Maximum Power Tracking Techniques in Wind Power Generation

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Abstract—Generation of wind power involves extraction of energy from the wind by use of a wind turbine generator. Wind power generated is dependent on various factors, some controllable and others uncontrollable. Techniques have been developed to extract maximum power from the wind available, thus ensuring that for any given wind speed, the wind turbine is able to produce power at its peak. An examination of various approaches utilized and an analysis of the strengths and weaknesses of each is presented in this paper.

Keywords—coefficient of power, maximum power point tracking, Tip speed ratio

I. INTRODUCTION

RENEWABLE energy is quickly gaining momentum as a viable driving force for powering industrialization and for domestic use in many countries. As the focus shifts towards green energy sources, methods for improving efficiency in power conversion take the limelight.

Wind energy is freely available and is clean and easily converted into electricity. Wind turbines are available in two major configurations: Vertical Axis Wind Turbines and Horizontal Axis Wind Turbines (HAWT). The more common HAWT may operate either with fixed rotor speed or variable speed.

Due to the constant variability of wind speed, design of controllers capable of extracting maximum power from the wind is a constant challenge, and various techniques have been developed to obtain higher efficiency from wind turbines. This should, in the long run, make wind power an economically viable alternative to non-renewable energy sources.

II. WIND TURBINE CHARACTERISTICS

The amount of power produced by a wind turbine is expressed as shown:

$$P_T = 0.5 c_p \rho A V^3 \tag{1}$$

where ρ is the air density A is the cross sectional area of the turbine V is the wind velocity

The coefficient of power(c_p) is a value dependent on the ratio between the turbine rotor's angular velocity, (ω_T) and the wind speed (V). This ratio is known as the Tip speed ratio (TSR), and is represented by λ. TSR is given by:

$$\lambda = \frac{\omega_T R}{V} \tag{2}$$

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where R is the radius of the turbine.

A wind turbine is generally characterised by its c_p versus λ curves obtained for different wind speeds, and usually takes the shape shown in Fig.1.

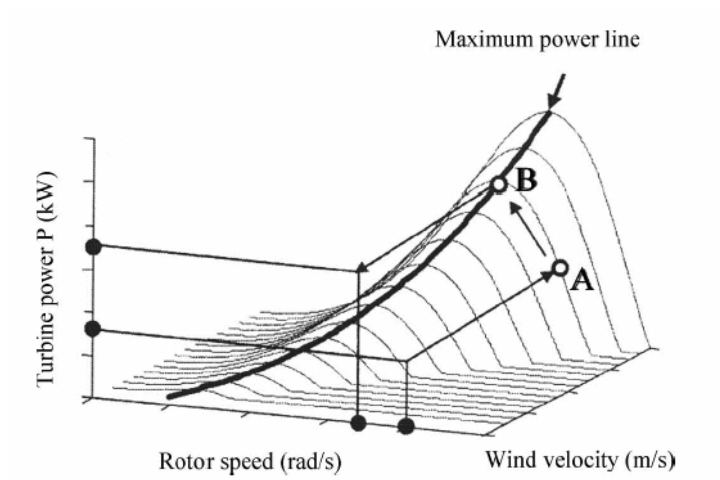

Fig. 1. Wind Turbine Power Curves

From the relationship between TSR and c_p, it is possible to devise a control strategy that ensures that the wind turbine operates around or at the peak point of the curve. Such strategies are commonly referred to as Maximum Power Point Tracking (MPPT) techniques.

MPPT techniques fall into two broad categories:

- Techniques that employ known turbine characteristics
- Techniques that allow optimization without knowledge of turbine characteristics

1) Techniques based on Known Turbine Characteristic: From the wind turbine power equation expressed in (1), the size of the turbine may be used to calculate the power. Maximum power point tracking is achieved either by Speed control [1] or torque control [2].

1) Speed Control This is used where a pulse width modulation (PWM) converter is used in association with the Permanent Magnet Generator attached to the wind turbine. The converter is vector controlled with a speed loop.

