Fuzzy Logic Controller based SAPF for Isolated Asynchronous Generator

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Abstract— **This paper deal with performance of fuzzy logic controller based SAPF (series active power filter) to voltage control of IAG (Isolated Asynchronous Generator) feeding three-phase linear and nonlinear loads. The IAG is used for constant speed prime mover type isolated power generation like biogas, biomass, diesel engine, gas turbine etc. The IAG with excitation capacitor is unable to control source voltage with loaded condition. Therefore FLC (fuzzy logic controller) based SAPF is proposed to maintain constant source and load voltages with sinusoidal currents. The PI controller based SAPF is also implemented with comparison from FLC based SAPF. The mamdani-type fuzzy logic controller does not require accurate mathematical model with improved transient performance of IAG connected system. The SAPF is modeled using IGBT (Insulated Gate Bipolar Junction Transistor) based voltage source converter (VSC) with self supported DC bus. The 7.5kW, 415V, 50Hz SEIG based generating system with SAPF is designed, modeled and simulated in MATLAB environment. The simulated results are presented to demonstrate the capability of IAG system with series voltage controller for feeding three phase resistive, reactive and nonlinear loads.**

Keywords-Fuzzy Logic Controller, Isoleted Power GenerationSelf Exited Induction Generator, Series Active Power Filter,voltage regulation.

I. INTRODUCTION

Isolated power generation has enough potential for world interest. So many sources like solar, wind, small hydro, biogas, biomass, gas turbine, diesel etc can be used in isolated power generation. The existing power system networks are not able to transfer power at each utility centers. Thereby isolated power generations are very much important for hilly, air, submerse, remote and industrial area. Isolated power generation has also improved power quality, stability and reliability of power across consumer loads. Due to low cost, reduced maintenance, rugged and brushless construction the self exited induction generator (SEIG) is recommended for isolated power generation. The SEIG in isolated power generation is initially exited with external capacitor bank. The external capacitor bank is not able to fulfill requirement of reactive power to maintain constant terminal voltage under varying load condition. Hence the limitation of an SEIG system with capacitor self excitation is poor voltage regulation, which results in under utilization of the machine. In order to regulate its terminal voltage with the load and to utilize the machine to its rated capacity an external source of the reactive power is required. [1-3]

The power generation with constant speed prime mover such as bio-gas, biomass, diesel, gas turbine driven SEIG feeding three phase load has problem of voltage regulation. In this case reactive power sources like static compensator (STATCOM) play an important role for improving voltage regulation. Many authors have already designed shunt connected STATCOM for SEIG feeding three phase loads [4-6]. But STATCOM is bulky in size and have higher rating, which can be reduce with help of series compensation. The analysis of series compensation through introduction of additional capacitance in series between SEIG and load to obtain almost flat load voltage, improved voltage regulation and high overload capacity of SEIG is investigated [7]. The size, cost and rating of solid state devices based series voltage regulator is lower than from shunt connected STATCOM investigated for only three phase distribution system in [8, 9]. The different voltage regulation schemes are classified with performance of STATCOM and SSSC for SEIG feeding linear load only in [10]. The performance of SEIG with battery supported SSSC (static synchronous series compensator) and STATCOM to feed linear and dynamic loads are investigated in [11, 12]. However with SSSC, the DC bus was not self supported and also the effect of nonlinear load was not investigated. The SAPF with self support DC bus and control scheme having conventional PI controller for SEIG feeding linear load only is investigated in [13]. The PI controller required precise mathematical model, which does not give satisfactory performance in transient condition. So the fuzzy logic controller is used here over PI controller whose advantages are: It does not need accurate mathematical model, it can handle nonlinearity and it is more robust than conventional controllers. FLC based SAPF also improve transient performance during load change. The fuzzy logic in control system with shunt active power filter for distribution system is explained in [14-17]. Fuzzy proportional – integral based shunt connected voltage and frequency controller for isolated wind power generation system is implemented in [18].

An attempt is made here to work on constant speed such as biomass, diesel, gas turbine prime mover driven SEIG feeding linear and nonlinear load with series voltage regulator

(SAPF). The series active power filter (SAPF) is designed instead of STATCOM to reduce rating, physical size, weight, losses and cost of the controller, The SAPF is consisting voltage source converter (VSC), capacitor and interfacing transformer. SAPF with DC link capacitor is connected between SEIG and load through interfacing transformer. The SAPF provides leading and lagging KVAR according to requirement of load to maintain constant source and load voltage. Here Fuzzy Logic Controller (FLC) is used to implement control scheme of SAPF and which is compared with conventional PI controller. The harmonics in voltage and current increases the power losses, produces unequal heating and torque pulsation on the shaft of the generator. Therefore, effective and efficient operation of self exited induction generator with suitable voltage controller (SAPF) is investigated. A Hysteresis controller scheme is presented in SAPF to control the voltage of the system.

II. SYSTEM CONFIGURATION

Fig. 1 shows the system configuration of constant speed prime mover (like biogas, diesel) driven SEIG, with excitation capacitor, SAPF and consumer load. The star connected three-phase capacitor bank is used for generator excitation and value of excitation capacitors is selected to generate the rated voltage at no load. The interfacing transformers are used to connect voltage regulator (SAPF) with the system. The SAPF can absorb and supply reactive power according to reactive power requirement of system. Therefore SAPF compensates reactive power requirement of system to maintain constant terminal voltage with change in load condition.

