FUZZY LOGIC BASED CONTROL OF VARIABLE SPEED INDUCTION MACHINE WIND GENERATION SYSTEM

K. Kaur, Dr.S.Chowdhury, Dr.S.P.Chowdhury, Dr. K.B.Mohanty, Prof.A.Domijan

Abstract- The main objective of this paper is to analyze the performance of a variable speed wind generation system by using fuzzy logic principles for efficiency optimization and performance enhancement control. A squirrel cage induction generator feeds the power to a double-sided pulse width converter system, which feeds power to either an utility grid, or to an autonomous system. The generation system uses three numbers of fuzzy logic controllers. The first fuzzy controller tracks the generator speed with the wind velocity to extract maximum power. The second fuzzy logic controller programs machine flux for light load efficiency improvement. The third fuzzy logic controller provides robust speed control against wind vortex and turbine oscillatory torque.

I. INTRODUCTION

The global electrical energy consumption is rising and there is steady increase of the demand on power generation. The existing conventional energy sources are depleting .So alternative energy source investment are becoming more important now a days. Wind electrical generation systems are recently getting lot of attention, because they are most cost competitive, environmental clean and safe renewable power source, as compared to fossil fuel and nuclear power generation. The depletion reserves, increase in demand, and certain factors in world politics have together contributed to a sharp rise in the cost of thermal power generation. Many places also do not have the potential for generating hydel power. Nuclear power generation was once treated with great optimism, but with the knowledge of the environmental hazards associated with the possible leakage from nuclear power plants, most countries have decided not to install them anymore. The growing awareness of these problems led to heightened research efforts for developing alternative sources of energy for generation of electricity. The most desirable source would be one that is non- pollutant, available in abundance and renewable and can be harnessed at an acceptable cost in both large – scale and small scale systems. The most promising source satisfying all these requirements is wind, a natural energy source. Wind is a form of solar energy. The uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth cause winds. The maximum extractable energy from the 0-100 m layer of air has been estimated to be the order of 10^{12} KWh/annum, which is of the same order as hydroelectric potential. Over 1700 MW of wind generators are installed worldwide, Current generation is of 100 billion KWh of energy annually. Recent evolution of power semiconductors and variable frequency drive technology has aided the acceptance of variable speed generation systems. In spite of additional cost of power electronics and control, the total energy captured in a variable speed wind turbine system is larger and therefore the lifecycle cost is lower than with fixed speed drives. Denmark was the first country to erect windmill and the top five countries in the world to have the highest installed wind power capacity are Germany, Spain, Denmark, U.S.A and India respectively.

In this paper fuzzy logic principles have been used. Fuzzy logic is a powerful and versatile tool for representing imprecise, ambiguous and vague information. It also helps to model difficult, even intractable problems. In this paper, all the control algorithms have been validated by matlab simulation study and system performance has been evaluated in detail.

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II. WIND - GENERATION SYSTEM DESCRIPTION

A. CONVERTER SYSTEM

The converter system is shown in the fig.1. A wind turbine is coupled to the shaft of a squirrel cage induction generator through a speed up gear ratio, which is used to convert the low speed of wind turbine rotor to the high speed of induction generator. The induction generator is

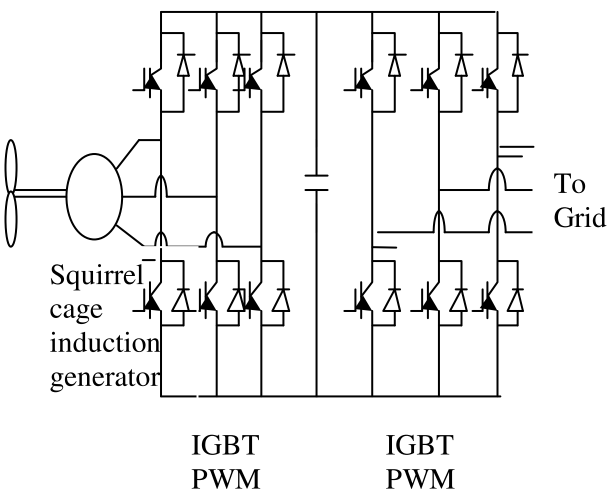

Fig.1: A voltage fed double PWM converter wind generation system

then connected to two double sided SPWM IGBT converters. Lastly the generation system feeds power to a utility grid. Some of its salient features are as follows:

- Line side power factor is unity with no harmonic current injection.
- The cage type induction machine is extremely rugged, reliable, economical, and universally popular.
- Machine current is sinusoidal and no harmonic copper loss.
- Rectifier can generate programmable excitation for the machine.
- Continuous power generation from zero to highest turbine speed is possible.
- Power can flow in either direction permitting the generator to run as a motor for start-up.
- Autonomous operation is possible either with the help of start up capacitor or dc link battery.
- Extremely fast transient is also possible.

B. TURBINE CHARACTERISTICS

There are two types of turbines: vertical and horizontal type. [7] A vertical type turbine need not be oriented with respect to wind direction because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easier servicing and a lighter weight, lower cost tower. It is therefore preferred for high power output. The aerodynamic torque of a vertical turbine is given by:

$$T_m = C_p(\lambda)\frac{0.5\rho\pi R_\omega^{\ 3}}{\eta_{GEAR}} v_\omega^{\ 2} \qquad (1)$$

Where, C_P=Turbine power coefficient,

λ = Tip speed ratio,

ρ = Air density,

R_ω=Turbine radius,

V_ω=Wind velocity,

η_{GEAR}=Turbine angular speed.

