EFFECTIVE POWER QUALITY MANAGEMENT IN GRID CONNECTED WIND ENERGY SYSTEM THROUGH PERFORMANCE ENHANCED STATCOM

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Abstract: *Power system accompanied by the drastic number of challenges like dynamic change in the system, power quality issues and power flow are found to be more prominent ingrid-connected renewable system. Power quality management which arises due to non-linear loads connected to the system. Power quality management is the major factor for renewable application due to stochastic nature affects the operation of sensitive applications. To maintain appropriate power quality traditional approaches uses Static synchronous compensator (STATCOM) incorporated with Proportional-Integral (PI) controller by the principle of point of common coupling (PCC). In this research to improve the power quality management of renewable system traditional PI controller in STATCOM is replaced with fuzzy logic controller (FLC), artificial neural network (ANN) controller and adaptive neuro-fuzzy inference system (ANFIS) controller. Replacement of FLC, ANN in PI controller approximates the linear functionality of the STATCOM for maintaining appropriate power level. The proposed approach performance is evaluate using MATLAB/SIMULINK environment with both synchronous Generator and doubly fed Induction Generator. Simulation results exhibit that replacement of controller in PI controller provides compensation current in PCC in an acceptable range. Further, the incorporation of controllers reduced the Total Harmonic Distortion (THD) value at a significant amount for ANFIS controller.*

Keywords - *Synchronous generator; static synchronous compensator; the point of common coupling; wind energy conversion system; a fuzzy logic controller; artificial neural network*.

1. Introduction.

In recent years, drastic growth and requirement in this modern technologies lead to power demand in worldwide with acceptable quality, reliability, safe and versatile ability. Due to the significant advantage in renewable energy system (RESs), it has been widely accepted in several terms like Wind, photovoltaic, and hydropower plants for generation of electricity. Among several renewable energy system wind energy has been promising technique due to environmental factors and electricity generation.But wind energy system, faces a critical issue of power quality management due to fluctuation in wind speed. Wind system itself contains several devices like the synchronous generator, grids, compensator and so on [19]. Generally, these device are affected by power quality parameter caused by certain technical constraints like real and reactive power variation, periodic change in sinusoidal waveform, variation in voltage and frequency level. This power quality fluctuating leads to harmonics in the wind turbine and causes heating. The serious impact of this unwanted harmonics variation in the system affects the stability and reliability of the wind turbine [20].

Wind turbine system contains synchronous generator at turbine to maintain appropriate reactive power. This synchronous generator is controlled using a gearbox of the wind turbine for the variation in wind speed. Other electrical devices included in wind turbine system for power maintenance and functionality are barking chopper for suppressing output power fluctuation flow from the permanent-magnet synchronous generator (PMSG) and for energy storage system (ESS) hybrid control scheme is utilized [2]. In case if grid fault occurs dc-link voltage maintained by the line-side converter is shifted and maintained by ESS [3]. To maintain the appropriate power quality management in wind energy system STATCOM is utilized in wind energy system. STATCOM in wind energy system is based on the principle of reactive power injection or absorption at the point of common coupling (PCC). In STATCOM compensating current depends on voltage drop incorporated in PCC. The main advantage of this STATCOM cost reduction, functional characteristics, improved performance, minimized size for maintaining active and reactive power by flexible voltage control. Whereas in the renewable energy system without STATCOM uses several electronic interfaces. Converters and power conditioning equipment which leads to increase in cost and size. Due to this advantages, renewable energy system uses STACOM rather than traditional wind energy system.

Because of several advantages, researchers focused on improving the STATCOM device in the renewable system. In the research carried out by [4] based on the performance of sub synchronous resonance (SRR) compensated with induction generator (IG). In this proposed approach based on eigenvalue, IG effect in SSR is evaluated incorporated with voltage controller located in STATCOM. In another research by [5] examined about the power, quality impacts are analyzed along with grid interconnection issues. Further in this research different control stages in the wind turbine are examined such as converter control, inverter control and generator control. Wind energy system utilizes control system with feedback control loops for maintaining variation in speed through pitch turbine and other variables for power quality management in wind turbine system [7]. In same research, it is stated that variation in voltage, harmonics and current needs to be balanced on the load side rather than source side. Some researchers use F-STATCOM controller for minimizing power quality issue in the renewable energy system [8]. The rule-based fuzzy logic controller has been used in some renewable energy system to maintain desired output power. To achieve desired output power utilizes pulse width modulation (PWM) inverter combined with vector pulse-width modulation (SVPWM) for controlling current in 3-phase voltage source inverters (VSI) [6]. An another research [9] developed an approach inverter based power quality management scheme combined with pulse width modulation scheme for achieving constant speed [9]. Grid connected operation is examined for existing generator technologies with appropriate development in wind energy system with the selection of generators. Environmental benefits and interconnection issues in the social environment are studied in [10]. The performance of the wind energy system depends on the harmonic distortion of wind energy system measured based on the standard IEEE std 518-1992 in research [11] and total harmonic distortion (THD) is measured. Cluster - oriented modeling uses Mamdani based Fuzzy is adopted with zero order Takagi - Sugeno model to balance the structural component between input and output space based on FCM method [12]. Tagaki-Sugino based fuzzy controller with rotor controlled oscillator with doubly fed Induction generator for maintaining desire active power in the electrical system. Electromagnetic transients located in wind turbine stator is examined by neglecting third-order. This type of fuzzy controller comparatively analyzes the fault ride comparison of DFIG with conventional PI controller [13]. Other researchers use the multi-level fuzzy controller, neural exhibits improved transient response with appropriate frequency stability in static synchronous compensator even in infinite bus system [14, 15]. Another researcher use neural network for enhancing the performance of PID controller with convergence speed with modified BP algorithm. This trained datasets in PID controller provides self-learning capability and adaptive system in a neural network based BP algorithm [16]. Further research on controller technique uses the hybrid controller in wind energy system utilizing conventional PID with neural network PID to eliminate variable frequency to minimize static error [17]. Recent researchers concentrate on adaptive neuro-fuzzy interface system (ANFIS) in the controller for minimizing error and deviation in speed control DC motor. In this type of ANFIS and PI controller dynamic behavior is improved in DC motor chopper circuit [18]. The various controllers for dc-dc converters has been reported [21-26]. The analysis of existing researchers in renewable energy system shows that ANFIS, PI controller provides the effective performance of rather than other existing approaches in terms of maintaining performance and stability parameters.

