Enhancement of Power Quality in Renewable Source Integrated Three Phase System with ICC Controller

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Abstract

Forthcoming generation of industrial revolution completely changes the living standards of world population. In addition, growing phase of industrial revolution has more impact on grid system in terms of power demand and topology. Traditional power generating system adopts renewable source integration to deal with dynamic energy demand. Coalescing of green energy sources and industrial revolution hinders Power Quality of overall system. Industrial non linear loads and uncertain source of renewable energy units are the major causes of PQ degradation. To enhance PQ in renewable source interfaced grid system, ANFIS based ICC controller is proposed for shunt connected active filter. Photovoltaic Unit is optimally interfaced to grid for aiding PQ enhancing process. ICC based APF performance is investigated in MATLAB/SIMULINK platform. Proposed controller performance is analyzed for balance and unbalance load conditions.

Keywords: Power Quality, Renewable Energy Sources, Active Power Filters, Fuzzy Controller, ANFIS Controller.

1 Introduction

Innovations in industrial and domestic equipment increases need of electrical power supply and usage of non linear loads. A non linear load increases harmonic content in power supply. Harmonic polluted supply has adverse affects on power system equipment and consumer loads [1–3]. Main challenges of modern power system are to provide reliable power supply, continuity in power supply and protecting consumer equipment from grid side abnormalities. Power Quality (PQ) improvement and renewable source integration attains utmost importance in modern power system. Malfunctioning of equipment, heating of winding, overloading and power losses are the adverse effects of harmonics. Reliable power can be achieved by alleviating PQ issues. Active power Filters plays a paramount role in achieving quality power supply [4, 5].

APF's with felicitous control methods enhance system power quality [6, 7]. In latest developments like Internet of Things (IoT), uncertain power demand is supplied by proper maintenance of renewable sources and traditional power generation units [8–12]. With statistical analysis in IoT, devices are integrated to achieve quality power supply and reduction in power losses. In support to IoT in power sector, this paper contributes optimal integration of renewable source and efficient control method for APF. Here, proposed APF acts like power conditioning device for interfacing renewable source and power quality enhancing device.

In literature various control techniques were proposed to generate reference signals for Active Filter. Such as instantaneous active and reactive current theory (dq), symmetrical component theory (SC), instantaneous reactive power theory (pq), synchronous reference frame theory (SRF) and Perfect harmonic cancellation (PHC) [12–19]. In [13], authors presented comparative study of 4 different control techniques. Here, SC, pq, dq and modified-dq controllers were studied for current harmonic suppression. Modified-dq controller achieved better %THD. Similarly, in [14] and [15] authors proven dq controller is efficient than pq control strategy in harmonics alleviation. For further PQ enhancement soft computing methods like Fuzzy [16], ANN [17, 18] and PSO [14, 19], have been implemented for shut connected active filters.

A modified dq control strategy is proposed for active filter in [3]. In this paper, controller considers supply voltage error and DC link error to generate more effective reference currents. Further, Fuzzy controller replaces PI controller for better THD improvement. In current research paper, we replaced modified dq controller with ICC controller and PWM controller with HCC
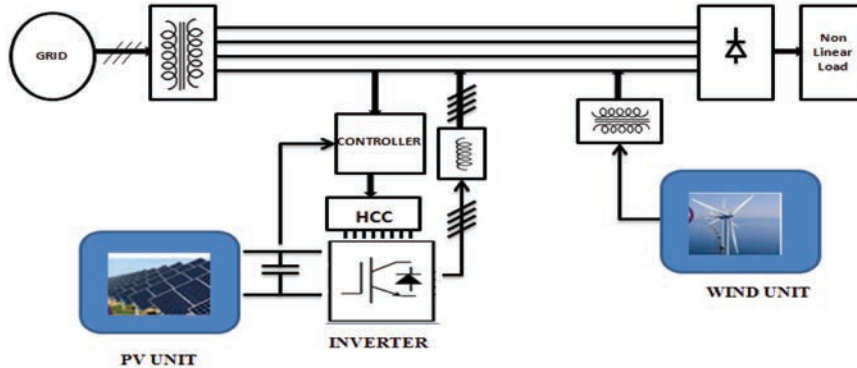
Figure 1   Block diagram of proposed renewable source integrated grid system.

controller. In addition, ICC controller performance is studied with PI, Fuzzy and ANFIS controllers. Comparatively dq controller has more computations and slow response than ICC controller.