C_P is defined as the ratio of output power from wind turbine to the total input available wind power. Tip speed ratio is defined as the ratio of turbine speed at the tip of the blade to the free steam wind speed. C_P is a non-linear function of tip speed ratio and is shown in fig. 2.

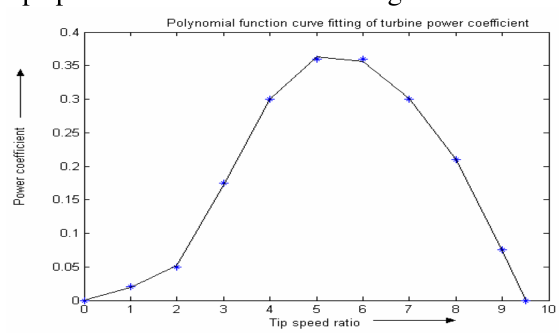

Fig.2: $C_P \sim \lambda$ Characteristics

Speed up gear ratio is defined as the ratio of high speed of generator to the low speed of wind turbine rotor. The oscillatory torque of the turbine is more dominant at the first, second and fourth harmonics of fundamental turbine angular velocity is given as follows:

$$T_{OSC} = T_m[A.\cos(\omega_\omega t) + B.\cos(2\omega_\omega t) + C.\cos(4\omega_\omega t)] \qquad (2)$$

Fig. 3 shows the model of wind turbine with oscillatory torque. And fig. 4 shows the turbine torque ~ turbine angular speed.

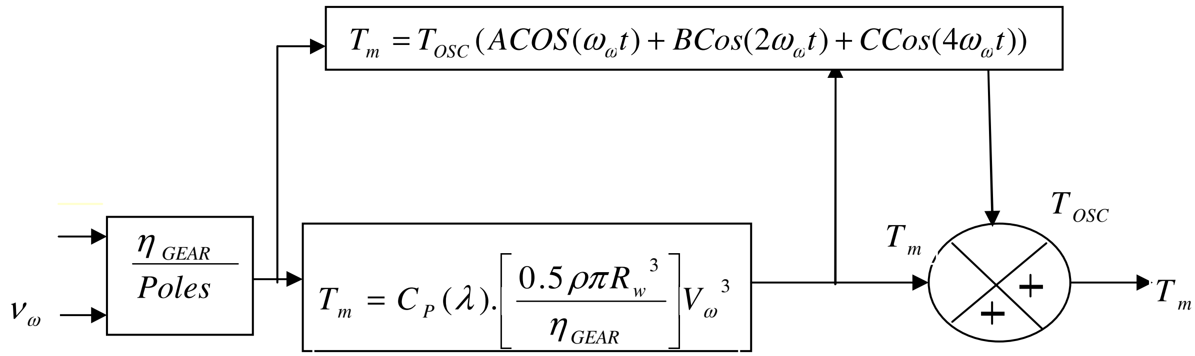

Fig.3 : Model of wind turbine with oscillatory torque

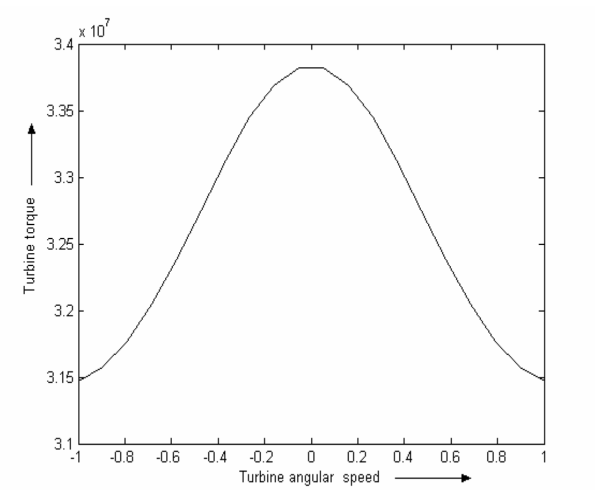

Fig. 4 : Turbine torque ~ turbine angular speed

C. CONTROL SYSTEM

The control block diagram of the wind generation system is shown in fig. 5. The variable frequency and variable voltage power generated by the machine is rectified to dc by IGBT SPWM that also supplies lagging excitation current to the machine. The dc link power is inverted to ac through IGBT SPWM [2] and fed to a utility grid at a unity power factor. The line power factor can further be controlled by means of active VAR compensator. The generator speed is controlled by indirect vector control with torque control in its inner loop. The line side converter is also vector controlled, using direct vector control and synchronous current control in the inner loop. The output line power Po is controlled to control the dc link voltage V_d. since an increase of the line power causes a decrease of dc link voltage, this causes a decrease of dc link voltage, the voltage loop error polarity has been inverted. The insertion of filter inductance Ls creates some coupling effect which is eliminated by a decouple in the synchronous current control loop. The system uses three numbers of fuzzy logic controllers.

III. FUZZY LOGIC CONTROLLERS

The heuristic way of searching the maximum could be based on a rule called as "Fuzzy Meta-rule", which is given as follows:

"If the last change in the input variable (x) has caused the output variable (y) to increase, keep moving the input variable in the same direction; if it has caused the output variable to drop, move it in the opposite direction."