In this research paper, proposed a performance enhanced STATCOM for wind energy conversion system for maintaining desired power quality. Renewable power system utilizes grid system for maintaining power management. Grid connected wind energy system is subjected to power quality management to improve the stability and reliability of the renewable system. Traditional grid connected system requires additional equipment which leads to increase in size and cost. To overcome these issues, this research comparatively examine the Fuzzy logic controller, ANFIS controller and Neural Network controller in STATCOM. The proposed approach replaces the traditional PI controller in STATCOM with fuzzy logic controller (FLC), artificial neural network (ANN) controller and adaptive neuro-fuzzy inference system (ANFIS) controller. ANN controller approximates the power flow in the device and FLC controller computes the output power flow from the power system approximated by the ANN. In final stage ANFIS controller in the PCC approximate the linear functionality of the STATCOM for maintaining appropriate power level. In grid-connected renewable system, main device is generator hence in this research performance is evaluated in the synchronous generator and doubly fed generator. Simulation results reveal that replacement of ANFIS controller with traditional PI controller rather than the fuzzy logic controller and Neural Network controller has best performance in power quality improvement. The entire paper is organized as evaluating wind energy conversion system followed by performance characteristics of the neural network, fuzzy logic controller, and ANFIS controller. In the next stage simulation performance of the controller is presented and interpreted.

2. Wind energy conversion system.

Among the various renewable energy system, electricity from the wind are widely accepted for the feasible alternative. The typical components present in the wind turbine system are gearbox, generators, the interconnection of the control system and apparatus box in wind turbine. While examining the overall review about wind energy system turbines are either vertical axis type or horizontal axis type. The majority of turbine manufacturers concentrate on minimizing gears while turbine running in low speed hence they generally opted for the 3-phase generator [20]. A generator located in the turbine coupled with the rotor of wind turbine this is also known as the direct drive to offer effective reliability with reduced cost. Electricity generation in wind turbine occurs when the moving wind strikes on the wind turbine blades kinetic energy is produced which in turns converted into mechanical energy and stored in the gearbox. Gearbox provides the balanced energy transfer between the rotor and the generator to provide high-speed electrical generation with minimal torque. The main functionality of this generator is the conversion of mechanical energy into electrical energy.

3. Wind generators.

In WECS (Wind Energy Conversion System) generators are the major component in the generation of electricity from the wind turbine. This generator can be either synchronous, asynchronous generators or Induction generator. Synchronous generator(SG) is used for constant speed application even it can be used in variable speed but efficiency is minimal. In order to overcome the drawback associated with the synchronous generator, asynchronous are evolved to operate wind turbine effectively in variable speed environment. In this research, controllers are placed in the designed wind turbine and replaced in both synchronous and DFIG which is an asynchronous generator.

A. Synchronous Generator

Synchronous generator is directly connected to the WRSG (Wound Rotor Synchronous Generator) when directly connected to the grid. Since it connected to the grid SG has fixed rotational speed based on grid frequency. The rotor in the SG is connected directly to the brushes and slip rings with the rectifier. The SG does not require gearbox and reactive power compensation where DC supply to the rotor excited and rotated at synchronous speed. The speed of the SG is obtained by the multiplication of a number of poles, frequency and rotation speed of the generator. The formula for identifying rotation speed of the SG is stated as (6) follows:

$$f_e = \frac{P}{120} n_m \qquad (1)$$

n_m – Rotational speed of the rotor, f – frequency, p – number of poles.

B. Doubly fed induction generator

Doubly Fed Induction Generator (DFIG) is the asynchronous generator which refers stator voltage to get energy from grid and power converter induced voltage in the rotor variables. Through the utilization of DFIG wind energy produces maximum energy even at low speed for optimizing wind turbine speed. In wind turbine through the optimal energy mechanism gusts based on the turbine mechanical stress in the wind turbine. The main advantage of the DFIG is to absorb or generate reactive power in the electrical converters and which does not requires capacitor and squirrel-cage generator.

4. Modeling of STATCOM.

Wind turbine system requires optimal power flow control with appropriate stability, reliability and AC transmission system. Modern wind turbine system utilizes FACT devices to optimize the power flow in the system. This power flow factor depends on impedance in line, the magnitude of end voltage and the phase angle between the voltages. The above-mentioned parameters need to be controlled properly for effective active and reactive power flow control the power system. FACT devices with shunt controller provide variable reactive current to variable shunt impedance when devices are connected in parallel. This voltage shunt controller will provide an effective voltage control through providing power flow control and better transient stability in the system. In power system, terminal voltages are varied by changing the reactive power from and out of the system.

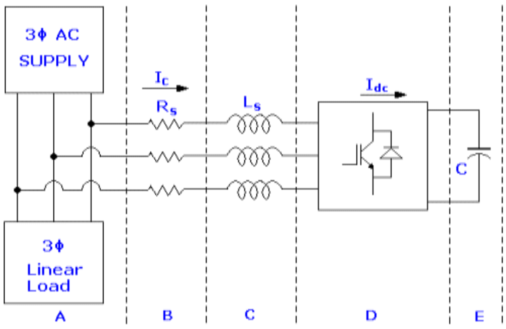

Fig. 1. STATCOM Model.

