Performance Assessment of a Wind Turbine using Fuzzy Logic and Artificial Network Controllers

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Abstract*—*This paper makes a comparison between two control methods for maximum power point tracking (MPPT) of a wind turbine modules using Permanent Magnet Synchronous Generators(PMSG) under fixed and different wind condition: the Fuzzy Logic (FL) and the Artificial Neural Network control (ANN). Both techniques have been simulated and analyzed by using Matlab/Simulink software. The simulated power transitions and the power tracking time realized by the fuzzy logic controller and the neural network controller has been evaluated in comparison with Tip Speed Ratio controller (TSR).

Keywords*— *Wind Turbine Modules, MPPT, Fuzzy Logic Control, Artificial Neural Network Control, Matlab/Simulink models, Tip Speed Ratio, FIS .

I. INTRODUCTION

Wind Energy Conversion Systems (WECS) have been attracting wide attention as a renewable energy source due to depleting fossil fuel reserves and environmental concerns as a direct consequence of using fossil fuel and nuclear energy sources [1]. The peak power points are tracked by the maximum power point tracking (MPPT) controller when the wind speed changes throughout the day.

Generally, MPPT methods can be broadly classified into those that do not use sensors and those that do use sensors. The methods without sensors track the MPP by monitoring the power variation. This classic method is widely divided into perturbation and observation (P&O) and incremental conductance (IncCond) methods [2-3]. The method uses sensors to track the MPP by the control of rotor speed and torque. Basically, it is named the TSR (tip speed ratio) control [4-5]. The TSR control directly regulates the turbine speed or torque to keep the TSR at an optimal value by measuring wind speed and turbine speed. In a fuzzy logic controller it is used instead of a typical proportional-integral (PI) controller to control the optimum rotor speed. This algorithm does not require a detailed mathematical model or linearization about an operating point and it is insensitive to system parameter variation. The turbine pitch angle is regulated according to the measured wind speed in Neural network and fuzzy logic control are applied to improve the performance [6].

In this paper, two intelligent control techniques using fuzzy logic control and neural network control are related to an MPPT controller, of wind turbine, in order to improve energy conversion efficiency. Simulation and analysis in Matlab/Simulink environment of these control techniques are presented, and its performances are evaluated.

This paper is organized as follows. Section 1 is the introduction which includes the background of renewable energy, and the purpose of this paper. Section 2 illustrate Wind Turbine array model. Section 3 present TSR, fuzzy logic and artificial neural network MPPT principles. Section 4 is dedicated to the modeling, simulation, analysis and discussion concerning the MPPT compared techniques. The conclusions are given in Section 5.

II. WIND TURBINE ARRAY MODEL

The mechanical power result by the blades of turbine is a function of the blade shape, the pitch angle β(in degrees), and the blade radius R(in meters) and the rotor speed of rotation V(in m/s) .

$$P_m = \frac{1}{2}\pi\rho C_P(\lambda,\beta)R^2V^3 \qquad (1)$$

Where ρ is the air density (typically 1.25kg/m3) and Cp(α,β) is the wind turbine power coefficient. The term λ is the tip speed ratio defined in equation (2)

$$\lambda = \frac{\Omega R}{V} \qquad (2)$$

Where Ω is the Wind Generator rotor speed of rotation(in rad/s).

When the blades pitch angle is β=0°, the wind turbine power coefficient is maximized to λ_{opt} value (tip-speed ratio optimal). The wind turbine power curves for various wind speeds are shown in fig.1. It is observed that, for each wind speed, there exists a specific point in the wind turbine output power versus rotating-speed characteristic where the output power is maximized. In order to have maximum possible power, the turbine should always operate at λopt. This is possible by controlling continuously the rotational speed of the turbine with MPPT control. The value of the tip-speed ratio is constant for all maximum power points (MPPs), while the wind turbine speed of rotation is related to the wind speed as follows:

$$\Omega_n = \lambda_{opt}\frac{V_n}{R} \qquad (3)$$

Where Ω_n is the optimal Wind turbine speed of rotation at a wind velocity V_n.