The Wind generation system consists of three no.s of fuzzy logic controllers [11]:

A. FLC-1 (GENERATOR SPEED TRACKING CONTROLLER)

For a particular wind velocity FLC-1 function is search the generator speed until the system settles down at the maximum power output condition. For wind velocity $V\omega_4$ in fig. 6, the output power will be at A if the generator speed is ωr1. The FLC-1 will alter [1], [8] the speed in steps until it reaches the speed ω_{r2}, where the output power is maximum at B. If the wind velocity increases to $V\omega_2$, the output power will jump to D, and then

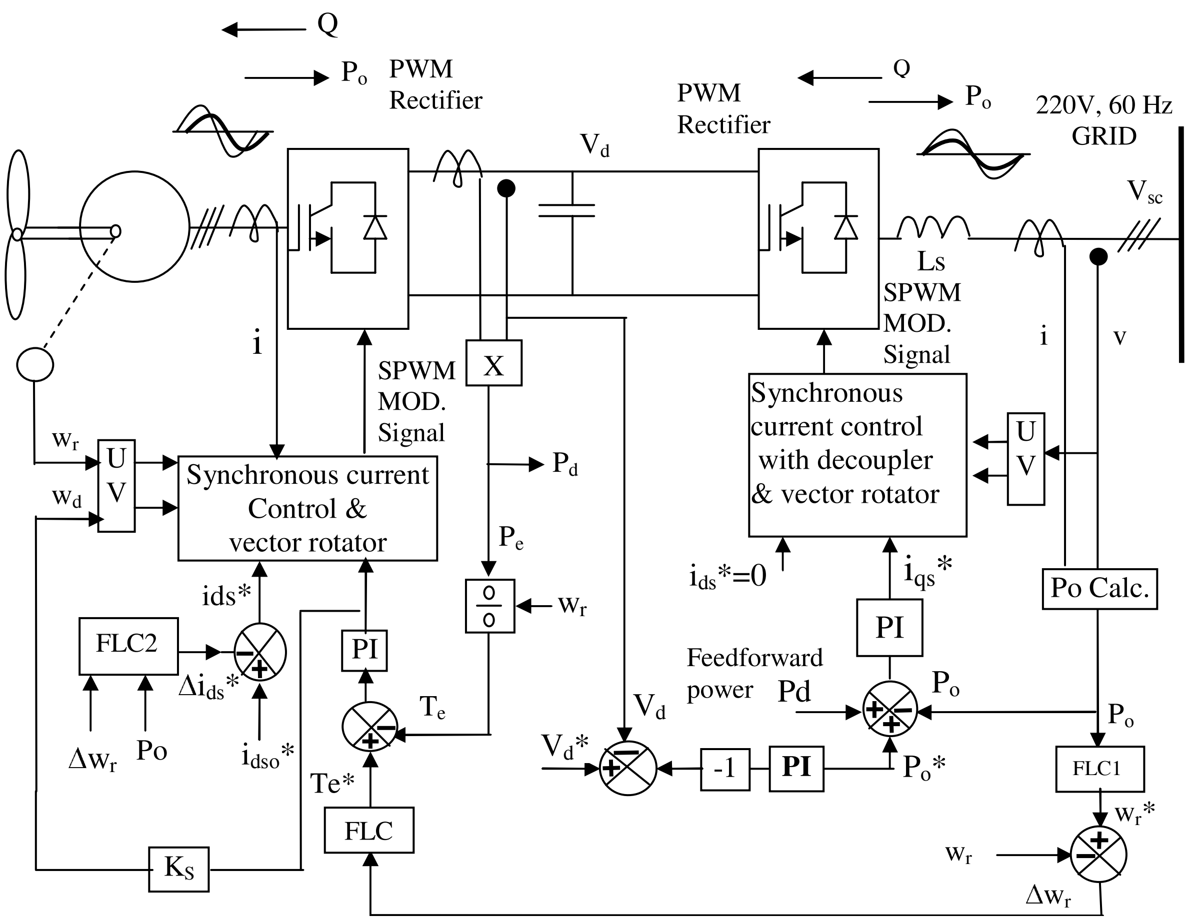

Fig. 5: Fuzzy logic based control block diagram of wind generation system

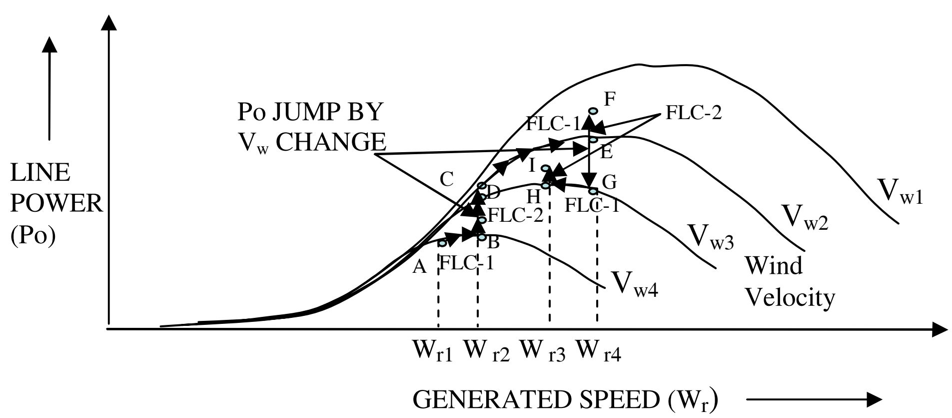

Fig. 6: Fuzzy Controllers FLC-1 and FLC-2 operation showing maximization of power.