Primary targets of proposed system are alleviation of harmonics in source current, reactive power compensation and effective renewable source integration. Proposed control method is engaged for harmonic mitigation and its performance is compared with traditional PI, Fuzzy and ANFIS controllers. Integrated renewable sources like PV/Wind units contribute part of load power. This inturn reduces real power supplied from grid. Block diagram of proposed three phase system is shown in Figure 1.

In this paper, exordium section presents the literature survey and objective. Proposed model and control scheme are well illustrated in Section 2. Section 3 presents interesting outcomes of proposed system. Final conclusions are drawn in section 4.

2 Proposed System Description

Proposed system uses ICC controller for Shunt Connected Active Filter (SCAF). Figure 2 describes proposed renewable source connected three phase system. From the proposed model, SCAF connected at source side in order to improve supply side power quality. Wind unit is interfaced at load side, which delivers real power and demands reactive power from line. PV unit is fed at DC side of SCAF. ICC controller is proposed for SCAF to suppress reactive power and harmonics at PCC. Integrated PV unit delivers part of real power required by load.
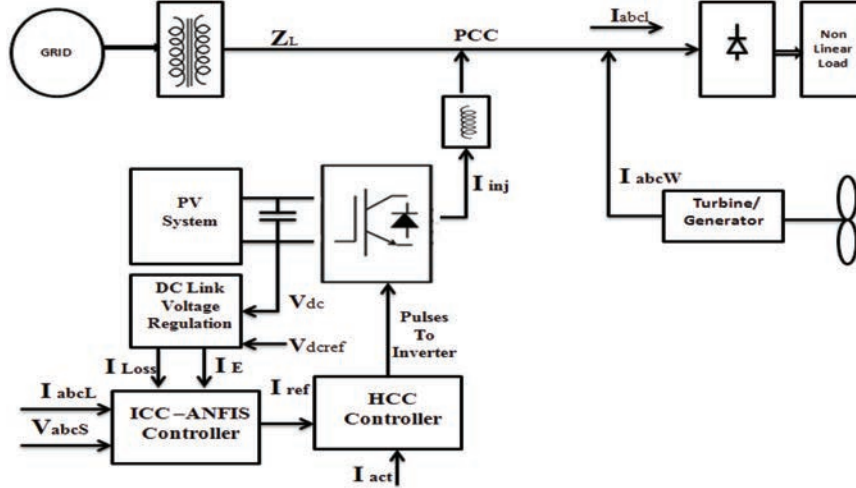
Figure 2   ICC controller based PV fed SCAF-Three phase system.

2.1 Wind System

Wind system comprises of wind turbine & asynchronous generator as shown in Figure 3. Asynchronous generator has merits, such as protection against short circuit and doesn't require additional field circuitry [12]. Power generated by wind unit depends on wind velocity and it is given by

$$P_{wind} = \frac{1}{2}\rho\pi R^2 V_{wind}^3 \tag{1}$$

Here, V_{wind} - speed of wind, R - Rotor radius & ρ - Density of Air. Relation among mechanical and wind power given by

$$P_{mech} = C_p \times P_{wind} \tag{2}$$

Here, P_{mech} is mechanical power developed by wind turbine given as

$$P_{mech} = \frac{1}{2}\rho\pi R^2 V_{wind}^3 C_p \tag{3}$$

The mechanical-torque is given by

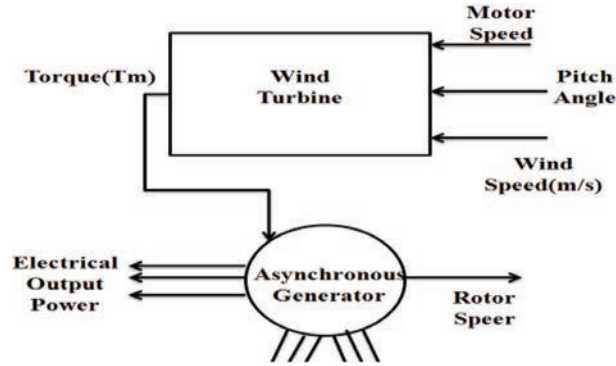$$T_{mech} = \frac{P_{mech}}{\omega_{mech}} \tag{4}$$

Figure 3 Wind unit.

