FUZZY CONTROL OF SQUIRREL CAGE INDUCTION MACHINE WIND GENERATION SYSTEM

B. Ravichandra Rao and R. Amala Lolly
Department of EEE Engineering, GNITS, Hyderabad, India

ABSTRACT
Artificial intelligence techniques, such as fuzzy logic, neural network and genetic algorithm are recently showing a lot of promise in the application of power electronic systems. This Paper describes the control strategy development, design and of a fuzzy logic based variable speed wind generation system. In this work cage type induction generator and double-sided PWM converters are used. The fuzzy logic based control of the system helps to optimize the efficiency and enhance the performance. The generation system uses three 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. The complete control system has been developed, analyzed, and simulated in Matlab.

KEYWORDS: Induction Generator, Fuzzy Logic Controller and Wind Generation system.

I. INTRODUCTION
GRID-connected wind electricity generation is showing the highest rate of growth of any form of electricity generation, achieving global annual growth rates in the order of 20 - 25%. Wind power is increasingly being viewed as a mainstream electricity supply technology. Its attraction as an electricity supply source has fostered ambitious targets for wind power in many countries around the world.

Wind power penetration levels have increased in electricity supply systems in a few countries in recent years; so have concerns about how to incorporate this significant amount of intermittent, uncontrolled and non-dispatchable generation without disrupting the finely-tuned balance that network systems demand.

Grid integration issues are a challenge to the expansion of wind power in some countries. Measures such as aggregation of wind turbines, load and wind forecasting and simulation studies are expected to facilitate larger grid penetration of wind power. In this project simulation studies on grid connected wind electric generators (WEG) employing Squirrel Cage Induction Generator (SCIG)[2].

Fuzzy Logic is a powerful and versatile tool for representing imprecise, ambiguous and vague information. It also helps to model difficult, even intractable problems. The system uses three fuzzy controllers, Fuzzy Programming of Generator Speed, Fuzzy Programming of Generator Flux, Fuzzy Control of Generator Speed Loop

II. WIND-GENERATION SYSTEM DESCRIPTION

2.1 Converter System
The AC/DC/AC converter is divided into two components: the rotor-side converter (Crotor) and the grid-side converter (Cgrid). Crotor and Cgrid are Voltage-Sourced Converters that use forced-commutated
power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor $L$ is used to connect $C_{\text{grid}}$ to the grid. The three-phase rotor winding is connected to $C_{\text{rotor}}$ by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals $V_r$ and $V_{gc}$ for $C_{\text{rotor}}$ and $C_{\text{grid}}$ respectively in order to control the power of the wind turbine, the DC bus voltage and the reactive power or the voltage at the grid terminals.

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.

The mechanical power and the stator electric power output are computed as follows:

$$P_m = T_m \omega_r \quad (1)$$

$$P_s = T \omega_s \quad (2)$$

For a lossless generator the mechanical equation is:

$$J \frac{d\omega_s}{dt} = T \quad (3)$$

In steady-state at fixed speed for a lossless generator $T_m = T \omega_s$ and $P_m = P_s + P_r$.

It follows that:

$$P_r = P_m - P_s = T_m \omega_r - T \omega_s = -T_m \frac{w_s-w_r}{w_s} w_s$$

$$P_r = -s T_m \omega_s$$

$$P_r = -s P_s \quad (4)$$

where $s$ is defined as the slip of the generator: $s = (\omega_r - \omega_s)/\omega_s \quad (5)$
Generally the absolute value of slip is much lower than 1 and, consequently, \( P_r \) is only a fraction of \( P_s \). Since \( T_m \) is positive for power generation and since \( \omega_s \) is positive and constant for a constant frequency grid voltage, the sign of \( P_r \) is a function of the slip sign. \( P_r \) is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, \( P_r \) is transmitted to DC bus capacitor and tends to raise the DC voltage. The design and performance evaluation of variable speed wind generation system [3]. For sub-synchronous speed operation, \( P_r \) is taken out of DC bus capacitor and tends to decrease the DC voltage. \( C_{\text{grid}} \) is used to generate or absorb the power \( P_{gc} \) in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter \( P_{gc} \) is equal to \( P_r \) and the speed of the wind turbine is determined by the power \( P_r \) absorbed or generated by \( C_{\text{rotor}} \).

### 2.2 Indirect Vector Control:

The Figure 3 explains the fundamental principle of indirect vector control with the help of a phasor diagram. The \( d^*-q^* \) axes are fixed on the stator but the \( d^*-q^* \) axes, which are fixed on the rotor, are moving at speed \( w_e \) as shown. Synchronously rotating axes \( d^*-q^* \) [4] are rotating ahead of the \( d^*-q^* \) axes by the positive slip angle \( \Theta_{sl} \) corresponding to slip frequency \( w_{sl} \). Since the rotor pole is directed on the \( d^* \) axes and \( w_e = w_r + w_s \) ------ (6)

we can write

\[
\Theta_e = \int w_e \, dt = \int (w_r + w_{sl}) \, dt = \Theta_s + \Theta_{sl} \quad (7)
\]

The rotor pole position is not absolute, but is slipping with respect to the rotor at frequency \( w_{sl} \). The phasor diagram suggests that the decoupling control, the stator flux component of current \( i_{qs} \), should be on the \( q^* \) axis, as shown.