FLC-1 will bring the operating point to E by Searching the speed to ω_{r4}. Similar is the case of decrease in wind velocity. With an incrementation (or decrementation) of speed, the corresponding incrementation (or decrementation) of output power is estimated. The controller operates on a per-unit basis so that the response is insensitive to system variables and the algorithm are universal to any system. The wind vortex and torque ripple can lead the search to be trapped in a minimum

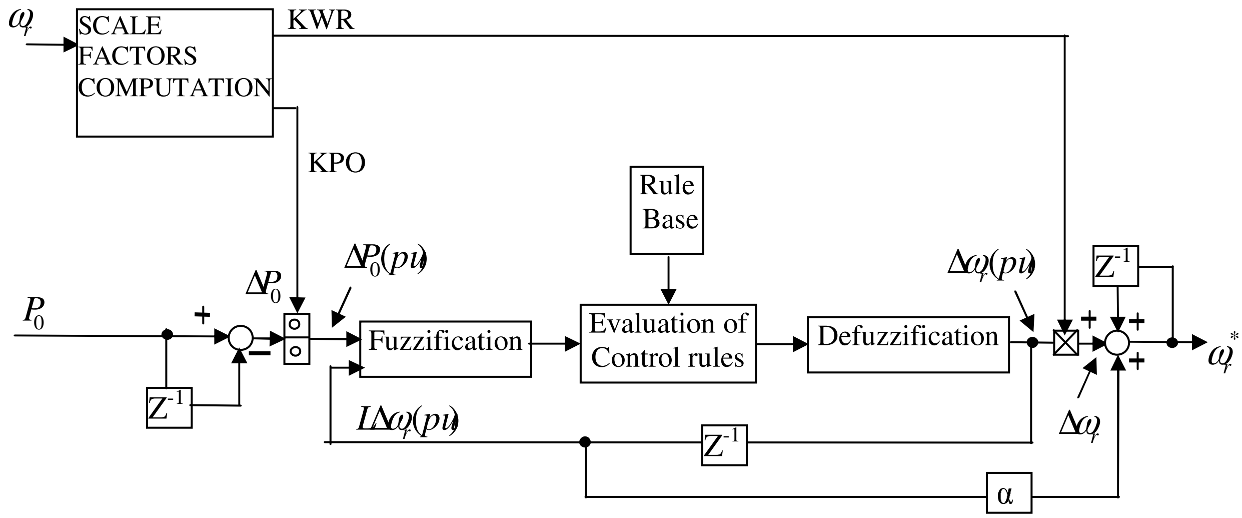

Fig. 7: Block diagram of FLC-1

which is not global, so the output $\Delta\omega_r$ is added to some amount of $L\Delta\omega_r$ in order to give some momentum to continue the search and to avoid such local minima[10]. The scale factors KPO and KWR , are generated as a function of generator speed so that the control becomes somewhat insensitive to speed variation. The scale factor expressions are given, respectively, as:

$$KPO = a_1\omega_r \quad (3)$$

$$KWR = a_2\omega_r \quad (4)$$

Where, a_1 and a_2 are the constant coefficients that are derived from simulation studies.

In FLC-1, there are two inputs $\Delta P0$ and $L\Delta\omega_r{}^*$ and one output $\Delta\omega_r{}^*$ .In the implementation of fuzzy control, the input variables are fuzzified ,the valid control rules are evaluated and combined and finally the output is defuzified to convert to the crisp value. In this paper , the above block diagram of FLC-1 was simulated using triangular membership function and the centroid method was used for defuzzification.

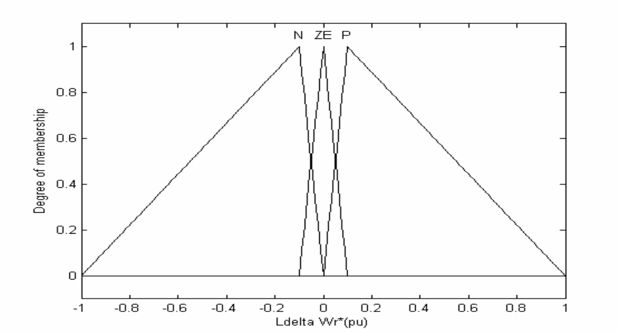

Fig. 8(a)

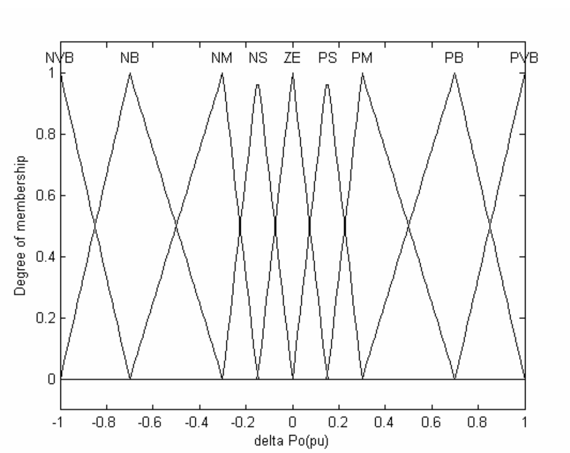

Fig. 8(b)