Besides the optimal energy production capability, another advantage of variable-speed operation is the stability and reduction of stress on the Wind turbine shafts and gears, since the blades absorb the wind torque peaks during the changes of the wind turbine speed of rotation. The disadvantage of variable-speed operation is that a power conditioner must be employed to play the role of the wind turbine apparent load.

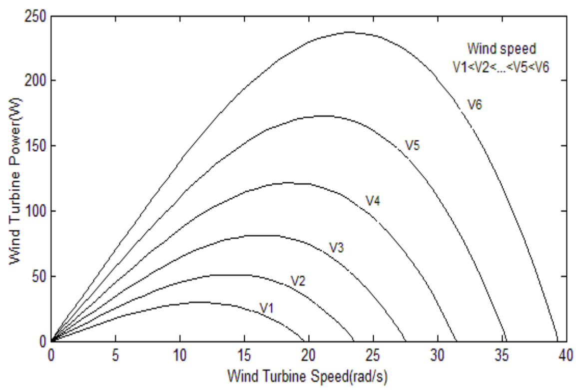

Fig.1: Wind Turbine power curves at various wind speeds

III. THE MPPT TECHNIQUES FOR WIND TURBINE

For a given wind speed, each power curve has a maximum power point (MPP) at which λ_{opt} is achieved. To extract the maximum available power from the wind at different wind speed, the wind turbine must be controlled.

In Fig. 2 it is shown our bloc diagram of a wind turbine module equipped with a MPPT controller. The Mechanic Power output (P) and wind turbine speed (Ω) of the wind turbine are controlled, in permanence, to adapt the load to the wind turbine source for the maximum power transfer at variable wind speed conditions.

Permanent Magnet Synchronous Generator (PMSG) is favored in Fig. 2 because of higher efficiency, high power density, availability of high-energy permanent magnet material at reasonable price, and possibility of smaller turbine diameter in direct drive applications.

In the following of this part, Tip Speed Ratio (TSR) and two intelligent MPPT techniques using Fuzzy Logic and Neural Network are related to MPPT controller of wind turbine.

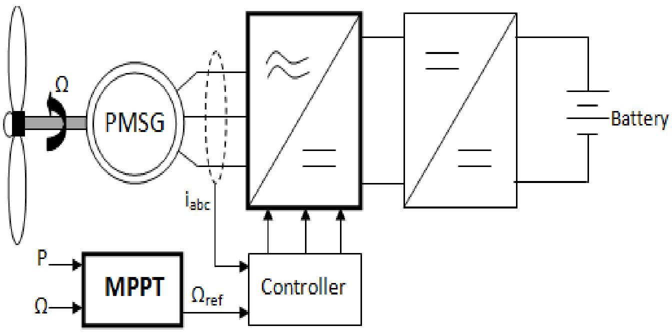

Fig. 2: The block diagram of wind turbine module with MPPT controller

A. The MPPT with Trip Speed Ratio (TSR) Control

The TSR for wind turbines is the ratio between tip speed of blade and the actual speed of the wind. The optimal point of the TSR can be determined experimentally or theoretically and stored as a reference as seen in fig.3. Although this method seems simple as wind speed is directly and continuously measured, a precise measurement for wind speed is impossible in reality and it increases the cost of the system, that why we use this technique as reference to evaluate other controller performance.