2.2 PV Unit

Proposed photovoltaic source is integrated at DC link side delivers power required by SCAF to achieve desired outcomes. PV unit comprises of DC/DC boost converter, MPPT controller and PV cell. Several MPPT methods are available [10, 20, 21]. Among them most oftenly used MPPT technique is P & O [22]. This method has advantages like fewer parameters and simple design. Figure 4 presents PV module and Figure 5 represents equivalent circuit of solar cell.

Power generated from PV source is given by equation

$$P_p = V_P \times I_P \tag{5}$$

PV Source voltage and current are given in [10] below equations,

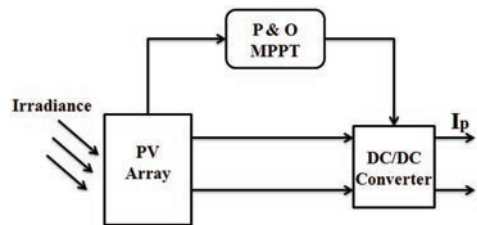$$V_P = \frac{AkT}{q} \ln \left\{ \frac{I_{sc}}{I_P} + 1 \right\} \tag{6}$$
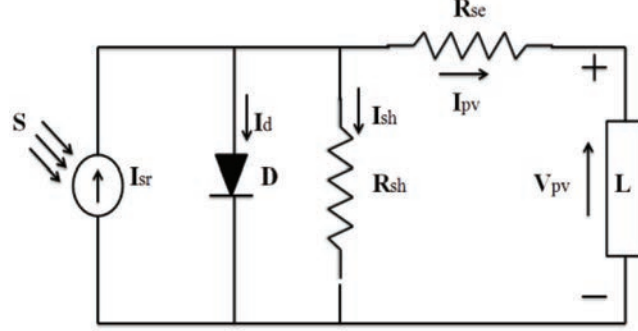

Figure 4 Photovoltaic unit.

Figure 5 Photovoltaic unit equivalent circuit.

$$I_P = I_{sc} - I_{sat}\exp\left[\frac{q}{AkT}(V_p + I_pR_{se}) - 1\right] - \frac{V_p + I_{sc}R_{se}}{R_{sh}} \quad (7)$$

Here, R_{sh} = Shunt Resistance, R_{se} = Series Resistance, A = Diode Ideality Factor and k = Boltzmann constant.

From Figure 4, MPPT controlled PV unit is connected to DC/DC converter. This combination maintains inverter's DC link voltage at fixed value.

2.3 ICC Controller

ICC controller is an effective technique for harmonic alleviation, compensation of reactive power and unbalanced load condition. Earlier in [3], authors proposed dq controller for harmonic compensation. This technique has more computations due to complex transformations [13]. Comparatively ICC controller has lesser computations and capable of unbalanced load compensation, reactive power compensation, harmonic suppression and UPF at supply side. In addition ICC based VSI injects part of real power from PV unit to the load. Here, ICC controller is designed for both balanced and unbalanced conditions. From Figure 6, proposed ICC control technique regulates both DC link voltage and source voltage. Active power delivery between grid and PV unit governed by V_{dc} regulation. The active component from PI controller is given in equation,

$$I_{mdsk} = I_{mds(k-1)} + K_{\mathrm{pVdc}}(V_{dcek} - V_{dce(k-1)}) + K_{Ivdc}V_{dcek} \quad (8)$$

I_{mds} is again combined with I cos component to produce I_{ds} which is given by