   From the definition of tip speed ratio, λ

$$\lambda = \frac{\omega R}{V} \tag{3}$$

   thus

$$V = \frac{\omega R}{\lambda} \tag{4}$$

Maximum power is obtained if

$$c_p(\lambda) = c_p(\lambda_{opt}) = c_p^{max} \tag{5}$$

Thus, the optimal turbine speed,

$$P_T^{max} = 0.5\frac{c_p^{max}\rho AR^3}{\lambda_{opt}^3}\omega^3 = K_{opt}\omega_{opt}^3 \tag{6}$$

with

$$K_{opt} = 0.5\frac{c_p^{max}\rho AR^3}{\lambda_{opt}^3} \tag{7}$$

Measurement of the transferred power allows one to calculate the speed reference, which allows for seeking of the optimal operation following the algorithm:

$$P[k] \rightarrow \sqrt[3]{\frac{P[k]}{K_{opt}}} \rightarrow \omega_{ref}[k+1] \tag{8}$$

The speed reference is used in a microcontroller to track the wind turbine's maximum power point.
Speed control has been achieved using a standard Voltage/Frequency converter by Miller et al [3], achieving control with a standard induction motor and drive and with minimum number of sensors.

2) Torque Control The optimal torque is obtained from angular velocity as shown:

$$T_{opt}(\omega) = 0.5\frac{c_p^{max}\rho AR^3}{\lambda_{opt}^3}\omega^2 = K_{opt}\omega_{opt}^2 \tag{9}$$

Thus, the load torque imposed to achieve optimum operation is:

$$T(\omega) = K_{opt}\omega^2 \tag{10}$$

The rotation speed gives directly the optimum reference torque such that:

$$\omega[k] \rightarrow K_{opt}\omega^2[k] \rightarrow T_{ref}[k+1] \tag{11}$$

In both speed control and torque control techniques, optimum operation is achieved after several iterations.

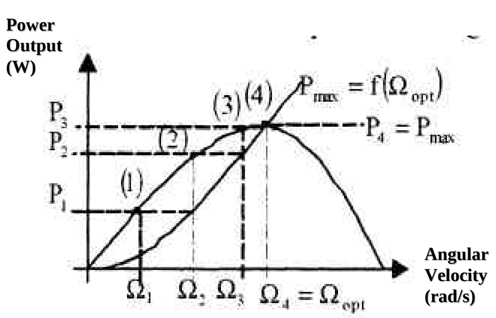

Fig. 2. Convergence of Speed Controlled Tracking

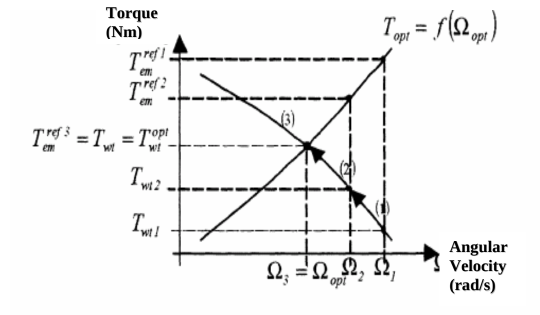

Fig. 3. Convergence of Torque Controlled Tracking

2) Techniques used where Turbine Characteristics are Unknown: Where wind turbine characteristics are unknown, the controller algorithm brings the operating point towards c_p^{max} by stepwise increases or decreases in the rotational speed of the wind turbine. This is known as the perturbation and observation method [2].
Generally, MPPT in this case is achieved using intelligent control methods. The most commonly used techniques are based on Adaptive Fuzzy Logic controllers [4], [5] and Neural-Network based controllers [6], [7]. Wang and Chang [8] have developed an algorithm that can be used either to create a lookup table for programming a controller or to generate training data for a neural network.