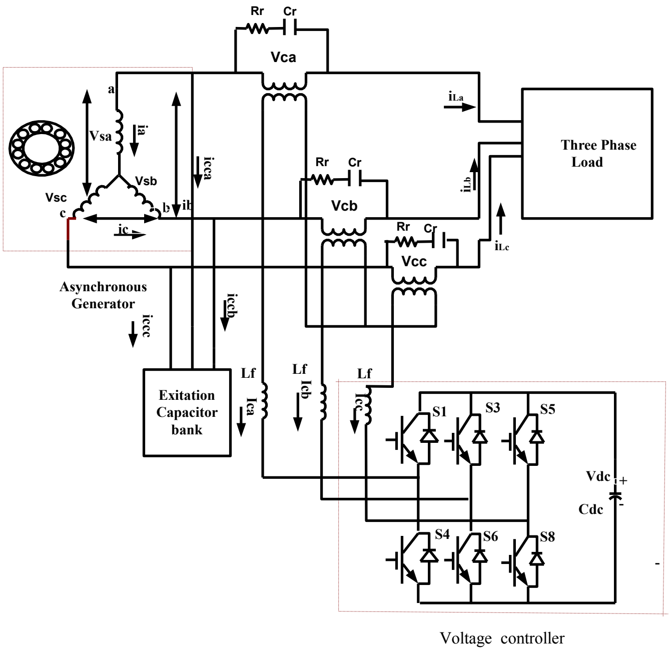

Figure 1 Schematic diagram of proposed system configuration

The SAPF is power electronic converter based series compensator that protects three-phase load from load disturbances. It injects voltage in quadrature with one of the line end voltages in order to regulate active power flow. It is a adaptable controller because it does not draw reactive power from ac system; it has its own reactive power provision in the form of a DC capacitor. This characteristic makes the SAPF capable of regulating both active and reactive power flow within the limit imposed by its rating. This device employs IGBT based solid state power electronic switches in a hysteresis controller structure. The fuzzy logic controller is used to estimate the in-phase component of the injected fundamental voltage by the SAPF. Three-phase unit voltage templates (U_{sad}, U_{sbd}, U_{scd}) are derived in-phase with the supply currents (i_{sa}, i_{sb}, i_{sc}). The DC bus voltage of the SAF is regulated using fuzzy logic controller over the sensed (V_{dc}) and reference values (V_{dc}*) of DC bus voltages. This fuzzy logic controller output is considered as the amplitude (V_{smd}*) when it is multiplied with (U_{sad}, U_{sbd}, U_{scd}) it generates the in-phase component of the injection voltages (V_{sa}*, V_{sb}*, V_{sc}*). The hysteresis controller is used over in-phase component of the injection voltages (V_{sa}*, V_{sb}*, V_{sc}*) and sensed source voltages (V_{sa}, V_{sb}, V_{sc}) to generate gating signals for the IGBT's of VSC. The gating pulses switch the IGBT's of the VSC for the compensation voltages. The control scheme is shown in Figure.2

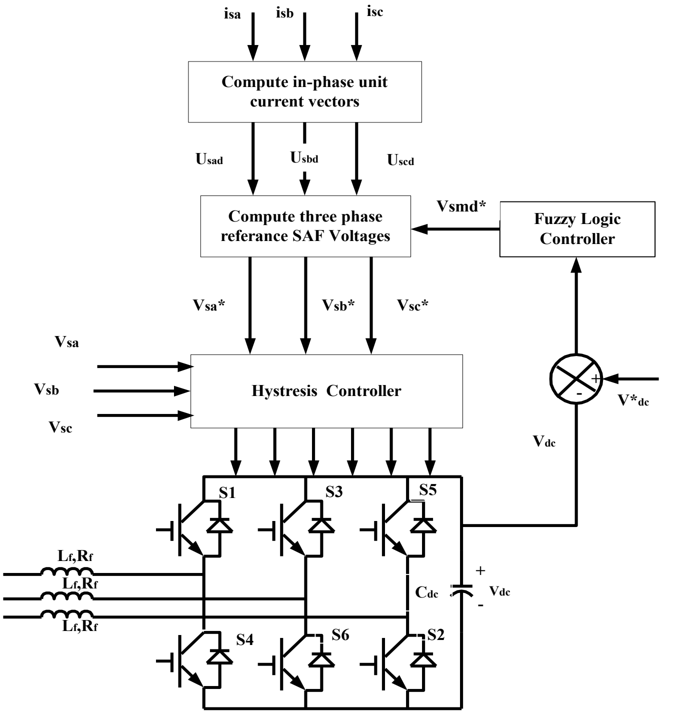

Figure 2 Control scheme of the SAPF

III. FUZZY LOGIC CONTROLLER

Fuzzy logic control is based on fuzzy set theory; and it was introduced by Zadeh in 1965. The basic structure of fuzzy logic controller has four principal components: fuzzification, knowledge base, decision-making logic and defuzzification. The function of fuzzification is convert input data into suitable linguistic values, which is defined with help of fuzzy sets. The knowledge base consists of data base and rule base. Decision-making has capability of simulating human decision-making based on fuzzy concept and defuzzification process transformed linguistic variable into crisp sets (real number). The FLC does not require any precise mathematical formula for calculations. The design of FLC is based on system experience and heuristics as mention previously, which is very easy to apply. In order to implement the fuzzy logic control algorithm of an SAPF in a closed loop, the DC-bus capacitor voltage is sensed and then compared with the desired reference value. The output of fuzzy logic controller maintains magnitude of DC link voltage. This DC link voltage takes care of the active power demand of the load for harmonics and reactive power compensation.