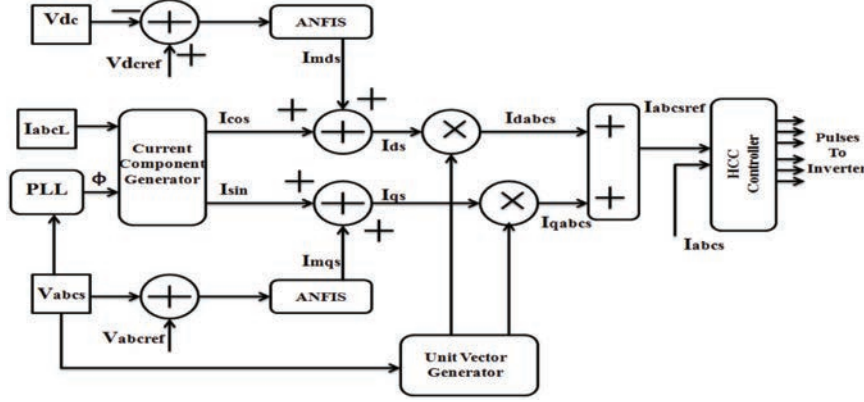$$I_{ds} = I_{mds} + I_{cos} \quad (9)$$

Figure 6 I Cosine current (ICC) control scheme.

$$I_{cos} = \frac{I_a cos\theta_a + I_b cos\theta_b + I_c cos\theta_c}{3} \tag{10}$$

Thus I_{ds} component is multiplied with unit vectors to generate reference direct component of current give by equations,

$$I_{das} = I_{ds} \times W_a^*, I_{dbs} = I_{ds} \times W_b^*, I_{dcs} = I_{ds} \times W_c^* \tag{11}$$

$$W_a = \frac{V_a}{V_m}, \quad W_b = \frac{V_b}{V_m}, \quad W_c = \frac{V_c}{V_m}, \tag{12}$$

Similarly reference quadrature component is generated as

$$I_{qas} = I_{qs} \times W_a^*, \quad I_{qbs} = I_{qs} \times W_b^*, \quad I_{qcs} = I_{qs} \times W_c^* \tag{13}$$

$$I_{qs} = I_{mqs} + I_{sin} \tag{14}$$

$$I_{sin} = \frac{I_a sin\theta_a + I_b sin\theta_b + I_c sin\theta_c}{3} \tag{15}$$

Final reference currents are generated as,

$$I_{asref} = I_{das} + I_{qas} \tag{16}$$

$$I_{bsref} = I_{dbs} + I_{qbs} \tag{17}$$

$$I_{csref} = I_{dcs} + I_{qcs} \tag{18}$$

Further, HCC controller [16, 23] is used to generate desired pulses from the difference of actual and reference currents. Switching functionality for Phase-A is given by

$$HB < (I_a^* - I_a) \to S_A = 1 \text{ and } HB > (I_a^* - I_a) \to S_A = 0 \tag{19}$$

Based on switching pulses, SCAF generates compensating currents which are injected into line to suppress harmonic content & reactive power at PCC.

2.4 Fuzzy Controller

Fuzzy controller [16, 24] is widely implemented logic in replacement of traditional controllers. For targeted signal generation, excitation signals will be passed through Fuzzification state, Fuzzy Inference state and Defuzzification state. Excitation signal E (error) & ΔE (change in error) response signal are transformed into fuzzy linguistic variables. 7 linguistics variables are chosen (HN, MN, SN, ZE, SP, MP and HP) with triangular membership function. In inference state fuzzy input values are associated to fuzzy output value based on rules in knowledge base. Figures 7 and 8 depicts chosen membership functions and fuzzy rules.
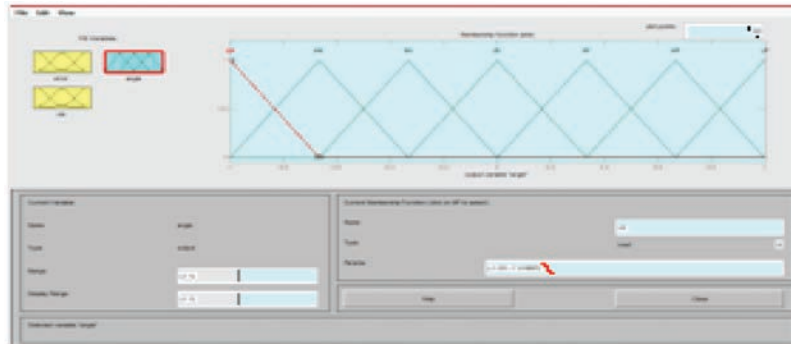