FACTS (Flexible Alternating Current Transmission Systems) devices in wind turbine are included to maintain appropriate power quality with effective system stability and reliability of the system. In this scenario by the utilization of STATCOM real and active power of the system is maintained and cost effective. In this STATCOM device, 3-phase stationary variables are included based on 3 - a coordinate system with vector 1200 apart from each other in 2-phase coordinate system αβ. The 2-phase coordinate system provides αβ with two axes are provided in rotating coordinates. Based on the Park's rule the abc co-ordinate is converted into dq transformation matrix. The conversion is performed since the circuit is complex hence it is partitioned into sub-circuits. The 3-phase system voltage Es,abc, lagging with the phase angle α to the STATCOM output voltage Eo, abc , and differential form of the STATCOM currents are defined.

$$V_{s,abc} = \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} V_s \begin{bmatrix} \sin(\omega t - \alpha) \\ \sin\left(\omega t - \alpha - \frac{2\pi}{3}\right) \\ \text{in}\left(\omega t - \alpha + \frac{2\pi}{3}\right) \end{bmatrix} \quad (2)$$

$$L_s \frac{d}{dt}(i_{c,abc}) = -R^i_{sc,abc} + v_{s,abc} - v_{o,abc} \quad (3)$$

$$L_s \frac{d}{dt}(i_{cq}) = -R_s i_{cq} - wL_s i_{cd} + v_{sq} - v_{oq} \quad (4)$$

The switching function S of the STATCOM can be defined as follows in equation (V):

$$S = \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \sqrt{\frac{2}{3}} m \begin{bmatrix} \sin(\omega t) \\ \sin\left(\omega t - \frac{2\pi}{3}\right) \\ \text{in}\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \quad (5)$$

The modulation index, being constant for a programmed PWM, is given by equation (VI),

$$MI = \frac{v_{o,peak}}{v_{dc}} = \sqrt{\frac{2}{3}} m \quad (6)$$

The STATCOM output voltages in dq transformation are

$$v_{o,qdo} = m\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^T v_{dc} \quad (7)$$

The dc side current in the capacitor in dq transformation

$$i_{dc} = m\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} i_{cq} & i_{cd} & i_{co} \end{bmatrix}^T \quad (8)$$

The voltage and current related in the dc side is given by equation (8)

$$\frac{dv_{dc}}{dt} = \frac{m}{c} i_{cd} \quad (9)$$

The complete mathematical model of the STATCOM in dq frame is obtained as given in equation (10)

$$\frac{d}{dt}\begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -w & 0 \\ w & -\frac{R_s}{L_s} & -\frac{m}{L_s} \\ 0 & \frac{m}{c} & 0 \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} + \frac{v_s}{L_s}\begin{bmatrix} -\sin\alpha \\ \cos\alpha \\ 0 \end{bmatrix} \quad (10)$$

With the assumption, the system voltage and STATCOM output voltage are in phase, the equation can be modified .

5. STATCOM and its control system.

STATCOM devices are changed in to control system STATCOM voltage is denoted by V2 and system voltage is mentioned as V_1. The connection between the STATCOM to the PCC is provided by the voltage source based converter and reactance. General STATCOM devices contain DC voltage regulator, current regulator, PWM modulator, PLL (Phased Locked Loop) and AC voltage regulator. PLL in the STATCOM uses synchronized positive-sequence components for primary voltage V_1. The output value from the devices is calculated based on the PLL angle output based on the quadrature and direct axis components for 3-phase AC voltage. Current in the STATCOM control system is named as V_d, V_q or I_d, I_q. Measurement system measures the direct and quadrature components of positive-sequence AC voltage and currents and the DC voltage V_{dc}. Single-line diagram of an STATCOM and its control system block diagram is given below,

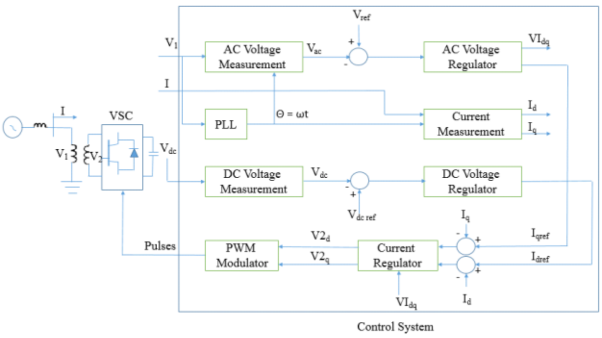

Fig. 2. Line Diagram of STATCOM.

In STATCOM output voltage system contains voltage regulator for both AC and DC components. Based on the reference currentI_{qref}AC voltage regulator regulates the output from DC regulator to the current regulator with respect to reference current I_d. Current regulator included in the circuit controls the magnitude and phase of the voltage regulator using PWM converter. In similar to DC regulator AC regulator also regulates the current in feed forward network. Through the feedforward network, V_1 measurement (V_{1d} V_{1q}) measures reactance from transformer leakage. By the utilization V_1, the V2 voltage output ($V2_d$ $V2_q$) are predicted.

6. Fuzzy logic controller.

The major functionality of the fuzzy logic controller is to overcome the problem of uncertainty. Major advantages associated with the fuzzy logic controller are a significant response, increased the speed of operation and less complexity compared with the existing conventional controller system. Fuzzy logic based controller solves the uncertainty problem in wind turbine through the application of technique based on human brain for controlling process of operation.

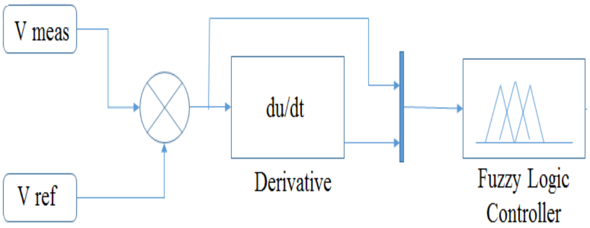

Fig. 3. Fuzzy controller for STATCOM.

WECS contains grid-connected devices which lead to the power quality problems due to variation in the wind speed. In order to resolve power quality issues in wind turbine with minimal uncertainty fuzzy logic controller is incorporated. To evaluate the performance of the fuzzy logic controller in WECS for the designed wind energy system STATCOM with PI controller connected with AC voltage regulator is replaced with a Fuzzy logic controller. A fuzzy controller is provided with error and variation in error for the trained value. To compute the control signal measures this error value are incorporated in the fuzzy logic controller. In this measured input, error is denoted as (e) and (dE) is stated as the change in error. Based on the calculated value desire final output is calculated based on the input with respect to e and dE.