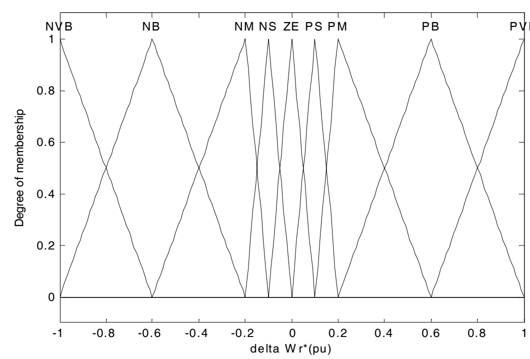

Fig. 8(c)

Fig. 8(a),(b) & (c) : Membership functions of FLC-1

The membership functions for all the variables are asymmetrical [2],[5] because they gives more sensitivity as the variables approaches zero value.

The rule matrix for FLC-1 [2],[11] is given below:

$L\Delta\omega_r^*$ / ΔP_0	P	ZE	N
NVB	NVB	NVB	PVB
NB	NB	NVB	PB
NM	NM	NB	PM
NS	NS	NM	PS
ZE	ZE	ZE	ZE
PS	PS	PM	NS
PM	PM	PB	NM
PB	PB	PVB	NB
PVB	PVB	PVB	NVB

Table 1: Rule matrix for FLC-1

A typical rule of FLC-1 can be read as follows:

"If ΔPo is PM (positive medium) AND $L\Delta\omega_r^*$ is P (positive) , THEN $\Delta\omega_r^*$ is PM (positive medium)."

B. FLC-2 (GENERATOR FLUX - PROGRAMMING CONTROLLER)

The function of FLC -2 is to program the machine rotor flux for light load efficiency improvement. The block diagram of FLC-2 is shown in fig. 9.The system output power Po(k) is sampled and compared with the previous value Po(k-1) to determine the increment ΔPo . In addition, the last excitation current decrement $L\Delta i_{ds}$ is reviewed. On these bases, the decrement step of i_{ds} is generated from fuzzy rules through fuzzy inference and defuzzification . It is necessary to process the inputs of FLC-2 in per-unit values[1],[9]. Therefore, the adjustable gains KP and KIDS convert the actual variable to variables with the following expressions:

$$KP = a\omega_r + b \qquad (5)$$

$$KIDS = C_1\omega_r - C_2 i_{qs} + C_3 \qquad (6)$$

Where a, b, C_1 ,C_2 and C_3 are derived from simulation studies. The membership functions are shown in fig. 10.

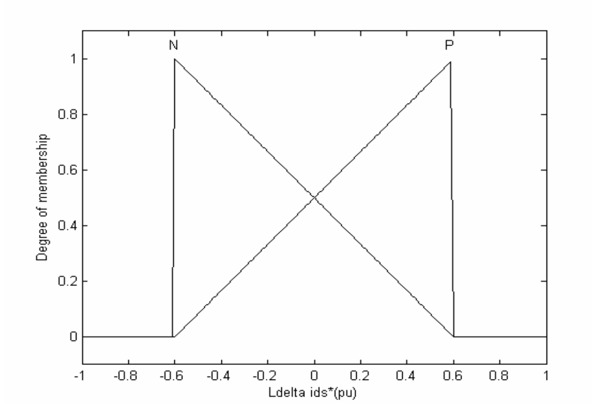

Fig.10(a)

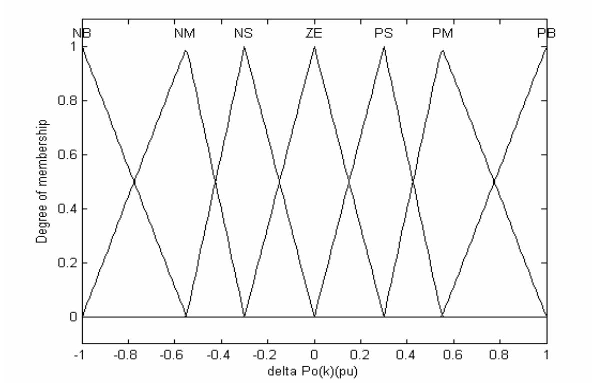

Fig.10(b)

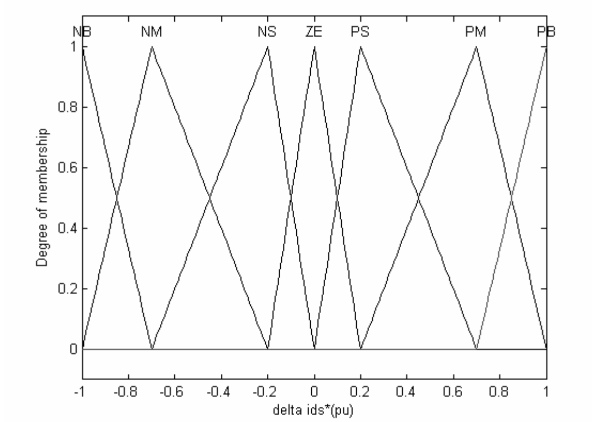

Fig. 10 (c)