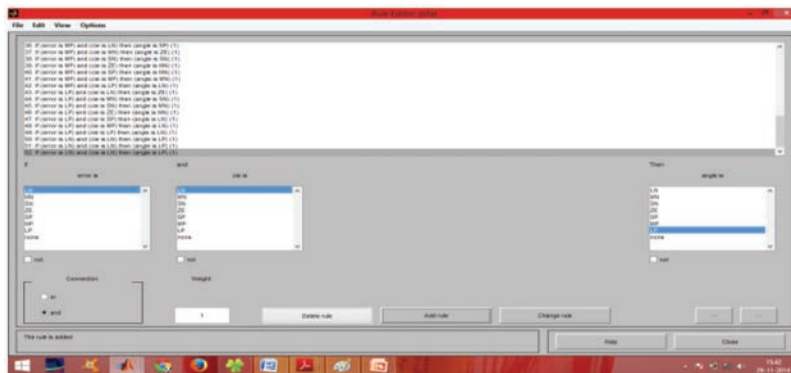**Figure 7** Fuzzy membership functions.

Figure 8 Fuzzy rules.

Fuzzy response from inference state are amalgamated in defuzzification state using centroid method to produce targeted crisp output value.

2.5 ANFIS Controller

In present model for better error tuning, traditional PI controller is replaced with ANFIS controller [25]. ANFIS has coalesced characteristics of Fuzzy [26] & Neural Networks [18, 27, 28]. ANFIS structure is presented in Figure 9. Error (E) & change in error (ΔE) are the inputs and current I_m is considered as output variable.

Primary layer response computed using equation

$$Y_1 = \mu f(E1) \tag{20}$$

Second layer nodes, performs multiplication of inputs as given in Equation (21). Second and third Layer nodes are fixed nodes.

$$Y_2 = \mu_{fi} f(E_1) \mu_{gi} f(E_2) \tag{21}$$

Where E_1 = Error and E_2 = Change in Error

In third layer, every node executes ratio of ith firing to sum of all firing strengths, given by

$$Y_3 = W_i' = \frac{W_i}{W_1 + W_2} \tag{22}$$

Fourth layer nodes are adaptive in nature and its function given by

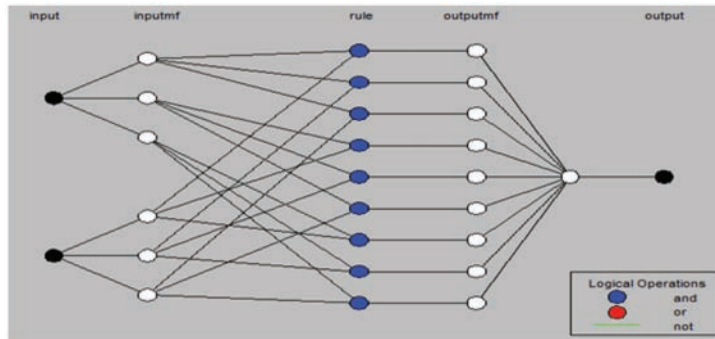$$Y_4 = W_i'(p_i E_i + Q_i E_2 + R_i) \tag{23}$$

Figure 9 Photovoltaic unit equivalent circuit.

Fifth layer consists of single fixed node whose function is to amalgamate all the inputs to deduce final outcome given by

$$Y_5 = \Sigma(Y_{4i}) \tag{24}$$

Here ANFIS learning is a two direction learning process. Least Square Error learning is adopted for forward learning process. Back propagation learning is utilized in backward direction. Current ANFIS model, 3 fuzzy linguistic values are selected (Low, Medium and High) for single output and two inputs variables.