The fuzzy logic controller is operated based on the certain set of rules hence in this simulation input is defined as 1 and 2 for the fuzzy logic controller. The input 1 is given as voltage error and input 2 is stated as a derivation of the voltage error of the WECS. In this fuzzy based controller error range of voltage is classified on a linguistic function like very small (VS), small (S), medium (M), big (B) and very big (VB) typically voltage error for the system is obtained between 0 to 1. Fuzzy logic controller trained the input and outputs of the wind turbine system based on the triangular membership function and produce a desired control signal from the renewable system.

Table 1.Linguistic Variables

dE/ dt E	NS	NM	NB	Z	PS	PM	PB
VS	VS	S	M	S	M	B	VB
S	S	VS	S	M	M	B	VB
M	S	VS	S	M	B	B	VB
B	M	S	VS	B	VB	VB	VB
VB	S	VS	S	VB	VB	VB	VB

The above table 1 provides the linguistics variables framed for the designed wind system for voltage error and variation in voltage error. Based on the 35 rules framed using triangular membership function variables are trained and performance is evaluated.

7. Neuro controller.

In context fuzzy logic controller and ANN controller are seems to be similar but still, both differ by the individual performance characteristics. ANN provides the opportunity for evolution and learning whereas in fuzzy logic controller performs based on calculation. Generally, in the neural network composed of three layers, they are input layer, the output layer, and hidden layer. ANN contains a huge number of neurons which are connected through weights. By the development of appropriate learning approaches computation is performed with the use of activation function and weights in the system. In the final stage of the neural networks, output layer provides the trained data set in the network with the proper format.

As similar to a fuzzy logic controller PI controller in STATCOM device is replaced with the neural network controller. Inputs provided by the neural network system are voltage error and the variation in the error voltage. Based on the input provided to the neural network entire system is trained and output angle is measured for the STATCOM with the neural network controller. The final decision in the neural network based on imprecise data similar to human thinking capability with fewer complexes. Fuzzy logic controller and ANN controller are utilized to solve the nonlinear problems even not specified or related to each other. In ANN learning algorithm is incorporated for training the data sets to obtain desire output from the wind energy system.

In this research to evaluate the performance of neural network controller in STATCOM back propagation algorithm is used to train a network. Further ANN uses sigmoidal transfer function for training dataset in multi-layer perceptron and non-linear intermediate mapping between input and output variables. Through the back propagation, approach weights are altered during training of data sets with the introduction of mean square error in the training period. In simulation analysis ANN controller exhibits better performance with desire accuracy with the minimal mean square error.

8. Neuro-fuzzy controller.

Among the various controller, ANFIS controller also known as universal estimator attracted researchers attention in recent years due to significant performance. ANFIS controller was evolved in 1990's based on the Takagi–Sugeno which is based in the fuzzy interface. In other words, ANFIS is the combination of neural network and fuzzy logic controller hence it combines the advantages of both controllers. ANFIS utilizes if-then rules for providing an interface based on learning capability in the system with nonlinear functional characteristics.

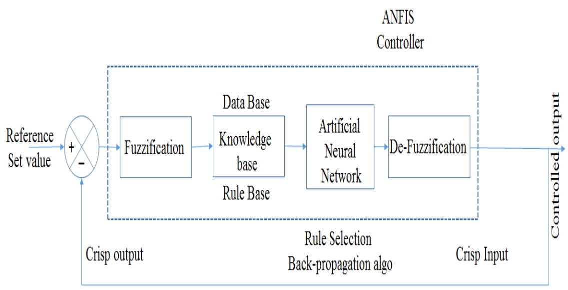

Fig. 3. ANFIS Controller Block.

ANFIS controller follows several functionality steps built in it which are ANN, fuzzification, knowledge base and defuzzification process. Input for the ANFIS controller is calculated by variation between the reference value and controller output value. Input for the system is provided with fuzzification block and rules for the block are developed for the controller. Since ANFIS is the combination of ANN and fuzzy it takes data from ANN and set of rules from fuzzy rules. Due to the combined utilization of both the techniques output from the ANFIS is generated after defuzzification process. ANFIS controller provides control to the system by evaluation of angle in STATCOM controller in the system. In the ANFIS controller training continues until to obtaining minimal error value which is significantly effective than other fuzzy and ANN controllers.

9. Results and discussions.

In the designed wind turbine system PI controller in STATCOM is replaced with fuzzy, ANN and ANFIS controller. The controllers are evaluated for performance in wind turbine under two scenario which is in the synchronous generator and DFID generator. Controller performance in the designed wind turbine is evaluated for characteristics like real power, reactive power, and THD performance. The simulation of the designed renewable system with controllers are evaluated using MATLAB/SIMULINK for performance evaluation. Simulation has been carried out under four scenario with conventional STATCOM device in SG and DFIG, fuzzy logic controller in SG and DFIG, neural controller in SG and DFIG and finally ANFIS controller in SG and DFIG.

A. Power Measurement in SG and DFIG

The main role of the controller is to maintain the voltage level of the system with enhanced real power flow in the system. In conventional renewable energy system, output waveform of the wind turbine is measured at PCC. In this research, performance is evaluated for STATCOM devices. STATCOM controller for WECS is connected at PCC to establish a coupling between WECS and STATCOM. The impact of placing STATCOM controller in WECS system is measured in terms of real and reactive power measurement.

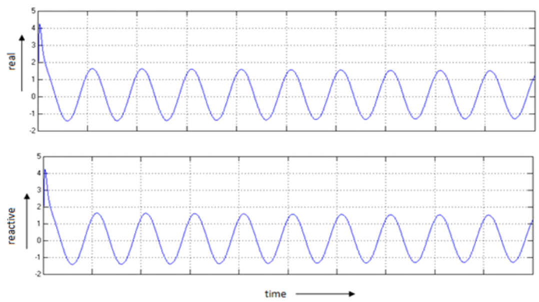

Fig. 4. Power Measurement at PCC with conventional PI STATCOM and SG based WECS.