Fig.10(a),(b) & (c) : Membership functions of FLC-2

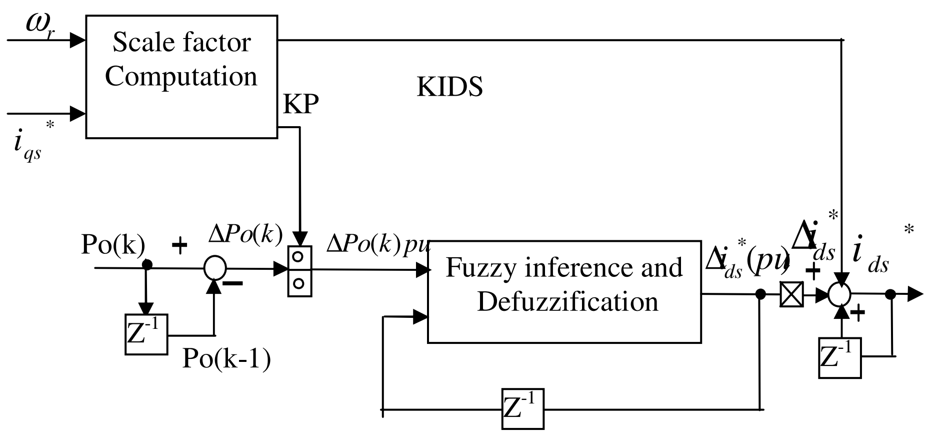

Fig.9: Block diagram of FLC-2

The rule matrix for FLC-2 [2],[11] is given below:

$L\Delta i_{ds}*(pu)$ $\Delta P_0(k)$	N	P
PB	NM	PM
PM	NS	PS
PS	NS	PS
NS	PS	NS
NM	PM	NM
NB	PB	NB

Table-2: Rule matrix for FLC-2

A typical rule can be read as follows:

"If $\Delta Po(k)$ is PM (positive medium) AND $L\Delta i_{ds}*$ is P (positive) , THEN $\Delta i_{ds}*$ is PS (positive small)."

C. FLC -3 (CLOSED LOOP GENERATOR SPEED CONTROLLER)

The block diagram of FLC-3 is given in fig.11.The speed loop error $E\omega_r*$ and error change $\Delta E\omega_r*$ signals are converted to per-unit signals, processed through fuzzy control, and then summed to produce the generator torque component of current $\Delta\ i_{qs}*$ .It has to be noted here that while fuzzy controllers FLC-1 and FLC-2 operate in sequence at steady wind velocity, FLC-3 is always active during system operation.

The membership functions of FLC-3 is shown in fig.12.

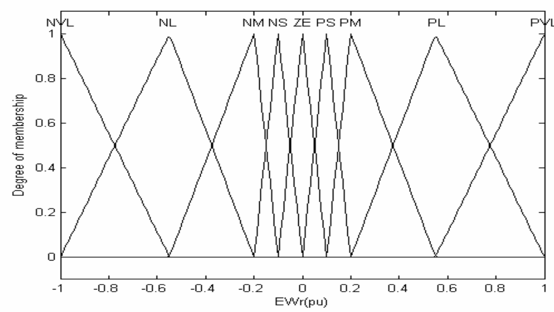

Fig. 12 (a)

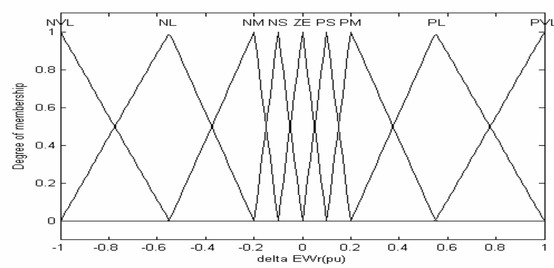

Fig. 12 (b)

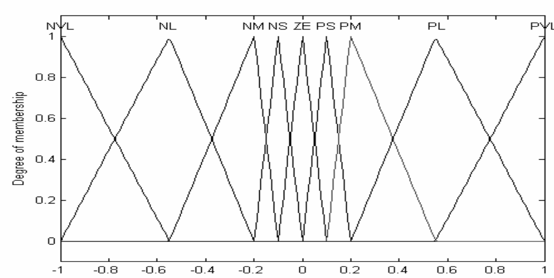

Fig.12 (c)