3 Results

Presented ICC based SCAF controller performance is studied in MATLAB/SIMUNLINK platform. Specifications considered for proposed system are depicted in Table 1.

3.1 Steady State Performance

Non linear loads connected to line causes harmonics in source current. Asynchronous generator of wind unit & load demands reactive power at PCC. To compensate these harmonics and reactive power demand at PCC, equal and opposite currents have been injected by SCAF. Ergo, source current is free from harmonics. Along with this, SCAF performance is studied for both balanced and unbalanced load conditions.

Table 1   Parameters of the system

S. no.	Terms	Ratings
1	Supply Voltage	3 Phase 220 V, 50 Hz
2	Source and Line Impedance	Ls = 0.05 mH $R_l = 0.02\Omega$ $L_i = 0.1$ mH
3	Wind Generator	1.6 KW, 10 m/s
4	Solar Energy Unit	35 V, 8 A, (6 × 10) array
5	Non Linear Load	(A-N) R = 26.66Ω L = 12 mH (C-N) R = 36.66Ω, L = 10 mH

Figure 10 presents performance of ICC-SCAF controller under balanced load condition. After $t = 0.1$ sec, due to the injection of compensating currents, source current is sinusoidal. Similarly, Figure 11 shows performance of ICC-SCAF controller under unbalanced load condition. Here, the load current is supplied by source, PV fed SCAF and wind currents.

ICC controller effectively deals with balanced and unbalanced non linear load conditions. Under both conditions, before activation of ICC controller source currents are harmonic polluted and both real & reactive powers served by source to load. After ICC controller inclusion, contribution of source real & reactive power is reduced and rest of the power
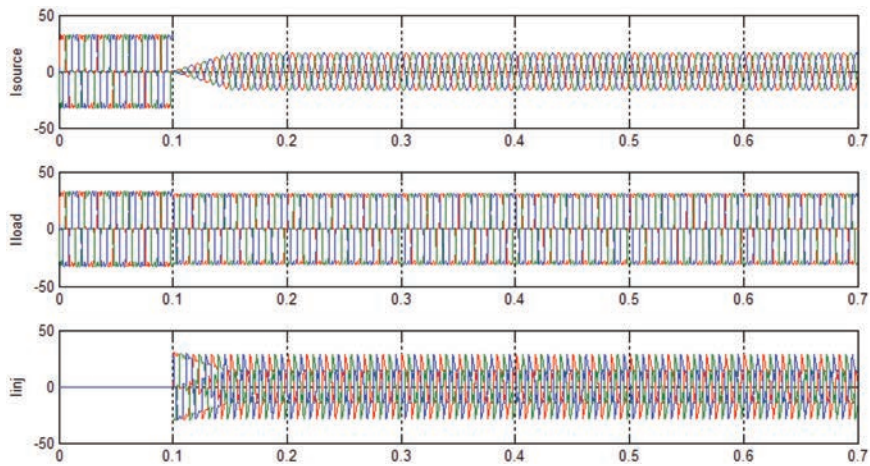

Figure 10   Grid current, load current and Inverter current with balanced load.
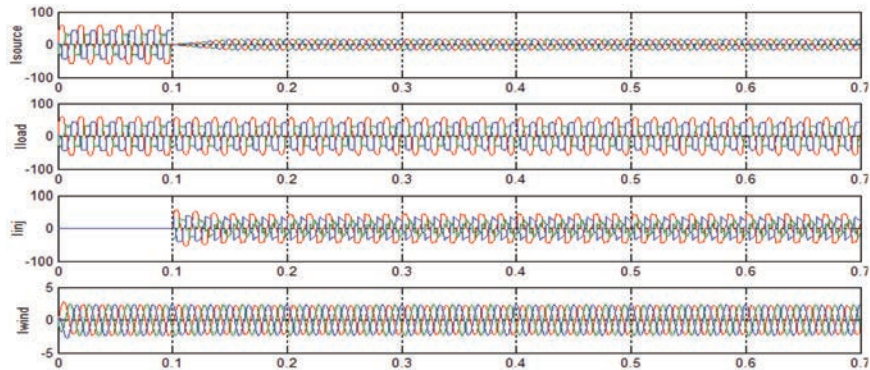

Figure 11   Grid current, load current, inverter current and wind current unbalanced load.

is delivered from PV fed ICC based active filter. Wind currents presented in [3] are not balanced and distorted. In this paper, wind system is properly designed and obtained balanced sinusoidal response currents from wind unit.