1) Fuzzy Logic Control in MPPT Fuzzy logic is a powerful tool since it allows the control of systems whose parameters are vague, incomplete or unknown, and as a result, are difficult to model mathematically. Fuzzy Logic Control consists of three main stages: input, processing and output. At the input stage, membership functions are used to fuzzify the input values. The now fuzzified input is fed into the processing stage where an inference mechanism applies the appropriate rule(s) from the knowledge base to come up with a set of fuzzy outputs. This output is then defuzzified using an appropriate technique. The result is a control output that can be applied to the process or plant being controlled. This is illustrated in the block diagram shown in Fig. 4.

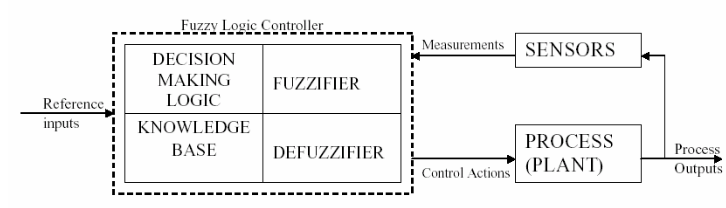

Fig. 4. Fuzzy control block diagram

Fuzzification involves use of linguistic variables to describe the actual input and output values being fuzzified, and generation of degrees of membership in the form of membership functions. A typical MPPT requires membership functions for inputs such as wind turbine rotor speed, change in wind power output and, where an anemometer is one of the sensors, change in wind speed. The outputs expected from the system, such as adjustment in rotor speed, are also expressed in terms of Fuzzy variables. The number of membership functions depends on the number of variables being measured, and this in turn affects the number of sensors required by the system. A typical membership function may take the form shown in Fig. 5, which gives the change in wind power output. The number of membership functions

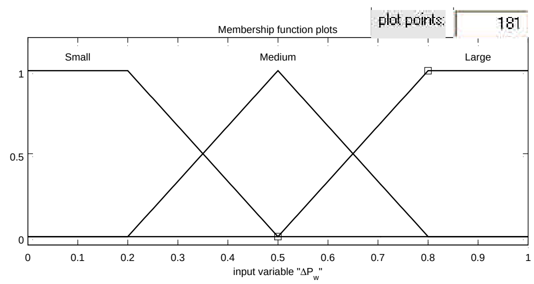

Fig. 5. Membership Function for Change in Wind Power Output from Turbine

may range from 3 upwards. The greater the number of membership functions, the greater the number of Fuzzy rules that will be required for the controller.

Generation of a rule base involves relating the input member functions to the output member functions using a set of if-then rules and logic functions such as AND, OR and NOT to combine several input fuzzy variables. Maximum power point tracking based on Fuzzy logic employs one of two methods depending on the sensors used. Where an anemometer is used, thus wind speed is known, the Fuzzy rules are geared towards matching the speed of the turbine rotor to the wind speed, thus improving the TSR of the wind turbine, and consequently, its power output. This strategy has been used by Yao et al [9] in the design of a Fuzzy Logic Controller that tracks wind speed and Generator output power to determine required adjustment in the turbine rotor speed and maximize wind power output. The rule base for the Fuzzy controller is shown in Fig. 6.

A second approach involves basing the adjustment in rotor speed adjustment on the difference in wind power output. The controller operates blind with regard to wind speed and adjusts the speed of the wind turbine rotor based solely on the change observed in wind power output. This is made possible by the nature of the wind power output characteristic curve, which levels out when the generated power reaches its maximum. Thus the controller adjusts the rotor speed until the change in wind power produced is zero, indicating that a maximum has been reached. A negative or positive change in the wind power output would indicate that the turbine is yet to reach the maximum power point.

$\Delta\omega^*_w$		ΔP_G						
		-3	-2	-1	0	1	2	3
$\Delta\omega_m$	-3	3	2	1	2	-2	-2	-3
	-2	2	1	1	1	-1	-2	-3
	-1	1	2	1	1	-1	-1	-2
	0	0	0	0	0	0	1	2
	1	-1	-1	-1	1	3	3	3
	2	-2	-2	-2	1	3	3	3
	3	-3	-2	-1	2	3	3	3

Fig. 6. Rule Base Relating Wind Speed(δw) and Power(δP_G)inputs to Optimum Speed(δw^*)

Since the aim of MPPT is to produce maximum possible electric power from wind available in order to adequately supply a load demand, it is possible to use the deficit in the load demand as an input to match the output power of the wind turbine to the load demand rather than constantly produce maximum power which may require dump loads to dispose of excess produced. Typical Fuzzy rules relating load deficit, wind power output and rotor speed adjustment are shown in Fig. 7. The rules were generated in Matlab, and the resultant rule surface is shown in Fig. 8.