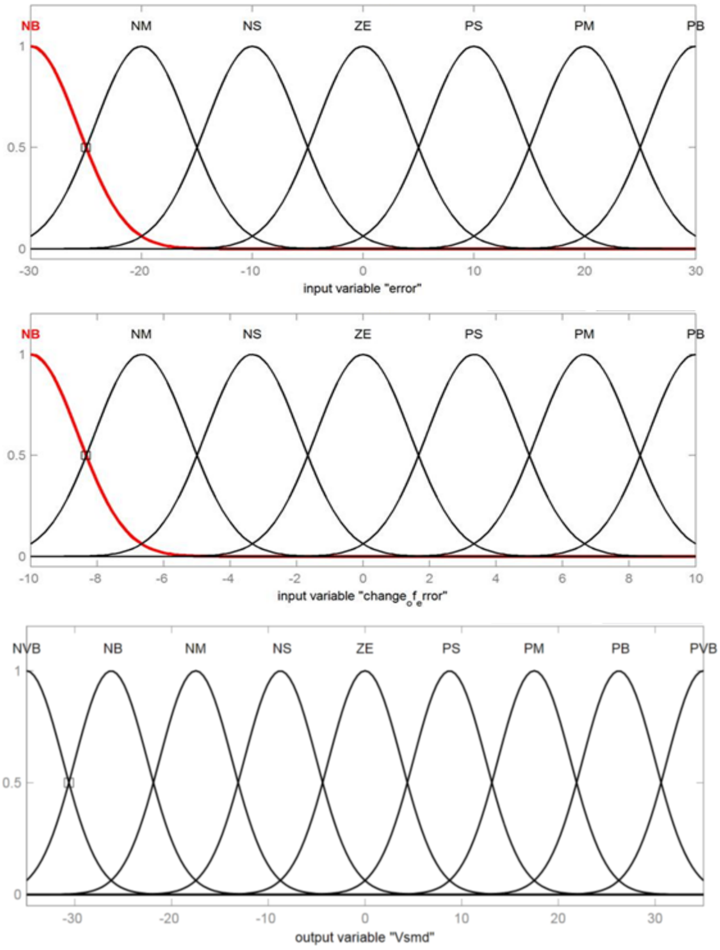

Figure 3 Membership Function eroor, change of error and output V_{smd}*

The fuzzy-logic controller for SAPF deals with two inputs: 1) the voltage error (reference DC link voltage minus actual dc link capacitive voltage, e), 2) the change of DC link capacitive voltage (previous error minus current error; ce). The two inputs are defined from sets of seven membership functions and expressed in linguistic values as negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB).The range for the voltage error (e) input is set as [-30 30] and range for change of capacitive voltage error (ce) is set as [-10 10]. The shape of these membership functions is varied and the effect on the system is studied. Thereafter input to the defuzzification process is a fuzzy set and the output is a single nonfuzzy number, obtained by the center-of-gravity (COG) method of defuzzification. The output (magnitude of reference supply voltage,) is represented by a set of nine membership functions (MFs) (NVB to PVB) whose shape is taken to be similar to the shape of the input MFs. The range for the output is set as [-35 35]. That membership functions are shown in fig.3. The AND method used during interpretation of the IF-THEN rules is “min” and the OR method used for “max”. Also “min” is used as the implication method whereas the “max” is used for aggregation method. The 49 fuzzy IF-THEN weighted rule bases are designed to maintain the capacitor voltage constant by providing the required reference voltage amplitude. Rule generation and weighting are decided based on the pendulum analogy [15-18].The resulting rule matrix with assigned weights is shown in Table I.

TABLE-1

RULE BASE

		Error (e)						
		NB	NM	NS	ZE	PS	PM	PB
Change of Error (ce)	NB	1 NVB	1 NB	1 NM	1 NS	1 ZE	1 PS	1 PM
	NM	0.9 NVB	.87 NB	.8 NM	.66 NS	.33 PS	.66 PS	.71 PB
	NS	.83 NVB	.75 NB	.66 NM	.33 NS	.66 PS	.83 PM	.89 PB
	ZE	1 NB	1 NM	1 NS	1 ZE	1 PS	1 PM	1 PB
	PS	.9 NB	.83 NM	.66 NS	.33 PS	.66 PM	.75 PB	.82 PVB
	PM	.77 NB	.65 NM	.33 NS	.66 PS	.83 PM	.89 PB	.92 PVB
	PB	1 NM	1 NS	1 ZE	1 PS	1 PS	1 PB	1 PVB

IV. MODELING OF IAG-SAF SYSTEM

Asynchronous generator, SAPF, interfacing transformer and loads models are used from available power system bosket toolbox of library in MATLAB environment.

A. *Modelling of control scheme of SAPF*

The control algorithm of IAG-SAPF system for feeding the three phase loads is given as follows. Three phase load currents of IAG is considered as a sinusoidal and hence their amplitude is computed as,

$$I_{Lmag} = [2/3(i_{La}^{2} + i_{Lb}^{2} + i_{Lc}^{2})]^{1/2} \qquad (1)$$

The in phase unit voltage vectors are computed by dividing individual load current by their amplitude as,

$$u_{sad} = i_{La}/I_{Lmag}; \;\; u_{sbd} = i_{Lb}/ I_{Lmag}; \;\; u_{scd} = i_{Lc}/ I_{Lmag} \qquad (2)$$

1) The in-phase components of the reference source voltage are computed as:

The error in DC bus voltage of SAPF, V_{dcer} (n) at nth sampling instant is as,

$$V_{dcer}(n) = V_{dc}(n)* - V_{dc}(n) \qquad (3)$$

Where $V_{dc}(n)$* is the reference DC voltage and $V_{dc}(n)$ is the sensed DC link voltage of the SAPF. The output of PI controller for maintaining DC bus voltage of the SAF at the nth sampling instant is expressed as,

$$V_{smd}(n)* = V_{smd}(n-1)* + K_{pd}\{V_{dcer(n)}-V_{dcer(n-1)}\} + K_{id}V_{dcer(n)} \qquad (4)$$

Where K_{pd} and K_{id} are the proportional and integral gain constants of the PI controller and $V_{smd}(n-1)^*$ is the amplitude of in-phase component of the reference source voltage at (n-1)th instant. In case of fuzzy logic controller accurate mathematical model is not required. The $V_{dcer}(n)$ and integration of $V_{dcer}(n)$ are two inputs of fuzzy logic controller. The output of FLC is in-phase component of the reference source voltage $V_{smd}(n)^*$.The output of FLC is multiplied with unit voltage vectors to generate in phase components of reference source voltage:

$$V_{sa}{}^*=V_{smd}{}^*U_{sad},\quad V_{sb}{}^*=V_{smd}{}^*U_{sbd},\quad V_{sc}{}^*=V_{smd}{}^*U_{scd} \tag{5}$$

These reference load voltages are comparing with sensed voltages (V_{sa}, V_{sb} and V_{sc}) and error signals are passing through a hysteresis controller to generate gating pulses for switch the IGBTs of the VSC.

V. DESIGN OF SERIES ACTIVE POWER FILTER

The design of SAPF includes voltage rating of VSC of SAPF, current rating of VSC of SAPF, the KVA rating of VSC of SAPF, interfacing transformer rating, dc bus voltage, dc bus capacitance, ac interfacing inductance and the ripple filter in case of linear and nonlinear loads.

A. Design Voltage Rating of VSC of SAPF

The voltage rating of VSC of SAPF depends on the maximum voltage to be injected in linear load condition. Consider a voltage fluctuate up to 25% of phase voltage hence maximum sag in the source terminal voltage is calculated as $(415/\sqrt{3})*0.75 = 179.7$ V and the injected voltage (V_c) is as:

$$\begin{aligned} V_c &= \sqrt{(V_s^2 - V_L^2)} \\ &= \sqrt{(239.6^2 - 179.7^2)} = 158.4 \text{ V} \end{aligned} \tag{6}$$

In case of nonlinear load the design of voltage of SAPF based on the dc bus voltage of the three phase rectifier load. The SAPF is eliminating harmonics in the source current and it injects only harmonics component of load voltage. Hence the fundamental component is as:

$$V_{LL} = (\sqrt{6}/\pi)\, V_d = 0.779*V_d \tag{7}$$

Where V_{LL} is the line voltage of 415 V, then V_d is 532.7 V. The voltage rating of the SAPF is obtained from the difference of source terminal and load voltage. Hence the SAPF voltage is calculated as:

$$V_{C(rms)}{}^2 = \frac{1}{\pi}\left[\left\{2\int_0^{\pi/3}(415\sqrt{2}\sin\theta - 0)\right\} + \left\{\int_0^{2\pi/3}(415\sqrt{2}\sin\theta - 532.7)\right\}\right]d\theta \tag{8}$$

$V_{C(rms)} = 145.56$ V is the voltage rating of VSC in nonlinear load. Then optimum value of voltage rating of VSC for combination of linear and nonlinear load is $V_c = 158.4$ V.