3.2 DC Link

PV fed ICC control technique maintains 300 V across DC link capacitor. DC link voltage is as shown in Figure 12.

3.3 UPF

The SCAF is integrated at T = 0.4 sec. Prior to this there is a deviation between current and voltage. Post SCAF is integration both current and voltage are in phase, inturn at PCC power factor becomes unity. In-phase grid current & voltage are as shown in Figure 13. After T = 0.1 sec, due to injection of required reactive power to line, source current is in phase with voltage. UPF is achieved with ICC controller where as dq controller in [3] achieves improved PF but not UPF. dq controller achieves PF of 0.96 and ICC controller achieves UPF.
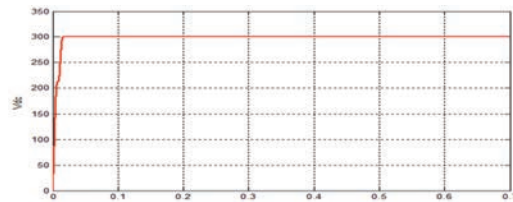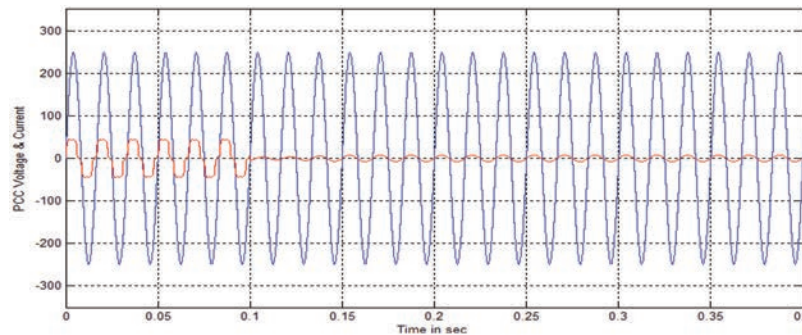

Figure 12   DC link voltage.

Figure 13   Source voltage and current waveforms.

3.4 Source Current Harmonics Under Balanced Source Voltage

Current harmonics suppression is studied under four different cases. Such as without SCAF, with PI-SCAF, with Fuzzy-SCAF and with ANFIS-SCAF.

Case 1: The % THD of source current without SCAF shown in Figure 14.

Case 2: SCAF is integrated to PCC at T = 0.1 sec. Post T = 0.1 sec, % THD of source current with traditional PI controlled SCAF is presented in Figure 15.

Case 3: SCAF is integrated to PCC at T = 0.1 sec. Post T = 0.1 sec, % THD of source current with Fuzzy-ICC based SCAF is shown in Figure 16.

Case 4: SCAF is integrated to PCC at T = 0.1 sec. Post T = 0.1 sec, % THD of source current using ANFIS-ICC based SCAF is presented in Figure 17.

Proposed ANFIS based ICC controller proves efficient performance in suppressing harmonics compared to PI & fuzzy controllers. In [3], PI & Fuzzy based dq controller achieves THD of 3.94% and 2.51% respectively. In this paper ICC controller achieves THD of 2.37%, 2.35% and 2.32% with PI, Fuzzy and ANFIS controllers respectively. With this analysis ICC
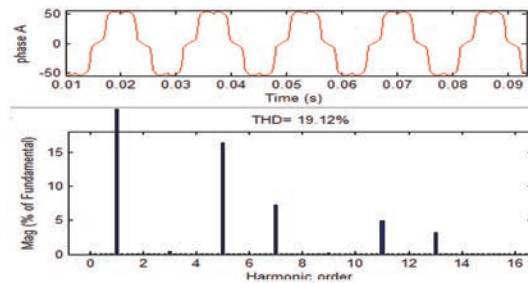