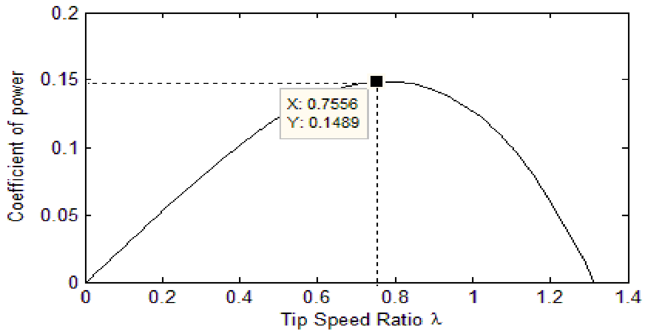

Fig.3: The characteristic of the power coefficient as a function of the tip speed ratio

B. The MPPT with Fuzzy Logic Control

The general structure of fuzzy logic controller is composed with three steps: Fuzzification, Inference rules base and Defuzzification.

Fuzzification: During fuzzification, numerical input variables are converted into linguistic variable based on a membership function. For the MPPT controller with fuzzy logic, the inputs are taken as a change in power and wind speed as well. There is a block for calculating the error (*E*) and the change of the error (*dE*) at sampling instants' *k*:

$$E(k) = \frac{dP}{d\Omega} = \frac{P(k) - P(k-1)}{\Omega(k) - \Omega(k-1)} \quad (4)$$

$$dE(k) = E(k) - E(k-1) \quad (5)$$

Where *P(k)* is the power output delivred by wind turbine module and Ω*(k)* is the wind speed of the module. Value of the error *E(k)* determines the MPPT controller output according to the sign. By example, if the operating point is located to the left of the MPP of the curve, the sign of the error *E(k)* is positive, and the reported load resistance to the wind turbine has to be increased .In order to avoid the final oscillations around the MPP, when the change of the error *dE(k)* decreases, the speed of convergence to the operating point has to be reduced. This is the way the MPPT controller can decide what will be the variation of the wind speed that must be imposed.

Inference Rules Base : Once *E(k)* and *dE(k)* are calculated and converted to the linguistic variables, the fuzzy logic controller output, which is thev wind speed, can be looked up in a rule base table.

The linguistic variables assigned to the wind speed for the different combinations of *E(k)* and *dE(k)* was established according to our knowledge.

Defuzzification: the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function.

From Matlab/Simulink library, we can use Fuzzy Toolbox to manage this structure and formulate fuzzy rules. Using this tool the user can program the command used subsequently in the block Fuzzy Logic Controller with *Rule viewer*.

- *The Fuzzification*. The following five linguistic variables have been used for the MPPT fuzzy controller: PG (positive big), PP (Positive Small), ZE (Zero), NP (negative small), and NG (large negative). The generation of the membership functions of these variables was performed based on user experience tow trapezoidal form (NG , PG) and three triangular form(NP,PP and EZ). After a number of tests under different winds speed conditions, the *E(k)* and *dE(k)* variables have been defined for solving continuing problems of MPP.
- *The Inference Rules*. For the MPPT fuzzy controller it was chosen the Mamdani type inference rules with logical operators MIN and MAX. These rules are introduced into the controller to obtain the right decision for its output wind speed Ω. In the TABLE I are shown the selected rules.

THE DEFUZZIFICATION. THIS OPERATION CONVERTS THE INFERRED FUZZY CONTROL ACTION INTO A NUMERICAL VALUE AT THE OUTPUT BY FORMING THE UNION OF THE OUTPUTS RESULTING FROM EACH RULE. THE METHOD OF THE GRAVITY CENTER HAS BEEN CHOSEN FOR THE DEFUZZIFICATION

TABLE.I: THE FUZZY LOGIC CONTROLLER INFERENCE RULES

	dE				
E	NG	NP	ZE	PG	PP
NG	NG	NG	NP	ZE	NP
NP	NG	NP	NP	PP	ZE
ZE	NG	NP	ZE	PP	PP
PG	ZE	PP	PP	PG	PG
PP	NP	ZE	PP	PG	PP

C. Matlab/Simulink model of the Wind Turbine System with MPPT Fuzzy Logic Control Algorithm

In Fig. 4 is shown the Fuzzy Matlab/Simulink toolbox, configured to control the wind turbine module