B. Design of Current Rating of VSC

The current rating of VSC depends on the connected load on the above system. For 7.5 kW unity pf and 0.8 pf loads, the currents are calculated as:

$$\sqrt{3}\, V_s I_s = 7500/pf \tag{9}$$

Where, I_s and V_s are the line current and line voltage respectively. For $V_s = 415$ V and unity pf, the current rating of VSC is $I_s = 10.43$A and for 0.8 pf, the current rating of VSC is $I_s = 13.043$A.

In case of nonlinear load the current rating of VSC depends on the fundamental component of load current. For a unity pf source current, 7.5 kW resistive load and load voltage $V_L = 415$ V, the current rating of VSC is calculated as:

$$I_s = P/(\sqrt{3}V_L) = 13.043A$$

The R_L is equivalent resistance of the dc load, which calculated as

$$P_{dc} = (V_d^2/R_L) \tag{10}$$

For $P_{dc} = 7.5$ kW and $V_d = 532.7$ V, the $R_L = 37.84\ \Omega$

C. KVA Rating of VSC of SAPF

The KVA rating of VSC of SAPF is calculated as

$$\begin{aligned} \text{kVA} &= 3\, V_c\, I_s/1000 \\ &= (3*158.4*13.043)/1000 = 6.198 \text{ kVA} \end{aligned} \tag{11}$$

D. Rating of Injection Transformer of SAPF

The kVA rating of the injection transformer is same as kVA rating of VSC.

$$\text{kVA} = 3\, V_c\, I_s/1000 = (3*158.4*13.043)/1000 = 6.198 \text{ kVA}$$

Hence the rating of the injection transformer is 6.198 kVA, 158/158 V.

E. DC Capacitor Voltage of VSC of SAPF

The dc capacitor voltage is depend of the VSC side voltage of the injection transformer voltage $V_{C(s)} = 158$ V

$$\begin{aligned} V_{dc} &> 2\sqrt{2}\, V_{C(s)} \\ &> 446.8 \text{ V} \end{aligned} \tag{12}$$

Hence $V_{dc} = 450$ V is selected for SAPF.

F. DC Capacitance of VSC of SAPF

The dc bus capacitance selection is depending on the transient energy required during change in load condition. Consider the energy store in capacitor equal to the energy demand of the load for a fraction of power cycle.

$$(1/2)\, C_{dc}\, (V_{dc}^2 - V_{dc1}^2) = 3\, V_{ph} * I_{ph} * t \tag{13}$$

Where V_{dc} is the rated dc bus voltage, V_{dc1} is the drop in dc bus voltage allowing in transient and t is the time for which support is required. Considering t = 400µsec, $V_{dc} = 450$ V, $V_{dc1} = 450 - 2\%$ of $450 = 441$ V and C_{dc} is dc bus capacitance.

$$1/2 * C_{dc}\, (450^2 - 441^2) = 3*239.6*13.043*0.40 \text{ ms}$$

$C_{dc} = 0.935$ mF, hence a dc bus of 1000 µF, 450V is selected.

G. Interfacing Inductor for VSC of SAPF

The value of interfacing inductance (L_r) is selected according to the ripple in the current of the SAPF. Consider the current ripple is 5%, and then value of inductor is calculated as

$$L_r = 0.866 m V_{dc} / (6 a f_s \Delta I) \tag{14}$$

For transformer rated 158.4/158.4 V, 13.043A in primary side, the current is in secondary side also I = 13.043A.The $f_s = 10$ kHz, loading factor (a = 1.2), modulation index (m = 1) and for safe side I is taken 30A.

$$L_r = 0.866*1*450/\{6*1.2*10k*(0.05*25)\} = 3.6 \text{ mH}$$

Hence, an interfacing inductor (L_r) of 3.6mH and 30A current carrying capacity is selected for the SAF.

H. *Design of Ripple Filter*

The design of ripple filter depends on the switching frequency. The capacitor offers a low impedance path for switching ripples and series inductor provides high impedance path for switching ripples. The reactance is provided by the capacitor and inductor at half of switching frequency (f_r = 5kHz) and which are calculated as

$$X_{Cr} = 1/\,(2*\pi*f_r*C_r) \qquad (15)$$

$$= 1/\,(2*3.14*5000*C_r)$$

$$X_{Lr} = 2*\pi*f_r*L_r \qquad (16)$$

$$= 2*3.14*5000*L_r$$

For $X_{Cr} = 3\Omega$, $C_r = 10.61\mu F$ and for $X_{Lr} = 100\Omega$, $L_r = 3.18$ mH Design values of IAG-SAPF system given in TABLE-II

TABLE-II

Rating of IAG-SAPF system

	IAG-SAPF
Rating of SEIG	7.5 kW
Source Voltage	415 V
KVA Rating of VSC	6.198 KVA
Current Rating of VSC	13.043 A
DC Bus Voltage	450 V
DC Bus Capacitance	1000 µF
Filters	3.18 mH,10.6 µF
Current Rating of IGBT	24.2 A
Voltage Rating of IGBT	562.5 V
Rating of Transformer	6.198 KVA, 158 V/158 V

VI. RESULT AND DISCUSSION

A Fuzzy logic controller based SAPF for voltage regulation of constant speed prime mover driven SEIG feeding three phase linear and nonlinear loads is designed, modeled and simulated in MATLAB environment.