For decoupling control, we can now make a derivation of control equations of indirect vector control with the help of \( d^*-q^* \) equivalent. The rotor circuit equation can be written as

\[
\frac{d\psi_{dr}}{dt} + R_r i_{dr} - (w_e - w_r) \psi_{qr} = 0 \quad (8)
\]
\[
\frac{d\psi_{qr}}{dt} + R_r i_{qr} - (w_e - w_r) \psi_{dr} = 0 \quad (9)
\]

The rotor flux linkage expression can be given as

---

Fig 2: The Power Flow diagram
\[ \psi_{dr} = L_r i_{dr} + L_m i_{ds} \quad \cdots (10) \]
\[ \psi_{qr} = L_r i_{qr} + L_m i_{qs} \quad \cdots (11) \]

From the above equations, we can write \( i_{dr} \) and \( i_{qr} \) as

\[ i_{dr} = \frac{1}{L_r} \psi_{dr} - \frac{L_m}{L_r} i_{ds} \quad \& \quad i_{qr} = \frac{1}{L_r} \psi_{qr} - \frac{L_m}{L_r} i_{qs} \quad \cdots (12) \]

![Fig 3: phasor diagram of indirect vector control](image)

The rotor current in above equations which are inaccessible, can be eliminated with the help of equations of \( i_{dr} \) and \( i_{qr} \) as

\[ \frac{d \psi_{dr}}{dt} + \frac{R_r}{L_r} \psi_{dr} - \frac{L_m}{L_r} R_r i_{ds} - w_{sl} \psi_{qr} = 0 \quad \cdots (13) \]
\[ \frac{d \psi_{qr}}{dt} + \frac{R_r}{L_r} \psi_{qr} - \frac{L_m}{L_r} R_r i_{qs} + w_{sl} \psi_{dr} = 0 \quad \cdots (14) \]

Where \( w_{sl} = w_e - w_r \) has been substituted.

For decoupling control, it is desirable that \( \psi_{qr} = 0 \)

That is

\[ \frac{d \psi_{qr}}{dt} = 0 \quad \cdots (15) \]

So that the total rotors flux \( \psi_r \) is directed on the \( d^e \) axis. By substituting the above equations we get

\[ w_{sl} = \frac{L_m R_r}{\psi_{dr} L_r} i_{qs} \quad \cdots (16) \]

The frequency signal can be estimated as follows

\[ \cos \Theta_e = \frac{\psi_{ds}}{\psi_s} \quad \text{and} \quad \sin \Theta_e = \frac{\psi_{ds}}{\psi_s} \quad \cdots (17) \]

### III. Power Circuit and Control Strategy

The Turbine at the left (a vertical type) is coupled to the cage – type induction generator through a speed up gear ratio. The variable frequency, variable voltage power generated by the machine is rectified to dc by a PWM voltage fed rectifier that also supplies the excitation current (lagging) to the machine.
The dc link power is inverted to 230V, 50Hz ac through a PWM inverter and fed to the utility grid. The Line current is sinusoidal at unity power factor, as indicated. The generator speed $w_r$ is controlled by an indirect vector control with a torque control for stiffness and a synchronous current control in the inner loops. The output power $P_0$ is controlled to the dc link voltage $V_d$ as shown in the figure 3. Because an increase in $P_0$ causes a decrease in $V_d$, the voltage loop error polarity has been inverted. The insertion of the line filter inductance $L_s$ creates some coupling effect, which is eliminated by a decoupler in the synchronous current control loops. The power can be controlled to flow easily in either direction. The vertical turbine is started with a motoring torque. As the speed develops, the machine goes into generating mode and the machine shuts down by regenerative braking.

### 3.1 Generator Speed Tracking Control (FLC-1)

With an incrementation (or decrementation) of speed, the corresponding incrementation (or decrementation) of output power $P_0$ is estimated. If $\Delta P_0$ is positive with last positive, $\Delta w_r$ indicated in the figure in per-unit value by $L\Delta W_r$(PU), the search is continued in the same direction.
If on the other hand $+\Delta w_r$ causes $-\Delta P_0$, the direction of search is reversed. The variables $\Delta P_0$, $\Delta w$, and $L\Delta w_r$ are described by membership functions and rule table. In the implementation of fuzzy control, the input variables are fuzzified, the valid control rules are evaluated and combined, and finally the output is defuzzified to convert to the crispy value. The wind vortex and torque ripple can lead the search to be trapped in a minimum which is not global, so the output $\Delta w_r$ is added to some amount of $Lw_r$ in order to give some momentum to continue the search and to avoid such local minima. The controller operates on a per-unit basis so that the response is insensitive to system variables and the algorithm is universal to any system. The membership functions of fuzzy logic controllers are explained in [4]. The scale factors $K_P$ and $K_W$, as shown in Fig. 4, 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

$$K_P = a_1 w_r$$
$$K_W = a_2 w_r$$

Where $a_1$ and $a_2$ are the constant coefficients that are derived from simulation studies. Such coefficients are converting the speed and power in per-unit values. The advantages of fuzzy control are obvious. It provides adaptive step size in the search that leads to fast convergence, and the controller can accept inaccurate and noisy signals. The FLC-1 [5] operation does not need any wind velocity information, and its real time based search is insensitive to system parameter variation.