1. If (deficit is NegLarge) and (winpow is NegLarge) then (Rotor is NegSmall) (1)
2. If (deficit is NegLarge) and (winpow is not NegLarge) then (Rotor is NegLarge) (1)
3. If (deficit is NegSmall) and (winpow is NegLarge) then (Rotor is PosSmall) (1)
4. If (deficit is NegSmall) and (winpow is NegSmall) then (Rotor is Zero) (1)
5. If (deficit is NegSmall) and (winpow is Zero) then (Rotor is NegSmall) (1)
6. If (deficit is NegSmall) and (winpow is PosSmall) then (Rotor is NegSmall) (1)
7. If (deficit is NegSmall) and (winpow is PosLarge) then (Rotor is NegLarge) (1)
8. If (deficit is Zero) and (winpow is NegLarge) then (Rotor is PosSmall) (1)
9. If (deficit is Zero) and (winpow is NegSmall) then (Rotor is Zero) (1)
10. If (deficit is Zero) and (winpow is Zero) then (Rotor is Zero) (1)
11. If (deficit is Zero) and (winpow is not PosSmall) then (Rotor is Zero) (1)
12. If (deficit is Zero) and (winpow is PosLarge) then (Rotor is NegSmall) (1)
13. If (deficit is PosSmall) and (winpow is NegLarge) then (Rotor is PosLarge) (1)
14. If (deficit is PosSmall) and (winpow is NegSmall) then (Rotor is PosLarge) (1)
15. If (deficit is PosSmall) and (winpow is Zero) then (Rotor is PosSmall) (1)
16. If (deficit is PosSmall) and (winpow is PosSmall) then (Rotor is PosSmall) (1)
17. If (deficit is PosSmall) and (winpow is PosLarge) then (Rotor is Zero) (1)
18. If (deficit is PosLarge) and (winpow is not PosLarge) then (Rotor is PosLarge) (1)
19. If (deficit is PosLarge) and (winpow is PosLarge) then (Rotor is PosSmall) (1)

Fig. 7. Rule Base Relating Load Deficit(deficit) and Wind Power Output(winpow) inputs to Rotor Adjustment(Rotor)

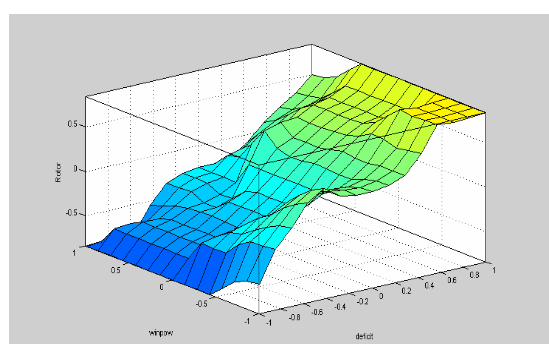

Fig. 8. Rule Surface Relating Load Deficit(deficit) and Wind Power Output(winpow) inputs to Rotor Adjustment(Rotor)

Fuzzy Logic based controllers employ different defuzzification methods. Kamal et al [4] make use of the

Takagi-Sugeno (TS) model, while Galdi et al [5] utilize the Takagi-Sugeno-Kang model in combination with Genetic Algorithms.

2) Neuro-Fuzzy Control For the Neuro-Fuzzy controllers, a Neural network is used to generate and adaptively tune the Fuzzy rules to match operational conditions of the system until the controller is operating at maximum efficiency. The basic structure of a neural network system is shown in Fig. 9.