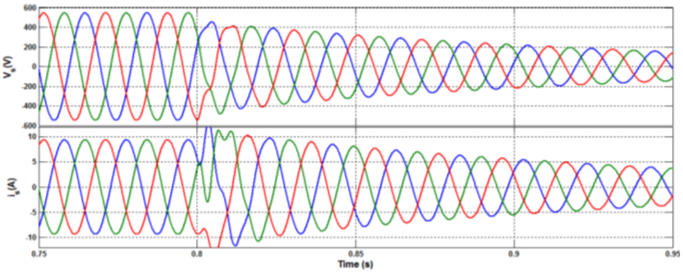

Fig. 4 SEIG feeding three-phase resistive-inductive load without SAPF

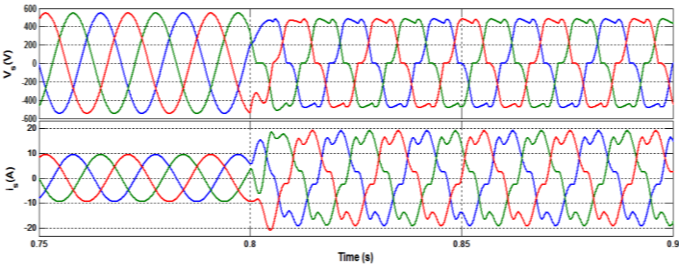

Fig. 5 SEIG feeding three-phase nonlinear load without SAPF

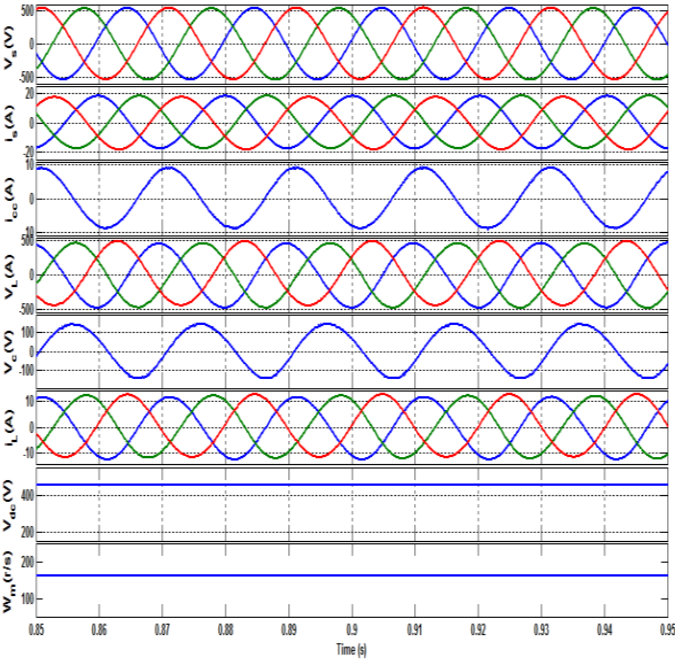

Fig. 6 SEIG feeding three-phase resistive load with FLC based SAPF

A 7.5 kW, 415V, 50Hz asynchronous machine is used as a generator. A 5 kVAR delta connected excitation capacitor is used to generate the rated voltage at no-load, while an additional demand of the reactive power of the generator during load variation is met by the proposed SAPF controller. SEIG has a problem of poor voltage regulation in pure resistive and resistive-inductive loads. The source voltage (V_s) and source current (i_s) of SEIG feeding three-phase 7.5kW, 0.8 pf (lagging) load without SAPF controller are shows in fig.4. SEIG feeding nonlinear loads face problem of poor voltage regulation and power quality is show in fig.5.

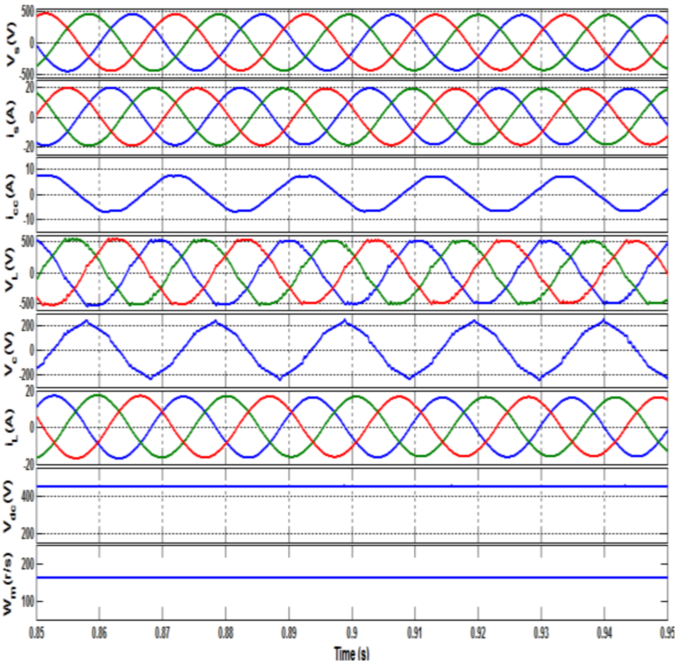

Fig. 7 SEIG feeding three-phase reactive load with FLC based SAPF

The fuzzy interference system (FIS) in fuzzy logic toolbox is used to generate rule base of fuzzy logic controller. The waveform of generated source voltage (V_s), source current (i_s), excitation capacitance phase current (i_{cc}), load voltage (V_L), SAPF compensated voltage (V_c), load current (i_L), DC link voltage (V_{dc}) and mechanical speed (ω_m) are shows performance of SEIG-SAPF system.

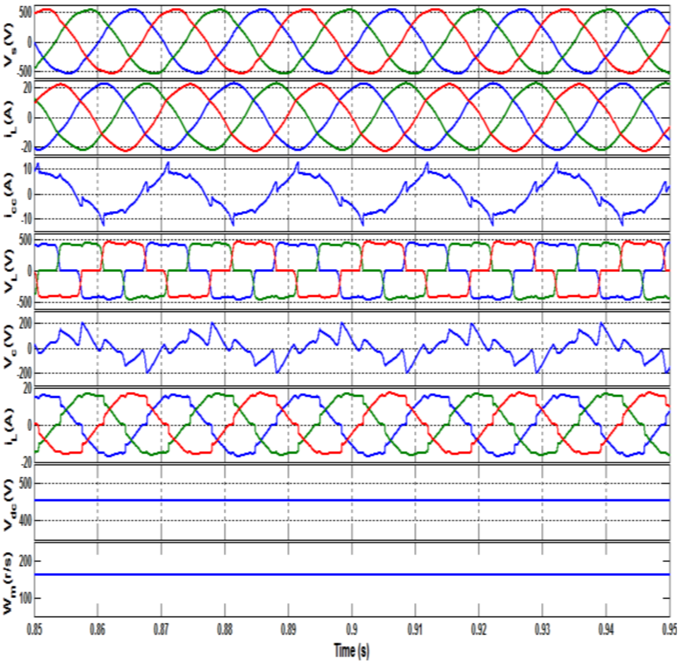

Fig. 8 SEIG feeding three-phase nonlinear load with FLC based SAPF

The performance of three -phases SEIG with FLC based SAPF is running feeding three phase resistive load of 7.5 kW and reactive load of 7.5 kW, 0.8pf are shown in fig 6 and fig 7 respectively. the source and load voltage are remaining constant with small transient for a few cycles.

