, Chung C Y & Zhou C, A review of STATCOM control for Stability enhancement of power systems with Wind / PV Penetration: Existing research and future scope, *Int Trans Electr*, **31** (2021).

6 Zahariah J & Tibbie Pon Symon V A, Harmonic mitigation in grid connected distribution energy systems using PI and fuzzy logic controller, *J Inst Eng (India)* Series B, (2021).

7 Qi J, Zhao W & Bian X, Comparitve study of SVC and STATCOM reactive power compensation for prosumer microgrids with DFIG based wind farm integration, *IEEE Access*, **8** (2020) 209878–209885.

8 Chandrasekaran K, Selvaraj J, Amaladoss C R & Veerapan L, Hybrid renewable energy based smart grid system for reactive power management and voltage profile enhancement using artificial neural network, *Energy Sources A: Recovery Util Environ Eff*, **43** (2021) 1–24.

9 Kulkarni S V, Gatade S, Samanvita N & Gaonkar D N, Comprehensive strategy for power quality improvement of inverter based distributed generation system, in *Emerging Research in Computing, Information, Communication and Applications*, edited by N R Shetty, L M Patnaik, H C Nagaraj, P N Hamsavath, N Nalini, Lecture Notes in Electrical Engineering, (Springer, Singapore) **790**, 2022, 185–195, https://doi.org/10.1007/978-981-16-1342-5_14.

10 Suvire G O & Mercado, P E, Improvement of power quality in wind energy applications using a DSTATCOM coupled with a flywheel energy storage system, in *IEEE-COBEP* (Bonito-Mato Grosso do sul, Brazil) 27th September–1st October 2009, 58–64.

11 Anulal A M, Mohan A & Lathika B S, Reactive power compensation of wind diesel hybrid system using

STATCOM with fuzzy tuned and ANFIS tuned PID controllers, *IEEE -ICCC* (Trivandrum, India) 19–21 November 2015, 325–330.

12 Wang J, Mu S, Zhou Q & Li Y J, Design and performance analysis of PV-SMES based microgrid integrated with power fluctuation suppression and active filtering control, *IEEE-TAS*, **318 (**2021) 1–5.

13 Rani P, Arora V P & Sharma N K, Improved dynamic performance of permanent magnet synchronous generator-based grid connected wind energy system, *Energy Sources A: Recovery Util Environ Eff*, (2022) 1–20.

14 Dash R L, Tripathy S, Mohanty B & Hota P K, Power quality improvement of grid connected wind system with STATCOM in *1st ICPEE* (Bhubaneswar, India) 2–3 January 2021, 1–6.

15 Gautam S & Agarwal S, Performance analysis of three phase grid connected PV array with ANN controlled SAPF, in *2nd GCAT* (Bangalore, India) 1–3 October 2021, 1–6.

16 Srikanth Goud B, BWO strategy for power quality improvement in HRES grid-connected DPFC system, *Smart Sci*, **93** (2021) 226–243.

17 Elzoghby H & Ramadan H S, Isolated micro grid stability reinforcement using optimally controlled STATCOM, *Sustain Energy Technol Assess*, **504** (2022).

18 Fanjip R C, Naoussi S R D, Kom C H, Nanfak A & Ngaleu G M, Fuzzy slide mode control of a shunt active power filter for harmonic reduction in grid connected photovoltaic systems, *JEEECCS*, 8 **27**(2021) 43–54.

19 Uddin N, Khallil Md E, Das T K & Sarker S, Evaluation of active filter design and harmonics analysis using MATLAB, in *IEEE ACMI* (Rajshahi, Bangladesh) 8–9 July, 2021.

20 Maheswari M & Gunasekharan S, Operation and control of microgrid: research anthology on smart grid and microgrid development, (IGI Global, US), 2022, 1437–1458.

21 Akpinar E, Hafezi H & Balıkcı A, Cascaded controller for single-phase shunt active power filter and STATCOM, *Int J Renew Energy Technol*, **13** (2022) 28–47.

22 Wang H & Wang Z, Analysis on the Effects of STATCOM for prevention of voltage instability, in *40th CCC* (Shanghai, China) 26–28 July 2021, 6840–6845.

23 Elgebaly A E, Mansour D-E A & Amr A M, Voltage control of 11-kV AC grid using STATCOM fed with DC microgrid, in *IEEE-EIConRus*, (St. Petersburg, Moscow, Russia) 26–29 January, 2021.

24 Coo L, Huang H-S, Lee M-F, Lin Y-S, Huang Z-H, Gao H-Y, Tseng C-W, Tseng C-C, Prokhorov A, Mokhlis H, Chua K H & Tripathy M, Stability improvement of a DC microgrid fed to a multimachine power system using a STATCOM, *IEEE IFEEC* (2021).

25 Ahmadi M, Sharafi P, Mousavi M H & Veysi F, Power quality improvement in microgrids using STATCOM under unbalanced voltage conditions, *Int J Eng Technol*, **34** (2021) 1455–1467.

26 Merritt N R, Chakraborty C & Bajpai P, An E-STATCOM based solution for smoothing Photovoltaic and Wind Power fluctuations in a Microgrid under unbalanced conditions, IEEE *Trans Power Syst*, (2021) 1–1, doi: 10.1109/TPWRS.2021.3106859.

27 Kumar T B & Rao M V G, Mitigation of harmonics and power quality enhancement for seig based wind farm using ANFIS based STATCOM, in *IEEE-ISEG* (Guntur, India) 19–20 September 2014, 1–7.

28 Liu C-H & Hsu Y-Y, Design of a self-tuning PI controller for a STATCOM using particle swarm optimization, *IEEE Trans Ind Electron*, **57** (2010) 702–715.