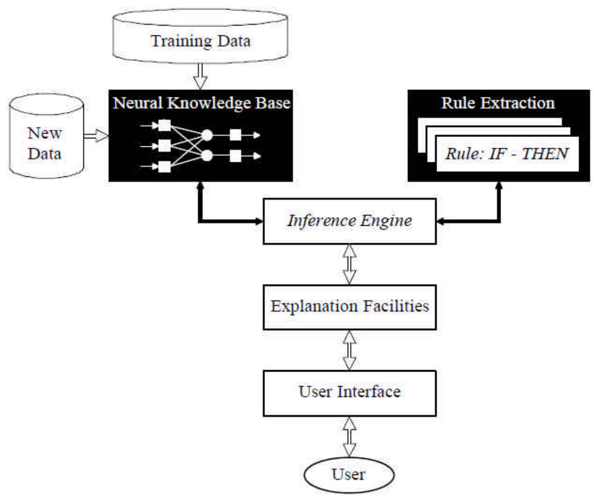

Fig. 9. Neural Network Basic Structure

Adaptive Neuro-Fuzzy Inference Systems (ANFIS) combine the strengths of Fuzzy Logic controllers and Neural Networks to create systems capable of controlling complex systems and adaptively learning to optimize control parameters.

The ANFIS structure is composed of several layers, as identified in Fig. 10.

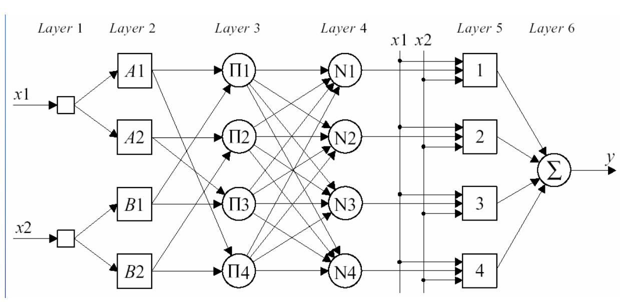

Fig. 10. ANFIS Structure

Layer 1, known as the **input layer** transfers directly each crisp input into the next layer.

Layer 2, known as the **fuzzification layer** converts each crisp input into a fuzzy input based on the membership functions related to that input. In this layer, each fuzzy set is represented by a neuron, and the activation function of the neuron is set to a triangular membership function corresponding to the relevant input.

Layer 3 is known as the **Fuzzy Rule Layer**, and each neuron in this layer corresponds to a single Fuzzy Rule from the Rule base used by the system.

Layer 4 is known as the **output layer**. Each neuron in this layer represents a fuzzy set used as a consequent of the fuzzy rules. The output from each neuron represents the firing strength of the particular consequent fuzzy set.

Layer 5 is known as the **defuzzification layer**, and it combines signals from layer 4, weighted by their respective firing strengths into a single crisp output which acts as the output of the ANFIS.

Differences in Neuro-Fuzzy approaches are mainly a difference in the learning algorithms employed by the Neural networks. Lin et al [7] employ a back propagation learning algorithm with Modified Particle Swarm Optimization (MPSO).

III. Comparative Study

A. *Speed-Based Control*

Advantages

- Capable of efficiently tracking the maximum power point.
- Simple design, easily implemented where turbine characteristics are known.

Disadvantages

- Limited to systems with known turbine characteristics.
- Tuning the speed controller is sensitive for high values of inertia.
- Instability during start up due to transients.
- Relies heavily on sensor accuracy and efficiency.

B. *Torque-Based Control*

Advantages

- Power and torque ripples are reduced.
- Higher efficiency than for Speed control.
- Simpler and more robust than Speed Controlled MPPT.
- Fast tracking time when below rated wind speed.

Disadvantages

- Requires knowledge of turbine characteristics.
- Is sensor-reliant

C. *Fuzzy Logic Control*

Advantages

- The control algorithm is universal and may be adapted to various systems with minimal adjustments.
- Low power fluctuation.
- Low rotational speed fluctuation.
- Fast tracking time when operating above rated wind speed.
- The controller relies on the actual performance of the wind turbine rather than on theoretical data on turbine characteristics.
- Few sensors are required.
- Relatively unaffected by variations in turbine inertia and wind speed.