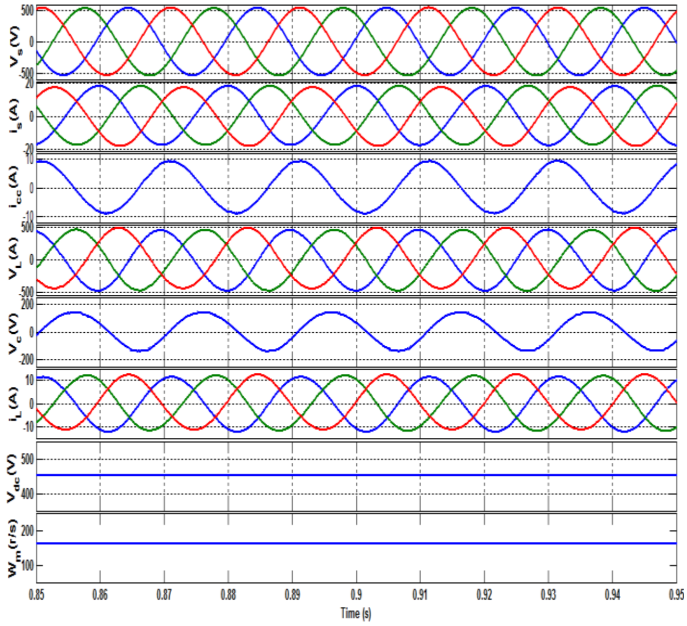

Fig. 9 SEIG feeding three-phase resistive load with PI based SAPF

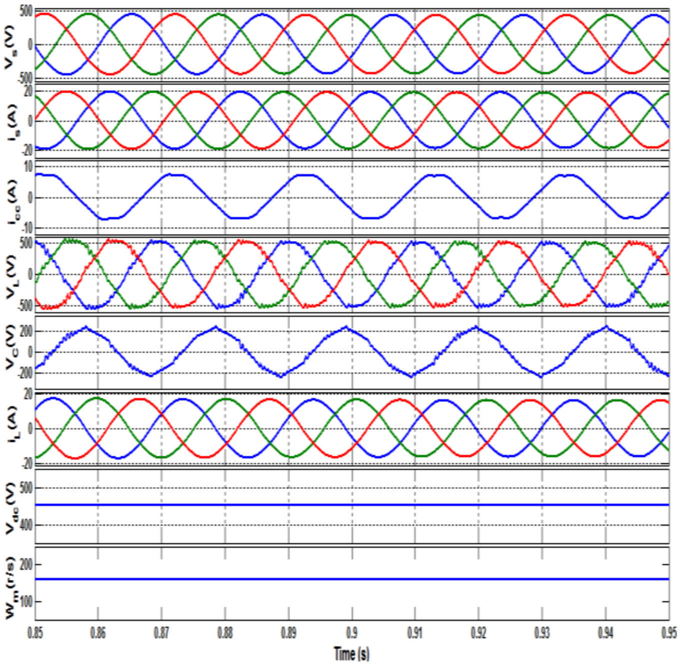

Fig. 10 SEIG Feeding three-phase reactive load with PI based SAPF

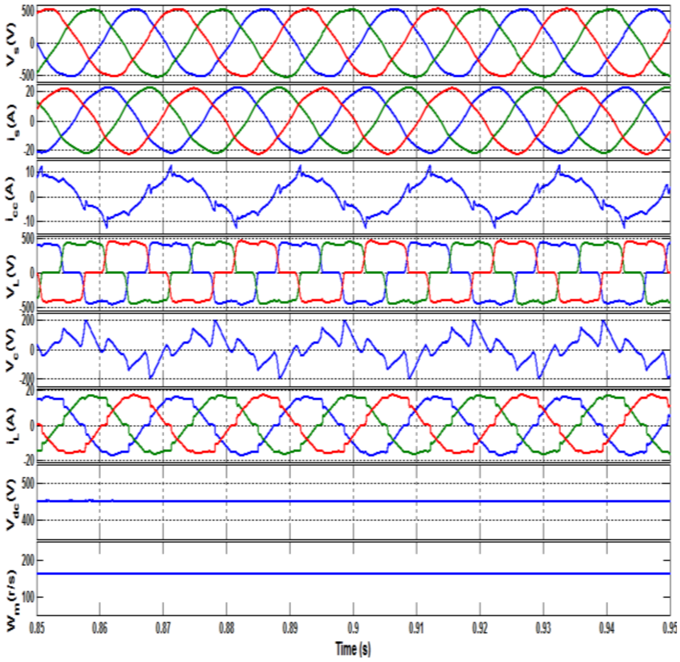

Fig. 11 SEIG feeding three-phase nonlinear load with PI based SAPF

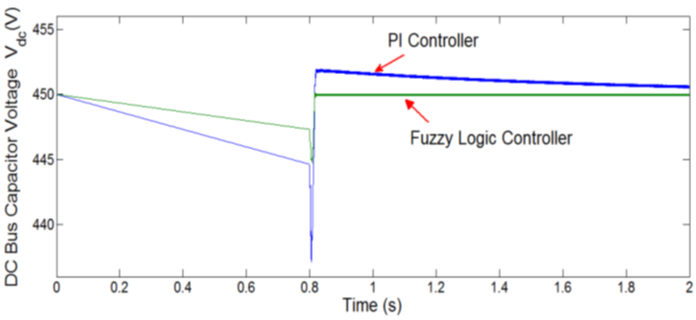

Fig. 12 Transient performance of FLC and PI based SAPF for resistive load

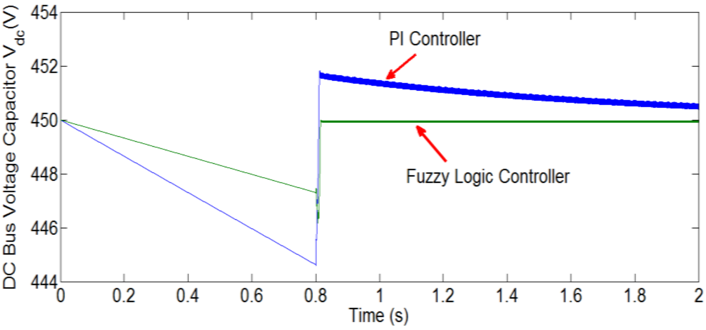

Fig. 13 Transient performance of FLC and PI based SAPF for reactive load

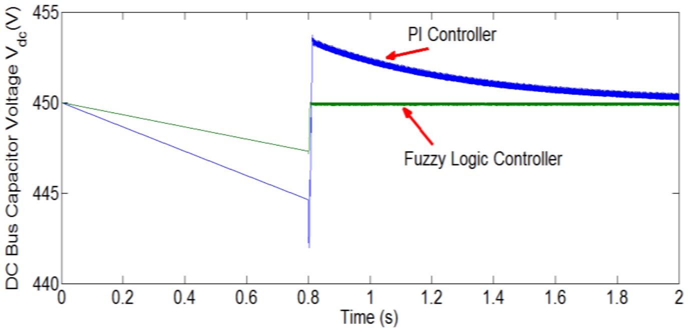

Fig.14 Transient performance of FLC and PI based SAPF for nonlinear load

The fig 8 shows the performance of above system with nonlinear load (uncontrolled rectifier with resistive load) of 7.5 kW. The above system with PI controller based SAPF for same resistive, reactive and nonlinear loads are shows in fig.9, fig.10 and fig.11 respectively.

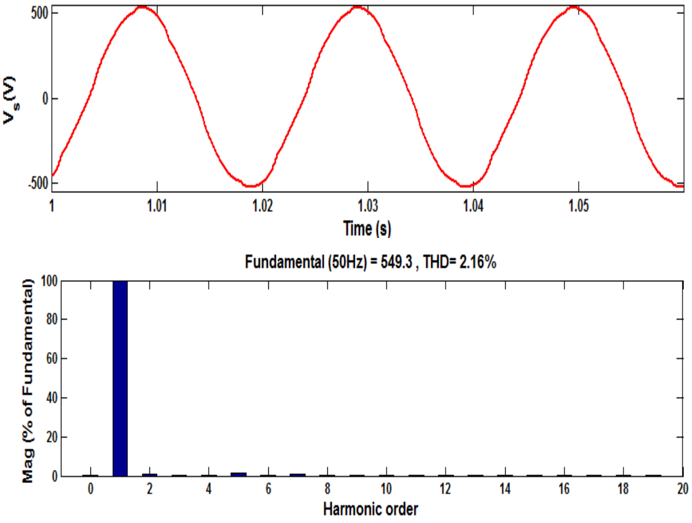

Fig.15 Harmonics spectrum of V_s for FLC based SAPF with nonlinear load