Fig. 12 (a), (b) &(c): Membership functions of FLC-3

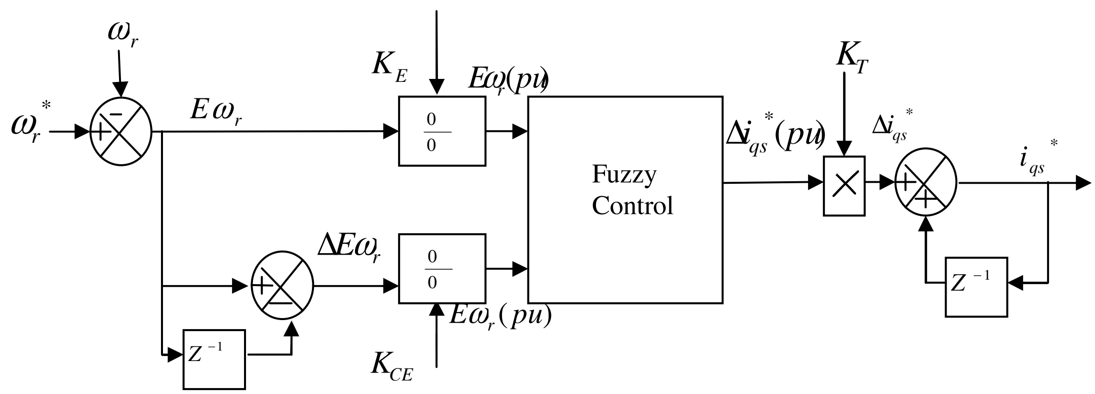

Fig. 11: Block diagram of FLC-3

$E\omega_r$ (pu) / $\Delta E\omega r$ (pu)	NVL	NL	NM	NS	ZE	PS	PM	PL	PVL
NVL					NVL	NL	NM	NS	ZE
NL					NL	NM	NS	ZE	PS
NM				NL	NM	NS	ZE	PS	PM
NS			NL	NM	NS	ZE	PS	PM	PL
ZE		NL	NM	NS	ZE	PS	PM	PL	
PS	NL	NM	NS	ZE	PS	PM	PL		
PM	NM	NS	ZE	PS	PM	PL			
PL	NS	ZE	PS	PM	PL				
PVL	ZE	PS	PM	PL	PVL				

Table-3: Rule matrix for FLC-3

IV. SIMULATION RESULTS

Wind - generation system, shown in fig.5 was simulated to validate all the control strategies and then evaluate the performance of the system. The machine and turbine parameters are given in the following table-4.

MACHINE PARAMETERS
3 phase, 7 hp, 230/450 V, 7.6A, 4 poles, 1500 r.p.m, R_s=0.25Ω, R_r=0.335Ω, L_{ls}=2.11 mH, L_{lr}=2.11 mH, L_m=65.5 mH.
TURBINE PARAMETERS
3.5KW, Tower=99.95m,11.1-22.2 r.p.m, η_{GEAR}=5.2, A=0.015, B=0.03, C=0.015

Table-4:Induction machine and turbine parameters

A.TURBINE AND SYSTEM MODEL SIMULATION (without fuzzy controllers)

(a) Turbine developed torque ~ generator speed

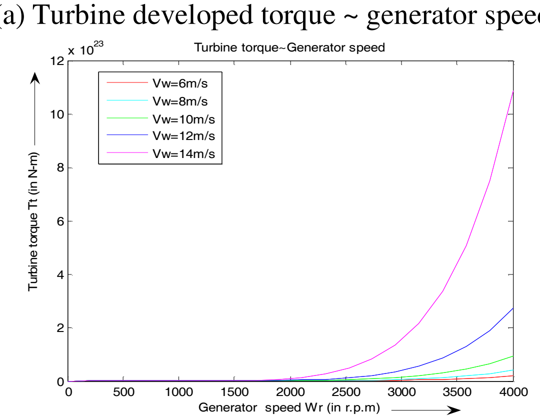

Fig. 13: Turbine developed torque ~ generator speed

(b)Turbine developed power ~ generator speed

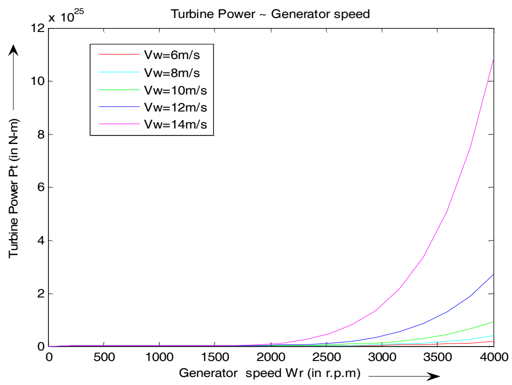

Fig. 14: Turbine developed power ~ generator speed

(c) Line side generated power ~ generator speed

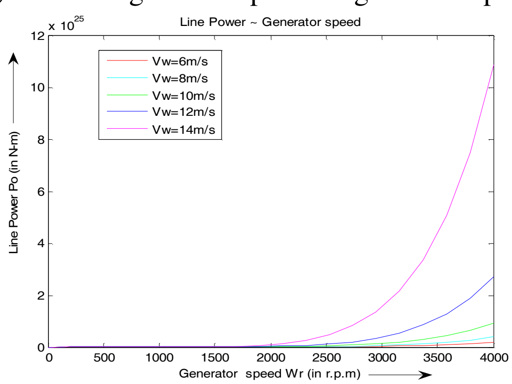

Fig. 15: Line side generated power ~ generator speed

DISCUSSION

It should be noted here that for simplicity, the turbine oscillatory torques are ignored in the system result.

Fig.13: This result reveals that for a particular generator speed , if the wind velocity is increased , its corresponding turbine torque is also increased.

Fig.14: As we know that power is torque multiplied with speed. So, fig. 13 will be same as fig. 14. This result reveals that for a particular generator speed , if the wind velocity is increased , its corresponding turbine developed power is also increased.

Fig.15: The system was assumed to be a lossless system, thus it can be said that the turbine developed power is equal to the line side power. This result reveals that for a particular generator speed , if the wind velocity is increased , its corresponding line side power is also increased.