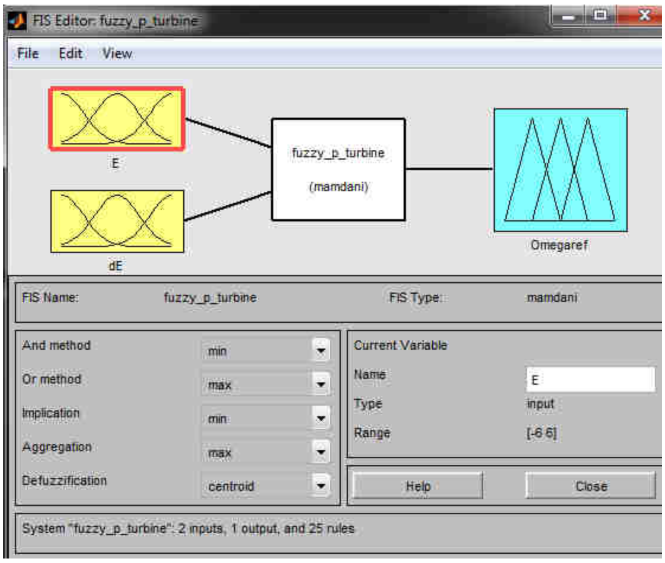

Fig. 4: Fuzzy of the Wind Turbine module

In Fig. 5 is shown the Matlab/Simulink model of a Wind Turbine module with MPPT fuzzy logic controller. It contains eight main blocks: the wind turbine, PMSG, the MLI bloc, the DC/DC converter, the DC Bus, the Rectifier, the battery and the block with fuzzy logic control.

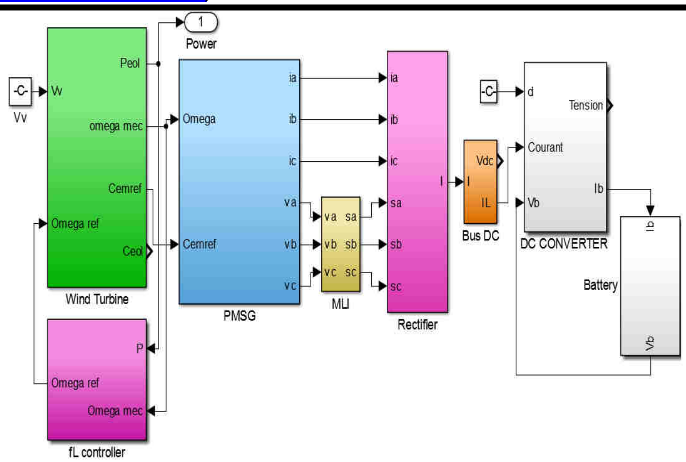

Fig.5: Simulink model of the Wind Turbine module with MPPT fuzzy logic controller.

In Fig. 6 is shown the structure of the MPPT fuzzy controller used from Simulink library.

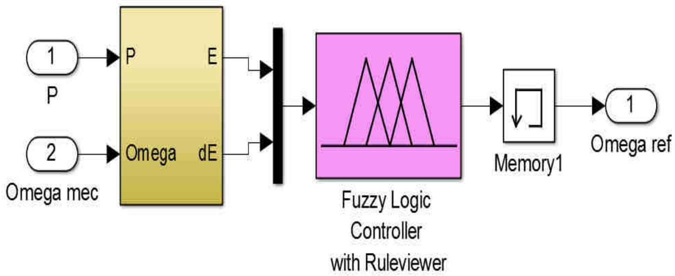

Fig.6: Simulink model of a fuzzy logic controller with Inference Rules viewer.

In Fig. 7 is shown the Matlab/Simulink model of E and dE used as input on fuzzy logic controller.