The performance of FLC based is SAPF better than to PI based SAPF for change in load condition with resistive, reactive and nonlinear loads is shows in fig.12, fig.13 and fig.14 respectively. The both FLC and PI based SAPF are able to maintain constant source and load voltage with sinusoidal source and load currents. But FLC gives better result in transient condition with simple rule base. The DC link voltage V_{dc} and speed of generator ω_m also remains constant. In all the above case, loads are applied at 0.8second. The settling time of FLC based SAPF is much lesser from PI based SAPF to maintain constant DC bus capacitance voltage. That means transient performance during change of load condition is good in case of FLC based SAPF.

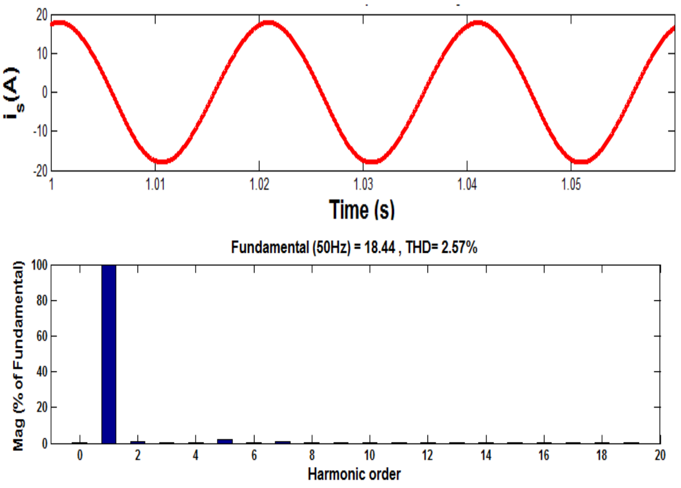

Fig.16 Harmonics spectrum of i_s for FLC based SAPF with nonlinear load

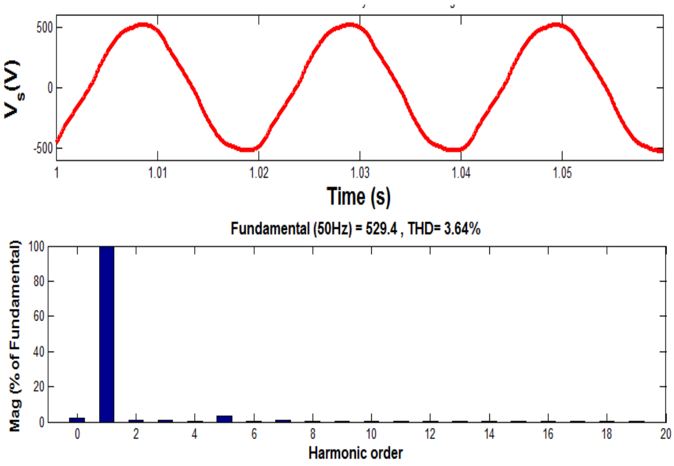

Fig.17 Harmonics spectrum of V_s for PI based SAPF with nonlinear load

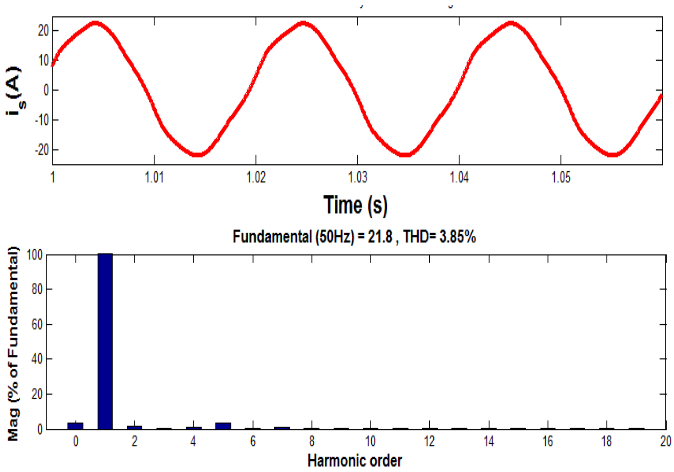

Fig.18 Harmonics spectrum of i_s for PI based SAPF with nonlinear load

The harmonic spectrum of source voltage and source current for SEIG feeding nonlinear load with FLC based SAPF and PI based SAPF are shows in fig. 15 fig. 16, fig.17 and fig.18 respectively. The THD's (Total harmonics distortion) of source voltage (V_s) and source current (i_s) are also lower in case FLC based SAPF from PI based SAPF.