The Fig-4 illustrates the real and reactive power obtained from WECS when PI controller is employed in STATCOM controller. Initially, the STATCOM controller is connected to wind design with SG and provides sinusoidal oscillation in both positive and negative axis. Real power obtained for STATCOM controller in SG are in the range from 1.5p.u to -1.5p.u. On examining reactive power measurement for different time interval reactive power is similar to that of real power which ranges from 1.5 to -1.5 with respect to time.

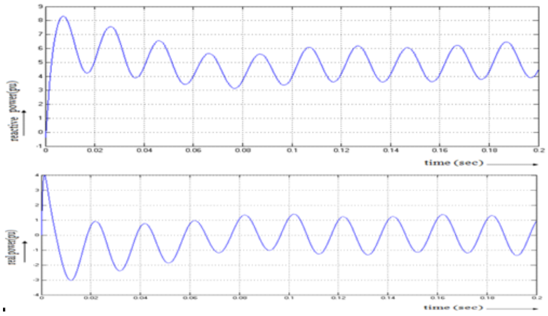

Fig. 5. Power Measurement at PCC with conventional PI STATCOM and DFIG based WECS.

In Fig-5, STATCOM controller in wind turbine performance is evaluated for operating with DFIG generator. The observation of real and reactive power in the DFIG system based STATCOM controller in WECS increases the harmonic range. Reactive power of the system is obtained in positive value with the maximum value of 6p.u. Real power with STATCOM controller is observed in the negative direction and power level is not maintained constantly. For the time period, 0 to 0.12sec harmonic values are minimal which is obtained as -1.

B.Power Measurement for FUZZY logic and Neural Network Controller

In secondary stage, for the designed wind turbine system fuzzy logic controller and neural network controller replaces the conventional PI controller. The difference between those two approaches is variation in the fuzzy based on the mathematical formulation rules and neural network based on the principle of evaluation of variables without mathematical formulations. The neural network works based on the principle of back-propagation mechanism to train a dataset in the network. The Fig-6 & Fig-7 describes simulation results obtained for fuzzy logic and neural network controller in case of SG and DFIG based WECS. Simulation is based on the principle of current flow from main voltage to the direct component voltage of the renewable system. The real and reactive power waveform obtained for the fuzzy logic controller and neural network controller in SG and DFIG are stated below. The simulation results demonstrate that through PLL the accurate current is extracted from the direct component with an effective source current waveform.

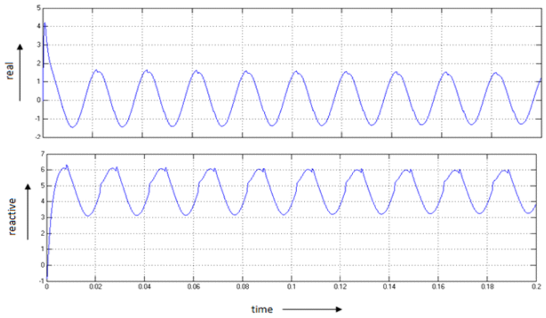

Fig. 6. Power Measurement at PCC with Fuzzy Controlled STATCOM and SG based WECS.

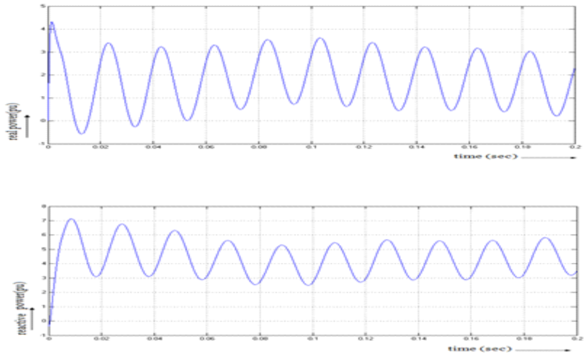

Fig. 7. Power Measurement at PCC with Fuzzy Controlled STATCOM and DFIG based WECS.

WECS with replaced fuzzy logic controller maintain appropriate real power with effective voltage maintenance. Through the use of fuzzy membership function fuzzy rules are framed and input and output are maintained. Based on the generated fuzzy rules real and reactive power are measured in the positive direction for DFIG controller with reactive power ranges from 5p.u to 7p.u.

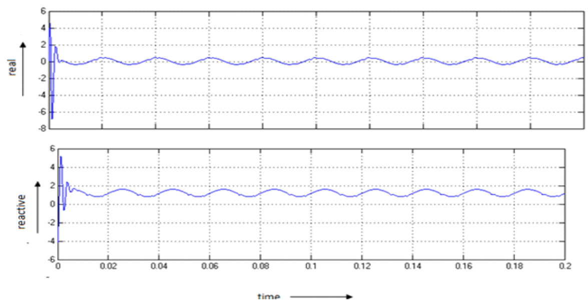

Fig.8. Power Measurement at PCC with Neural Controlled STATCOM and SG based WECS.

Neural network utilizes back propagation approach to evaluate the performance with voltage error and variation in voltage error. This defined neural network performs power measurement based on training data, a number of epochs, hidden layer in the system, transfer function and target data set. Using neural network controller with SG and DFIG generator real power gets increased significantly in the case of SG real power level is around 2 p.u in another hand for DFIG the real power level is 2 p.u.

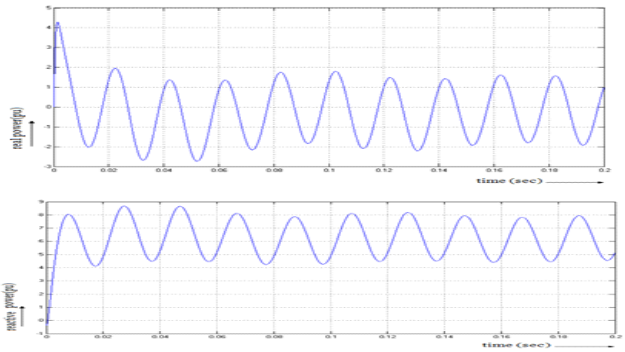

Fig.9. Power Measurement at PCC with Neural Controlled STATCOM and DFIG based WECS.