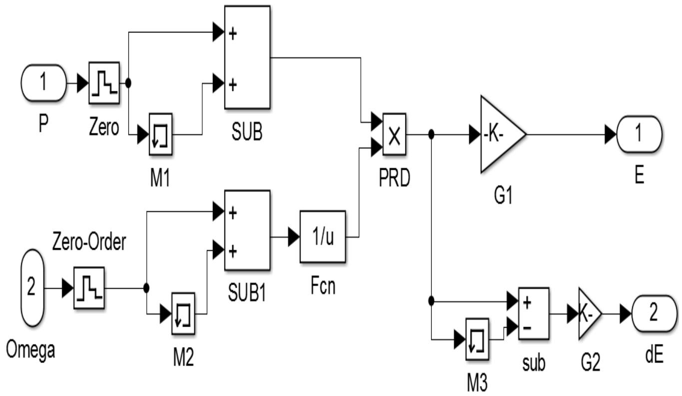

Fig. 7: The Matlab/Simulink model of the error and change of the error block.

D. The MPPT with Artificial Neural Network Control

Artificial neural network provides a method of deriving nonlinear models of a wind turbine system. Neural networks have a self-adapting capability which makes them well suited to handle the parameter variations.

In fig. 8 is shown the basic structure of a simple neural network. The artificial neuron consists of input, activation function and output with appropriate weight. In this simple feed forward neural network, the inputs are fed directly to the outputs via a series of weights. The weights of the artificial neuron are adjusted to obtaining the outputs for the specific inputs. The sum of the products of the weights and the inputs is calculated in each hidden node, and if the value is above some threshold (typically 0) the neuron fires and takes the activated value of (typically 1); otherwise, it takes the deactivated value (typically -1)[7].

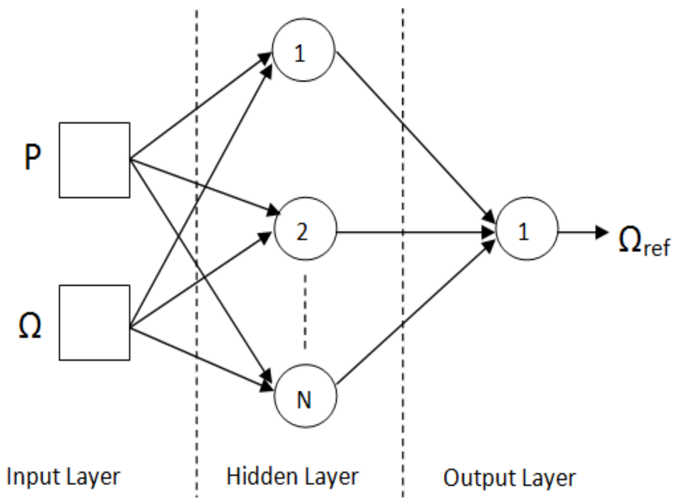

Fig. 8: The neural network basic architecture.

The back propagation training algorithm is used for training of the neural network; this algorithm needs only inputs and the preferred output to adapt the weight. The neural network was trained using MATLAB Software

E. Matlab/Simulink model of the wind turbine System with MPPT Artificial Neural Network Control Algorithm

In Fig. 9 is shown the general scheme of a wind turbine system with MPPT artificial neural network controller. It is similar with the scheme of Fig. 5, the only difference being the used controller.