Disadvantages

- Tuning a robust fuzzy algorithm versus wind characteristics, especially where turbulent conditions exist, is rather complex, requiring expert knowledge.
- The performance of the system is dependent entirely on the Fuzzy algorithm, and errors in the design of membership functions, rule base generation and choice of output method affect the resultant system performance.
- Prolonged turbulent conditions may result in stress on the shaft due to continually changing outputs from the controller.

D. Neuro-Fuzzy Control

Advantages

- Capable of tracking maximum mechanical power of the wind turbine at both dynamic and steady states.
- Sensors required are few and simple.
- Easily implemented where human expert knowledge is not reliable or is unavailable.

Disadvantages

- The final algorithm is not generalizable since it is adaptively tuned to a specific turbine.
- Training of the controller to achieve optimal performance may take a long time, depending on the learning algorithm selected.

IV. Conclusion

Maximum Power Point Tracking is an important component of efficiently harnessing wind power. Selection of the right control strategy is therefore important to ensure that the system performs optimally.

Techniques based on knowledge of wind turbine characteristics, that is, Speed and Torque based methods, provide a simple way of obtaining maximum wind power where the turbine characteristics have been provided by the manufacturer or have been obtained by experimentation, offering fairly cost-effective solutions. Controller hardware and software requirements are fairly simple, and the actual controller design does not require a lot of specialized knowledge.

Fuzzy Logic based and Neuro-Fuzzy controllers offer greater flexibility to the designer of the controller since prior knowledge of the turbine characteristics is not necessary and reliance on sensors is lower. Furthermore,the Neuro-Fuzzy controller requires no expert knowledge since the learning algorithm tunes the controller for optimum performance.

Research in the area of Maximum power point tracking has resulted in several alternatives routes for the user of the wind turbine for power generation. However, in general, research has omitted turbulence as a factor in controller design. This may be an area for further research.

References

[1] Mirecki A., Roboam X. and Richardeau F., "Comparative study of maximum power strategy in wind turbines," *IEEE Transactions on Energy Conversion*, pp. 993–998, 2004.

[2] Neammanee B., Krajangpan K., Sirisumrannukul S. and Chatrattana S., "Maximum peak power tracking- based control algorithms with stall regulation for optimal wind energy capture," *IEEE Transactions in Energy Conversion*, pp. 1424–1430, 2007.

[3] Miller A., Muljadi E., Zinger D, "A variable speed wind turbine power control," *IEEE Transactions on Energy Conversion*, vol. 12, pp. 181–186, 1997.

[4] Kamal E., Koutb M., Sobaih A. and Kaddah S, "Maximum power control of hybrid wind-diesel-storage system," *Hindawi Publishing Corporation Advances in Fuzzy Systems (Article ID 963710)*, vol. 2008, 2008.

[5] Galdi V., Piccolo A. and Siano P., "Designing an adaptive fuzzy controller for maximum wind energy extraction," *IEEE Transactions on Energy Conversion*, vol. 2, pp. 559–569, 2008.

[6] Chedid R., Karaki S. and El-Chamali C., "Adaptive fuzzy control for wind-diesel weak power systems," *IEEE Transactions on Energy Conversion*, vol. 15, No 1. March 2000, pp. 71–78, 2000.

[7] O. T. L. K. Lin W., Hong C. and H. C., "An intelligent maximum power tracking control strategy for wind-driven ig system using mpso algorithm," in *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2009.

[8] W. Q. and C. L., "An intelligent maximum power extraction algorithm for inverter-based variable speed wind turbine systems," *IEEE Transactions on Power Electronics*, vol. 19, No. 5 September 2004, pp. 1242–1249, 2004.

[9] Yao X., Guo C, Xing Z, Li Y. and Liu S., "Variable speed wind turbine maximum power extraction based on fuzzy logic control," in *International Conference on Intelligent Human-Machine Systems and Cybernetics*, 2009.