The active and reactive power reference magnitude of the controller with reference to the magnitude is increased in terms of real and reactive power measurement. Real and reactive power measured using fuzzy logic and neural network controller is presented in the above Fig-9. In both cases (i.e. fuzzy controller and neural controller) reactive power of the system in a positive direction which means DFIG operates as the generator. In this scenario, reactive power of the stator will be minimal which may be around zero hence stator current shape voltage is opposite in phase which means active power is sent effectively on the wind turbine system. At this point, DC reference voltage is varied with rising and fall in the electrical current to regulate the V_{dc} voltage. From the simulation results, it is clearly stated that performance of neural network system is constantly increased with respect to increasing in voltage magnitude compared with the fuzzy logic controller.

C. Power Measurement in ANFIS controller

In the final stage, for designed wind turbine system controller is replaced with ANFIS controller which is based on the combination of both fuzzy logic and neural network controller. Same as above three cases performance of ANFIS controller is measured in both SG and DFIG generator of the wind turbine.

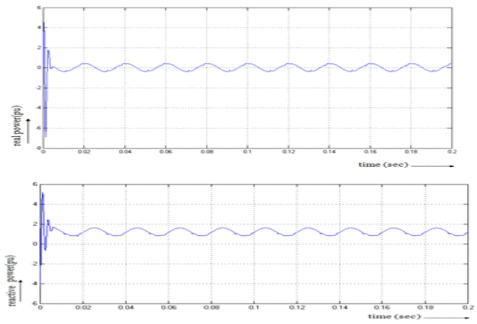

Fig. 10. Power Measurement in ANFIS controller in SG based WECS.

Table 2. Comparison of Power Measurement factors in SG based WECS

	Real power(p.u)	Reactive power(p.u)
Without STATCOM	0.4	3.834
With STATCOM	1.1	3.807
With fuzzy controller in STATCOM	1.22	1.136
With neural controller in STATCOM	4.138	1.133
With ANFIS in STATCOM	4.180	1.132

The Real power, Reactive power in WECS with Synchronous Generator and different controllers in STATCOM are given in table. While evaluating the performance of the wind turbine with the placement of SG and DFIG generator it produces significant improvement in the real and reactive power of the system with respect to time. For the time measurement ranges from 0 to 0.2sec sinusoidal harmonics are in the positive direction while operating with SG. The power fluctuation in the system is minimal when compared with the other three controllers i.e., STATCOM, Fuzzy logic and Neural network controller. The comparison table also demonstrates the ANFIS controller in wind turbine provides effective performance rather than other controller logic techniques.

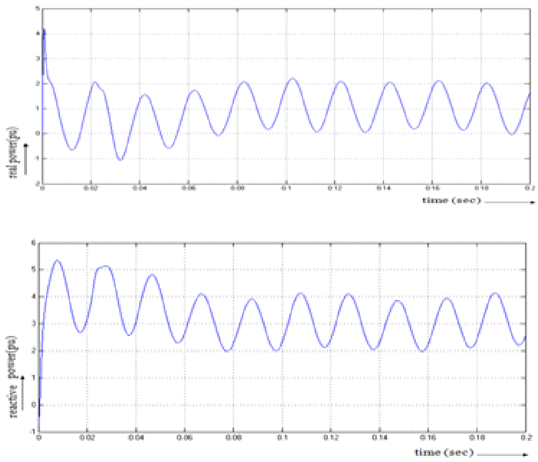

Fig. 11. Power Measurement in ANFIS controller in DFIG based WECS.

Table 3. Comparison of Power Measurement factors in DFIG based WECS

	Real power(p.u)	Reactive power(p.u)
Without STATCOM	0.9	4.4
With STATCOM	0.947	5.13
With fuzzy controller in STATCOM	0.97	5.17
With neural controller in STATCOM	1.595	3.47
With ANFIS in STATCOM	2.282	2.53

Simulation performance of the system associated with DFIG with ANFIS controller is measured for both active and reactive power measurement of the system. In the case of DFIG real and reactive power is significant rather than SG. Even for varying time reactive power almost constantly maintained in a positive direction with the range of 2 p.u which is effective than other controllers. In comparison table for various controller logic circuit, it is observed that in real power measurement is higher for ANFIS and reactive power is the minimum for ANFIS controller alone hence ANFIS controller provides effective power quality maintenance factor.

D. Analysis of Total Harmonic Distortion (THD) performance in controller

To evaluate the contribution or impact of load distortion or generator performance it is necessary to measure the harmonic current value which is combined with different phase angle measurement. Harmonic distortion is connected with bus system of the renewable system which is usually lower in magnitude with the arithmetic magnitude of the renewable power system. In context magnitude and phase angle of the system will vary with time hence it is difficult to harmonic of the system in particular time. Harmonics change in wind energy system depends on power from generators, the impedance of the system, environmental condition, technologies adopted and so on. To calculate the harmonic current IEC 61000-3-6 defined a particular formula to calculate which is given as follows in equation (11):

$$I^{\sigma}_{h,sum} = \sum_i I^{\sigma}_{h,i} \quad (11)$$

Where sigma is the summation exponent, I_h, sum is the summated harmonic current, and $I_{h,i}$ are the individual harmonic components of the same order. In this research to evaluate the comparative performance evaluation incorporated controllers TDH are identified under both working conditions with SG and DFIG. The THD at PCC of WECS with SG and STATCOM employed with different controllers are given in the table 4.