B.TIME DOMAIN CLOSED LOOP SIMULATION

(a)Wind velocity ~ time(in sec)

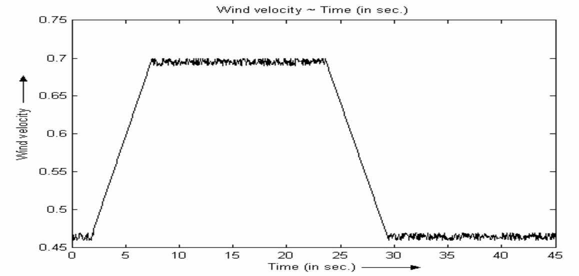

Fig.16: Wind velocity ~ time(in sec)

(b) Generator speed ~ time (in sec.)

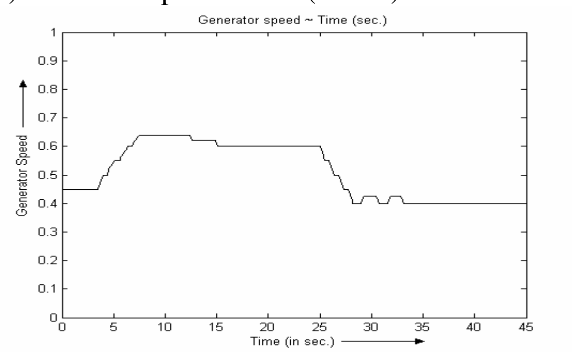

Fig. 17: Generator speed ~ time (in sec.)

(c) Flux current ~ time (in sec.)

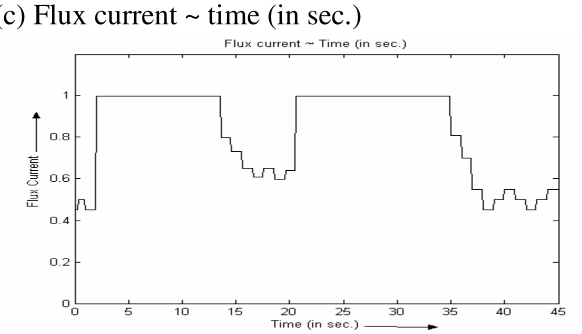

Fig. 18: Flux current ~ time (in sec.)

(d) Output power ~ time (in sec.)

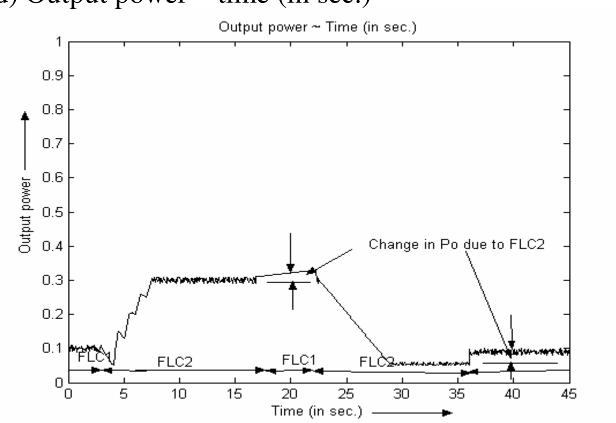

Fig. 19: Output power ~ time (in sec.)

DISCUSSION

The fig.16 has been taken as the input for obtaining closed loop response of the wind generation system. With respect to the change in the wind velocity , the outputs are observed and are shown with the help of fig.17- fig.19 . Here the turbine is modeled with aerodynamic torque(T_m) and turbine oscillatory torque (T_{OSC}) and some turbulence has also been added with the wind velocity to verify the robustness of FLC-3.

FLC-1 will track the generator speed with the change in wind velocity to extract maximum power. So as the wind velocity increases, generator speed is also increased by FLC-1.As a result of which the corresponding line output power is also increased during the interval FLC-1 is active by assuming a lossless system. Similar is the case for the decrease in wind velocity.

FLC-2 will reduce the generator rotor flux for light load efficiency improvement.FLC-2 reduces the flux component of current i.e. i_{ds} . Thus core loss of machine decreases but on the other hand torque component of current i_{qs} is increased , which in turn increases the copper loss of the machine. However, the total system loss i.e machine and converter loss decreases , resulting in an increase of total generated or output power Po. That's why in fig. 19 the output power Po is increased by FLC-2 ,which has been shown in the fig. by means of ΔPo . i.e change in output power.

V. CONCLUSION

The fuzzy logic based variable speed cage machine wind generation system has been analyzed. The system performances has been studied with matlab- simulation to validate all the theoretical concepts.

There are three fuzzy logic controllers in the generation system :

- The first fuzzy controller FLC-1 searches on line the optimum generator speed so that the aerodynamic efficiency of the wind turbine is maximum.
- The second fuzzy controller FLC-2 programs the machine flux by an on line search so as to optimize the machine converter efficiency.
- The third fuzzy controller FLC-3 performs robust speed control against turbine oscillatory torque and wind vortex.

The main conclusions of this paper are :

- The system was found to be parameter insensitive with fuzzy controllers.
- The system shows a fast-convergence with fuzzy controllers.
- The system can accepts noisy and inaccurate signals.
- The fuzzy algorithms used in the system are universal and can be applied retroactively in any other system.
- The performance of the system was found to be excellent with all the fuzzy logic controllers.

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BIOGRAPHIES

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