### 3.2 Generator Flux Programming Control (FLC-2)

Since most of the time the generator is running at light load, the machine rotor flux can be reduced from the rated value to reduce the core loss and thereby increase the machine-converter system efficiency. The principle of online search based flux programming control by a second fuzzy controller FLC-2 is explained in Fig. 5. This causes increasing torque current $i_q$ by the speed loop for the same developed torque. As the flux is decreased, the machine iron loss decreases with the attendant increase of copper loss. However, the total system (converters and machine) loss decreases, resulting in an increase of total generated power $P_0$.

![Fig 5: Block diagram of FLC-2](image)

The principle of fuzzy controller FLC-2 is somewhat similar to that of FLC-1. The system output power $P_0(k)$ is sampled and compared with the previous value to determine the increment $\Delta P_0$. 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, as indicated. It is necessary to process the inputs of FLC-2 in per-unit values. Therefore, the adjustable gains $K_P$ and $K_{IDS}$ convert the actual variable to variables with the following expressions

$$K_P = a_1 w_r + b$$
$$K_{IDS} = c_1 w_r - c_2 i_{qs} + c_3$$
where $a$, $b$, $c_1$, $c_2$, and $c_3$ are derived from simulation studies. The current $i_{qs}$ is proportional to the generator torque, and $\Delta w_1$ is zero because the fuzzy controller FLC-2 is exercised only at steady-state conditions. The FLC-2 controller operation starts when FLC-1 has completed its search at the rated flux condition. If wind velocity changes during or at the end of FLC-2, its operation is abandoned, the rated flux is established, and FLC-1 control is activated.

### 3.3 Closed-Loop Generator Speed Control (FLC-3)

The speed loop control is provided by fuzzy controller FLC-3, as indicated in Fig. 6. As mentioned before, it basically provides robust speed control against wind vortex and turbine oscillatory torques. The disturbance torque on the machine shaft is inversely modulated with the developed torque to attenuate the modulation of output power and prevent any possible mechanical resonance effect. In addition, the speed control loop provides a deadbeat type response when an increment of speed is commanded by FLC-1.

![Fig 6: Block Diagram of FLC - 3](image)

The speed loop error ($Ew_1$) and error change ($\Delta Ew_1$) signals are converted to per-unit signals, processed through fuzzy control, and then summed to produce the generator torque component of current. Note that, while fuzzy controllers FLC-1 and FLC-2 operate in sequence at steady (or small turbulence) wind velocity, FLC-3 is always active during system operation.

### IV. SIMULATION RESULTS

Wind - generation system is simulated to validate all the control strategies and then evaluate the performance of the system. The machine and turbine parameters are given as:

**Machine Parameters:**
- 3 Phase, 7 hp, 230/450v, 7.6A, 4 poles,
- 1500rpm, $R_1 = 0.25\text{ohm}$, $R_r = 0.335\text{ohm}$

**Turbine Parameters**
- 3.5KW, Tower = 99.95m, 11.1-22.2r.p.m, $\eta_{gear} = 5.2$,
- $A = 0.015$, $B = 0.03$, $C = 0.015$
Simulation of wind generation system is performed in matlab and results are presented in fig 7. Generator speed, output power, flux current and wind velocity with respect to time are plotted.

V. CONCLUSION

The fuzzy logic based variable speed cage machine wind generation system has been analyzed. The system performances have 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 accept 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.

REFERENCES

[1] K.Kaur,Dr.S.Chowdhury,Dr.S.P.Chowdhury,Dr.K.B.Mohan ty,Prof.A.Domijan “Fuzzy Logic Based control of variable speed Induction machine wind generation system” IEEE Transactions.


Authors

B. Ravichandra Rao has received B.Tech from Sri Krishnadevaraya University, Anantapur in 2002 and M.E from Pune University, Pune in 2004 and pursuing Ph.D in electrical engineering from S.V. University, Tirupathi. He is presently working as Assistant Professor of EEE Department, G.Narayanamma Institute of Technology and Science, Hyderabad, India.

Amala Lolly, R received B.Tech from Jawaharlal Nehru Technological University Kakinada in the year 2009 and pursuing M.Tech in G.Narayanamma Institute of Technology and Science (for women), Hyderabad, India.