Table 4. Comparison of TDH in SG based WECS

Without STATCOM	With STATCOM	With fuzzy controller in STATCOM	With neural controller in STATCOM	With ANFIS in STATCOM
4.57%	3.49%	3.31%	3.18%	2.91%

Simulation performance evaluation of TDH is tabulated in table 4 under SG where ANFIS based controller provides minimal TDH in SG rather than other controllers. In normal wind turbine system which means without any controller location, TDH value is obtained as 4.57%. By the incorporation of STATCOM controller TDH value is minimized to 3.49% further the replacement of controller to the fuzzy logic controller the TDH value is minimized to 3.31%. Through the back propagation approach, the neural controller exhibits a slight difference in the TDH value of 3.18%. The ANFIS based controller provides the TDH value of 2.91%.

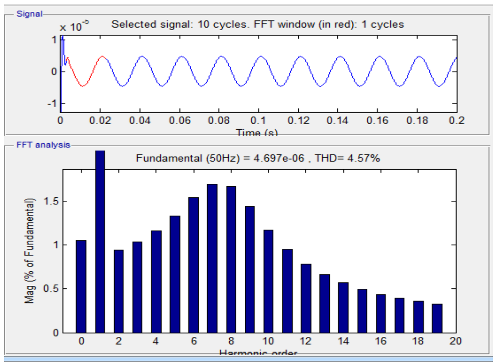

Fig. 12. THD in SG without STATCOM based WECS.

The evaluation TDH value in WECS system with STATCOM device is examined using FFT analysis which is working in 50Hz. Fundamental value considered in this research are 4.697e-06 with TDH value of 4.57%. Figure states the TDH value obtained for the WECS without any STATCOM devices.

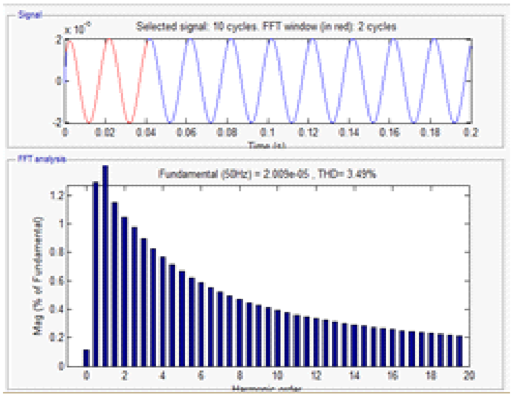

Fig. 13. THD in SG based WECS With PI Controlled STATCOM.

The above figure 13 provides the TDH performance of the WECS system with STATCOM incorporated in the system. The incorporation of STATCOM in WECS minimizes the power quality level to 3.49% for the wind energy system. STATCOM device is located in the PCC point and examined for FFT analysis in the power quality measurement system.

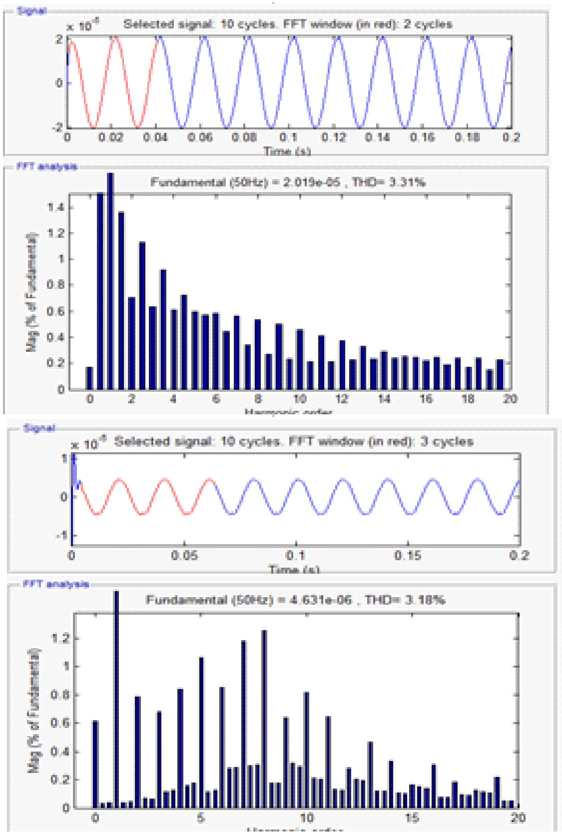

Fig. 14. THD in SG based WECS with Fuzzy and Neural Network Controller.

The above figure 14 exhibits the comparative analysis of WECS replaced with the fuzzy logic controller and neural network controller. In context, both fuzzy logic and neural network are similar in performance characteristics hence both methods exhibits similar characteristics in TDH value. For fuzzy logic, TDH value is obtained as 3.38% and for neural network controller TDH value is obtained as 3.18%. From the figure 15 it is revealed the THD with ANFIS controller still reduced to 2.91

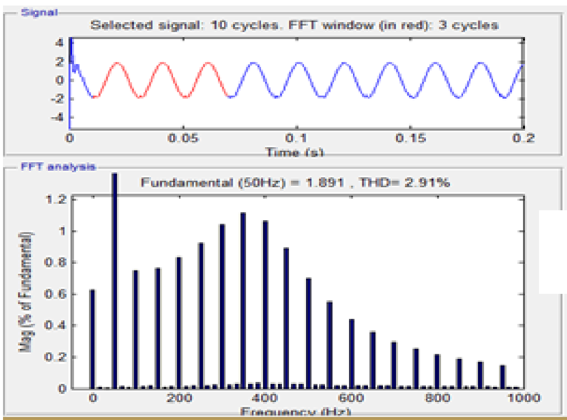

Fig. 15. THD in SG based WECS with ANFIS Controller.

For paper constraints, TDH values obtained for DFIG controller values are provided in tabular format. Same as SG controller are placed in PCC DFIG controller and values are provided in table 5.