VII. CONCLUSION

Nowadays self excited induction generator (SEIG) is used world-wide used in isolated power generation through renewable and non renewable energy sources. In this paper the capability of SEIG-SAPF system has been demonstrated for feeding three- phase resistive, reactive and nonlinear loads for constant speed prime mover based power generation. The proposed FLC and PI based SAPF controller is suitable for good voltage regulation. The SAPF is able to maintain constant source and load voltages with sinusoidal source current. The rating, size and cost of voltage source converter in SAPF are reduced from previously proposed STATCOM. Rating of DC link capacitor is also reduced and is easy to handle for implementation. The artificial intelligent based fuzzy logic rule based technique is simple and gives better performance in transient condition with respect to settling time and overshoot.

APPENDIX

A. *The parameters of 7.5kW, 415V, 50Hz, Y-Connected, 4- Pole asynchronous machine are given below.*

$R_s = 1\ \Omega$, $R_r = 0.77\ \Omega$, $X_{Lr} = X_{Ls} = 1.5\ \Omega$, $J = 0.1384$ kg-m^2
$L_m = 0.134$ H ($I_m < 3.16$)
$L_m = 9e\text{-}5 I_m^2 - 0.0087 I_m + 0.1643$ ($3.16 < I_m < 12.72$)
$L_m = 0.068$ H ($I_m > 12.72$)

B. *Controller parameters*

$L_f = 2$ mH, $R_f = 4\ \Omega$, $C_f = 10\ \mu F$ and $C_{dc} = 1000\ \mu F$.
Three numbers of single phase transformers each rating of 3 kVA, 300 V/300 V and DC link voltage is 450 V.

C. *Consumer Loads*

Resistive load of 7.5 kW
Reactive load 7.5 kW, 0.8 pf lagging
Nonlinear loads of 7.5 kW resistive with uncontrolled Rectifier

D. *Prime Movers Characteristics*

$T_{sh}. = K_1 - K_2\omega_m$
$K_1 = 16100$, $K_2 = 100$

REFERENCES

[1] S .P . Singh, Bhim Singh and M. P . Jain, "Performance characteristics and optimum utilization of a cage machine as capacitor excited induction generator", *IEEE Trans. Ener. Con.,* vol. 5, no. 4. Dec. 1990.

[2] Bhim Singh and L.B. Shilpakar, "Analysis of a novel solid state voltage regulator for a self-excited induction generator", *IEE Proc.-Gener. Trans. Distrib.,* vol. 145, no. 6, November 1998.

[3] E.Levi and Y.W.Liao, "An experimental investigation of self-excitation in capacitor axcited induction generators", *Electrical Power and Systen Research*, vol 53, pp 59-65, 2000.

[4] B. Singh, S.S. Murthy and S. Gupta, "Analysis and design of STATCOM-based voltage regulator for self-excited induction generators", *IEEE Trans. Energy Con.,* vol.19, no.4, pp. 783- 790, Dec. 2004.

[5] T. Ahmed, O. Noro, E. Hiraki, and M. Nakaoka, "Terminal voltage regulation characteristics by static var compensator for a three-phase self-excited induction generator", *IEEE Transactions on Industry Applications ,* vol.40, no.4, pp. 978- 988, July-Aug. 2004.

[6] Bhim Singh and Gaurav Kumar Kasal, "Solid state voltage regulator for isolated asynchronous generators supplying 3-phase 4-wire loads", *Proc. of India International Conference on Power Electronics,2006.*

[7] B Singh, L.Shridhar and C.S. Jha, "Improvement in the performance of self-excited induction generator through series compensation", *IEE Proc. on Generation, Transmission and Distribution,* vol. 146, no. 6, pp. 602 – 608,Nov. 1999.

[8] M.H.Haque, "Compensation of distribution system voltage sag by DVR and STATCOM", *IEEE Porto Power Tech Conference Portugal*, 10-13 September 2001.

[9] A. Ghosh, "Performance study of two different compensating devices in a custom power park", *IEE Proc.-Gener. Transm. Distrib.,*vol.152, no.4,pp. 521 – 528, july 2005.

[10] Y.K. Chauhan, S.K. Jain, and B. Singh, "A Prospective on voltage regulation of self-excited induction generators for industry applications," *IEEE Transactions on Industry Applications,* vol.46, no.2, pp.720-730, March-April 2010.

[11] Y.K. Chauhan, S.K. Jain and B. Singh "Performance of a three-phase self-excited induction generator with static synchronous series compensator", *IEEE PEDES and Power India conference* , pp 1-6. 2010.

[12] Y.K.Chouhan, S.K.Jain and B.singh, "Operating performance of static series compensated three-phase self-excited induction generator", *Electrical Power and Systen Research*, vol 49, pp 137-148, 2013.

[13] S.Tiwari, S.Gupta, S.Jain and B.singh, "Series active filter based voltage controller for an isolated power generation", *IEEE International Conference on Power Electronics, Drives and Energy System*, Bengaluru, India, 16-19 Dec. 2012.

[14] Chuen Chin Lee,"Fuzzy logic in control systems: fuzzy logic controller-part I", *IEEE Transaction on System,Man,and Cybernetics,* vol. 20, no.2, March/April. 1990.

[15] Parmod Kumar and Alka Mahajan, " Soft computing techniques for the control of an active power filter", *IEEE Trasaction on Powe Delinery*, vol. 24, no. 1, January 2009

[16] T.Narasa Reddy and M.V. Subramanyam, "Fuzzy logic controlled shunt active power filter for mitigation of harmonics with different membership functions", *IEEE International Conference on Advances in Computing, Control, and Telecommunication Technologies*, 2009

[17] Sailendra sharma and Bhim Singh, "Fuzzy proportional-integral regulator for stand-alone wind energy conversion system" *IEEE conference,*2010.

[18] P.Karuppanan and KamalaKanta Mahapatra, "PLL with fuzzy logic controller based shunt active power filter for harmonic and reactive power Compensation" *IEEE Conference*, 2011