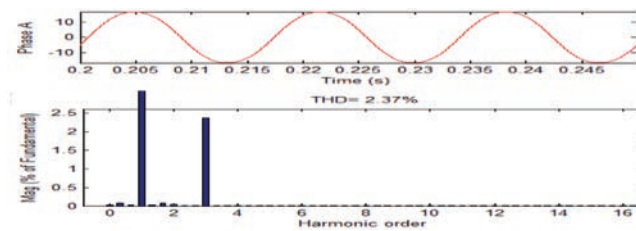**Figure 14**   %THD of source current I_a without ICC-SCAF controller.

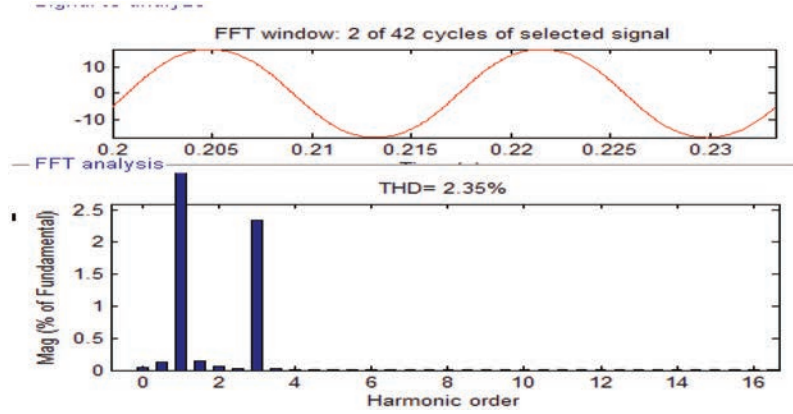**Figure 15**   %THD of source current I_a with PI-ICC-SCAF controller.

Figure 16 %THD of source current I_a with Fuzzy-ICC-SCAF controller.
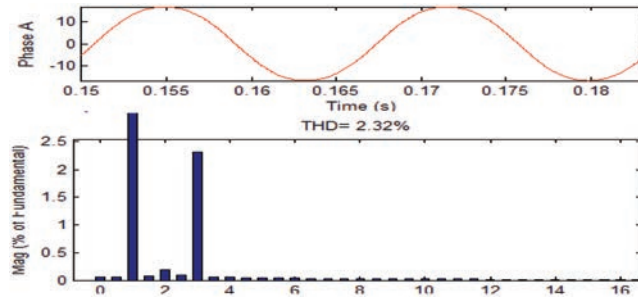
Figure 17 %THD of source current I_a using ANFIS-ICC-SCAF controller.

controller provides better performance than dq controller in harmonic reduction. Proposed ICC controller requires fewer computations than dq controller. HCC controller has faster response. Efficient ANFIS tuning ability aids ICC controller performance. From Table 2, it can be concluded that ANFIS-ICC controlled SCAF effectively alleviates harmonics of source current from 19.12% to 2.32% THD.

Table 2 Comparison of source current % THD and power factor

Terms	Without ICC-SCAF	With PI-ICC-SCAF	With Fuzzy ICC-SCAF	With ANFI-ICC-SCAF
Power Factor	0.86	1	1	1
%THD of Current				
Phase-A current (I_a)	19.12	2.37	2.35	2.32

4 Conclusion

Performance of proposed felicitous ICC control technique for SCAF is extensively studied in MATLAB/SIMULINK platform, in order to improve PQ issues in renewable source fed three phase system. Proposed controller effectively works for targeted PQ issues like harmonics in source current, non linearities in source current, unbalanced load condition and reactive power compensation. Renewable source fed at SCAF contributes part of load current delivery. Congruous design presented in this paper eliminates additional power conditioning devices for renewable source integration. Endurance functioning of ANFIS aids ICC controller in alleviating source current harmonics and brings unity power factor. Following are the vigorous outcomes of proposed model,

1. Harmonics of Source current are alleviated within IEEE limits.
2. Achieved UPF at PCC.
3. Renewable source contributes part of load current.

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Biographies

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