Fuzzy control of a variable-speed wind power generating system

I Jahmeerbacus and C Bhurtun, University of Mauritius

The power output from wind turbines varies nonlinearly with the wind speed, the speed of the turbine blade tips and the blade pitch angle. At a given pitch angle and wind velocity, maximum power is obtained at a specific turbine angular speed. Since wind speeds typically vary over a wide range, the turbine speed needs to be continuously adjusted so that its power output can be maximised. This paper presents a control scheme based on fuzzy logic for adjusting the turbine speed so as to track the maximum power point. The proposed system is tested under various operating conditions to validate its performance.

With the rising cost and limited availability of fossil fuels, much attention has been focused on the use of renewable energy sources for electrical power generation. Being a widely available resource in many areas, wind energy represents a viable alternative for reducing the dependence on fossil fuels. In recent years, there has been significant development of wind power generation systems worldwide. Typically, wind energy is used to propel a wind turbine, which in turn drives a generator to provide electrical power.

However, in a wind power generation system, the proportion of available wind power converted to mechanical power of the turbine is largely dependent on the blade-tip speed to the wind speed ratio of the turbine [1]. Consequently, the power generated is a nonlinear function of the turbine angular speed and the wind speed, for a fixed blade pitch angle. With large and abrupt variations in wind speed, it is therefore necessary to extract maximum power from the wind under normal operating conditions. As a result, the generating system is also required to operate at variable speed, giving significant improvements in power efficiency, compared to fixed speed operation [2]. In this context, variable speed induction generators are widely used, due to their rugged construction and relatively low maintenance costs.

The generator output is interfaced to the power grid through a dual converter system, consisting of a current controlled rectifier and dc to ac inverter. Such a dual converter allows power transfer from the variable speed, variable frequency generator to the constant frequency grid side [3]. To optimize power capture from the wind, it is required to operate the turbine at the torque-speed combination which corresponds to maximum power transfer. Several schemes have been proposed to extract maximum power from variable-speed wind turbines.

In [4] a maximum power tracking method is presented, where the system requires online training of the order of hours prior to normal operation. In the normal operating mode, the time taken to operate at maximum power is also relatively long. In [5], fuzzy logic based control of a wind generation system is described, where three fuzzy controllers are used for controlling the generator speed, torque and machine flux, respectively. However, the controller input gains depend on the operating speed, and the operation at maximum power coefficient under varying wind speed is not demonstrated.

In this paper we present a fuzzy controlled maximum power point tracking system suitable for the induction generator operating at variable speeds. The proposed system uses the generator speed and power output measurements to search for the optimum speed at which the turbine should operate for producing maximum power. The effectiveness of the proposed control scheme is validated through computer simulations under varying wind speeds.

**Fuzzy-controlled generator**

A block diagram of the fuzzy-controlled wind-powered generating system is shown in Fig. 1. It is assumed that the turbine blades have a fixed pitch angle, so that the power output, \( P_w \), varies non-linearly with the turbine angular speed (\( \omega_m \)) and the wind speed (\( v \)), as shown in Fig. 2. Hence maximum power is extracted at a particular angular speed, for a given wind speed. The induction generator output is a variable voltage, variable frequency AC, which is converted to DC by the current regulated AC to DC converter.

A field-oriented control scheme is used to regulate the generator speed to the optimum value at which maximum power is obtained. The proposed fuzzy controller generates the optimum speed command, which is used to regulate the input current of the AC to DC converter. The output of the converter is inverted back to a constant frequency, constant voltage to supply AC loads.

**Turbine and generator modeling**

The power output from the turbine can be expressed as:

\[
P_w = \frac{1}{2} \rho A_c \lambda v^3
\]  

Where \( \rho \) is the density of air, and \( \lambda \) is the area swept by the turbine rotor blades. The power coefficient of the turbine, \( c_p(\lambda) \) is a non-linear function of the tip-speed ratio, defined as:

\[
\lambda = \frac{\omega_m R}{v}
\]

**Fig. 1: Fuzzy-controlled power generating system.**
$R$ being the rotor radius. If the turbine is delivering maximum power, the prevailing blade-tip speed and wind speed combination should correspond to the maximum power coefficient [6]. The turbine output power drives the inertial and frictional load of the rotating system, as well as the electrical load. Hence:

$$P_m - P_G = \omega J \frac{d\omega}{dt} + B\omega^2$$  \hspace{1cm} (3)

where $P_m$ is the induction generator output power, $J$ and $B$ are the system moment of inertia and frictional damping coefficient, respectively. With field-oriented control applied to the induction generator, the machine stator current command can be decomposed into the flux and torque producing components ($i_{ds}^*$ and $i_{qs}^*$) respectively. If the flux level is maintained constant, the machine torque can be controlled as a function of $i_{qs}^*$ so that:

$$T_q = \frac{3P_m i_{qs}^*}{4}$$  \hspace{1cm} (4)

where $P$ and $L_m$ are the number of poles and magnetizing inductance of the induction generator, respectively. The torque command aims at driving the error between the speed reference ($\omega_m^*$) and actual speed ($\omega_m$) to zero.