Table 5. Comparison of TDH in DFIG based WECS

Without STATCOM	With STATCOM	With fuzzy controller in STATCOM	With neural controller in STATCOM	With ANFIS in STATCOM
6.09%	4.10%	3.84%	2.6%	2.41%

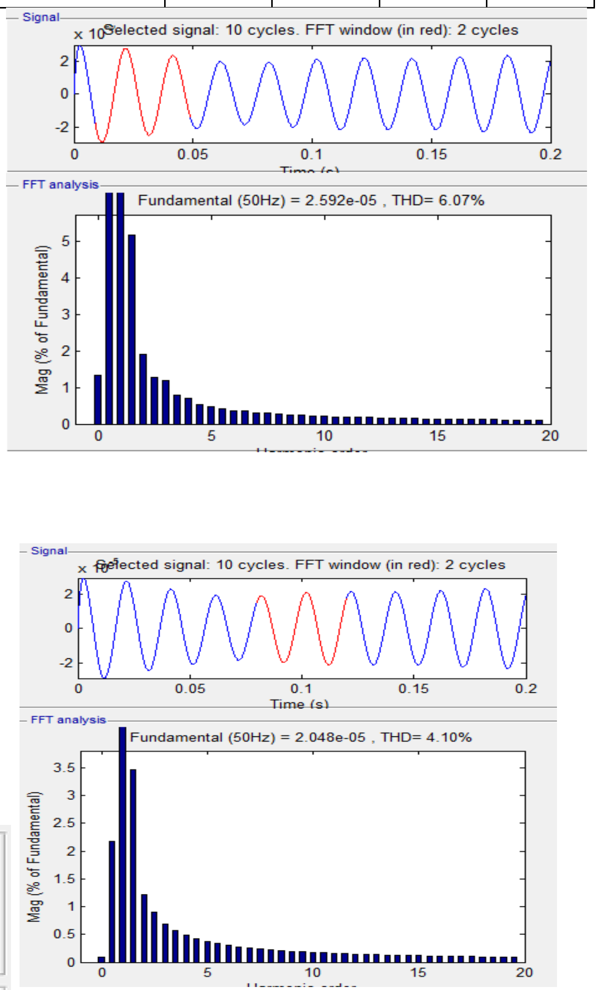

Fig. 16.THD in DFIG based WECS without and with PI Controlled STATCOM

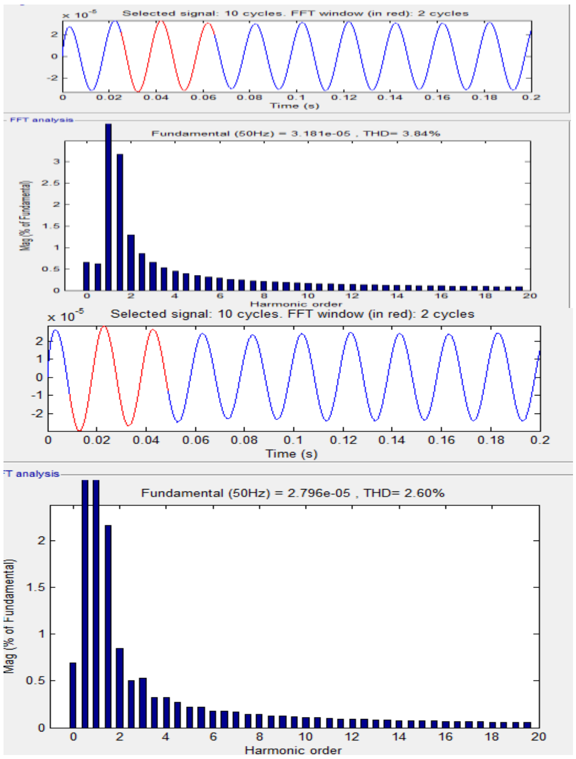

Fig.17. THD in DFIG based WECS with Fuzzy and Neural Network Controller.

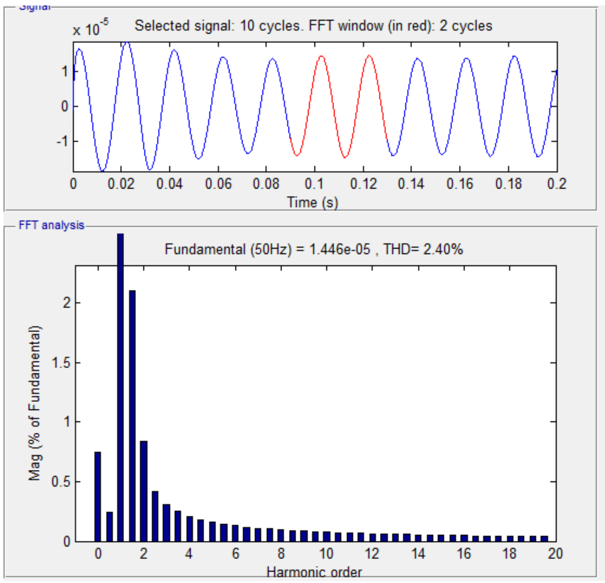

Fig. 18.THD in DFIG based WECS with ANFIS Controller.

Synchronous based WECSin Doubly fed Induction generatorbased WECS also, TDH value is reduced with ANFIS controller rather than other controllers such as a fuzzy logic controller, neural network controller, and PI controller. For sinusoidal waveform, the system will provide the minimal ripple which is almost equal to constant value. TDH value in DFIG system is minimized from 6.09% to 2.41% in frequency spectrum component which exhibits significant filtering with less compensation of reactive power. The total harmonic is the cumulative distribution which is based on 95% to 99% of level probability with maximum current, power in the inverter. As per the standard EN 50160 99% of confidence level harmonic level will be minimum which is satisfied by the ANFIS controller hence it is stated that ANFIS controller performs effectively of power quality management.

10.Conclusion

The penetration of the wind energy on the grid causes the power quality problems due to their variable nature with respect to time. Both synchronous generator and DFIG can be used for the wind energy conversion. Under the variable wind speed conditions harmonics produced at the Wind Energy Conversion System. So the STATCOM used at the point of common coupling point where the wind system and the grid are met to obtain the better control. The performance of the STATCOM with fuzzy, neural controllers analyzed. The results show that the harmonics at the point of common coupling reduced in synchronous generator based wind energy conversion system with the FACTS device STATCOM and other controllers due to its effective control of real and reactive power flow. Compared to all above the neural controller gives better performance for the THD reduction and maintenance of grid stability and reliability.

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