**Fuzzy controller**

The fuzzy controller searches for the optimum speed ($\omega_m^*$) at which the wind turbine should operate, so that maximum power is produced at the prevailing wind speed. A block diagram of the fuzzy controller is shown in Fig. 3. The controller applies small changes in the speed command at regular intervals, and monitors the corresponding changes in the actual speed ($\Delta \omega_m$) and generator output power ($\Delta P_G$), respectively. The controller does not require measurement of the wind speed to search for the optimum operating point.

The inputs to the fuzzy controller at the $k$th sampling instant are respectively given by:

$$\Delta \omega_m(k) = G_{\omega_m} [\omega_m(k) - \omega_m(k-1)]$$  \hspace{1cm} (5)

and

$$\Delta P_G(k) = G_{P_G} [P_G(k) - P_G(k-1)]$$  \hspace{1cm} (6)

where $G_{\omega_m}$ and $G_{P_G}$ are the input scaling gains to the controller. These input gains, along with the output gain, $G_0$, are tuned so that the speed command eventually converges to the required value for maximum power output.

Five membership functions, normalised in the range [-1, +1], are used to describe...
each of the input and output variables of the controller. Uniformly distributed, symmetrical triangular membership functions used throughout, except for the outer membership functions of $\Delta\omega_m(k)$ and $\Delta P_G(k)$, which saturate at ±1. The controller real-valued input variables are fuzzified by mapping onto the input membership functions. Each linguistic variable can take a numeric linguistic value from ‘-3’ to ‘+3’, representing real values ranging from very large negative to very large positive. The term ‘0’ represents the set of real values which are very close to zero. The designed rule-base for the fuzzy controller consists of 25 rules, as shown in Table 1, in terms of numeric linguistic values. The min operator is used for premise quantification and determination of the implied fuzzy set for each rule that is active. In the defuzzification stage, the center of gravity (CoG) method is used on the implied fuzzy sets to generate a crisp output, corresponding to the change in speed command, $\Delta\omega^*_m$. The speed reference signal is computed as:

$$\omega^*_m(k) = G_c [\Delta\omega_m(k) + \omega^*_m(k-1)] \quad (7)$$

where $T$ is the sampling time period.

**Simulation tests and results**

An 8,2 kW wind turbine power generation system, with parameters shown in Table 2, is used to test the performance of the proposed fuzzy control system. The power coefficient variation as a function of the tip-speed ratio is shown in Fig. 4. It is observed that the turbine delivers maximum power at $c_p = 0.374$.

The turbine is initially operated with a wind speed of 8 m/s. However, the control system does not have any information of the prevailing wind speed. The speed command is set to 11 rad/s, corresponding to the turbine speed at the cut-in wind speed. Fig. 5(a) shows the corresponding power output response when the fuzzy controller is not activated. The power output from the turbine is 1.08 kW at $t = 20$ s. The turbine speed also converges to the reference value in the steady state, as shown in Fig. 5(b). At time $t = 25$ s, the wind speed undergoes a step change to 12 m/s. The corresponding output power from the turbine increases to only 1.96 kW in the steady state.

Fig.6(a) and (b) show the corresponding responses when the fuzzy controller is activated to search for the optimum turbine speed for maximum power output.

When the wind speed is at 8 m/s, the fuzzy controller progressively searches for
the turbine angular speed corresponding to maximum power within 15 s, giving a power output of 2.40 kW at $t = 20$ s. When the wind speed is changed to 12 m/s at $t = 25$s, the controller searches for the new optimum angular speed, and the turbine power output increases to 8.16 kW. Fig. 7 shows the variation of the turbine power coefficients for both test cases. With the fuzzy controller, the power coefficient settles to the maximum value in the steady state.

Conclusion

A fuzzy control scheme for extracting maximum power from a variable speed wind turbine has been presented. It has been shown that the turbine power output depends nonlinearly on its angular speed and the wind speed. Fuzzy control is well suited for searching the optimum speed at which the turbine should operate under varying wind conditions. The performance of the proposed scheme has been simulated under abrupt changes in wind. It has been shown that the fuzzy controller adjusts the angular speed so that the turbine power coefficient converges to its maximum value in the steady state.

References


Acknowledgement

This article was originally presented as a paper at the ICUE 2008 conference: Cape Town and is republished with permission.

Contacts Prof. C Bhurton, charlie@uom.ac.mu