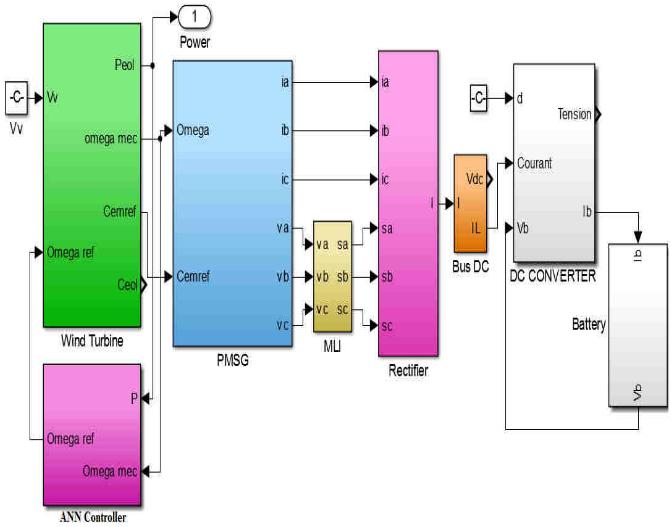

Fig. 9: Simulink model of the PV module with MPPT ANN controller.

IV. THE SIMULATION RESULTS

The comparison of the MPPT performances of the two analyzed control algorithms were made for a wind speed of 7.5m/s. the MPPT with TSR control it will be used as theoretical results.

For the wind turbine MPPT neural network controller, six structures given in the Table II were chosen.

TABLE.II: THE STURCTURES OF ANALYZED ANN CONTROLLERS

Controller Type	ANN structure	1st layer	2nd layer	3rd layer
1	***Neuron numbers***	1	1	-
	Activation function	sigmoid	sigmoid	-
2	***Neuron numbers***	2	1	-
	Activation function	sigmoid	linear	-
3	***Neuron numbers***	10	1	-
	Activation function	sigmoid	sigmoid	-
4	***Neuron numbers***	10	1	-
	Activation function	sigmoid	linear	-
5	***Neuron numbers***	1	1	1
	Activation function	sigmoid	sigmoid	sigmoid
6	***Neuron numbers***	1	1	1
	Activation function	sigmoid	linear	linear

MPPT fuzzy controller MPPT of the wind turbine was with Mandani type inference rules and the gravity center was the used defuzzification method.

The simulation results, for the analyzed cases, are given in the following six figures.

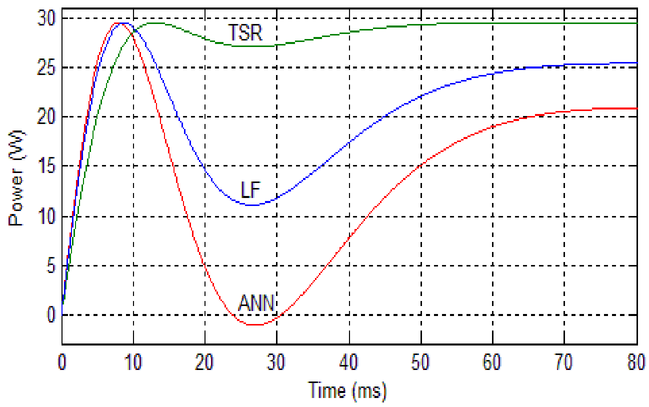

Fig.10: MPPT performances of Fuzzy Logic Controller and ANN Controller Type number 1.

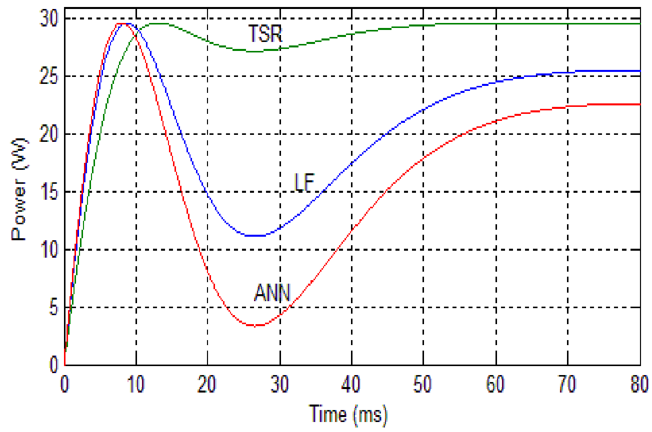

Fig.11: MPPT performances of Fuzzy Logic Controller and ANN Controller Type number 2.

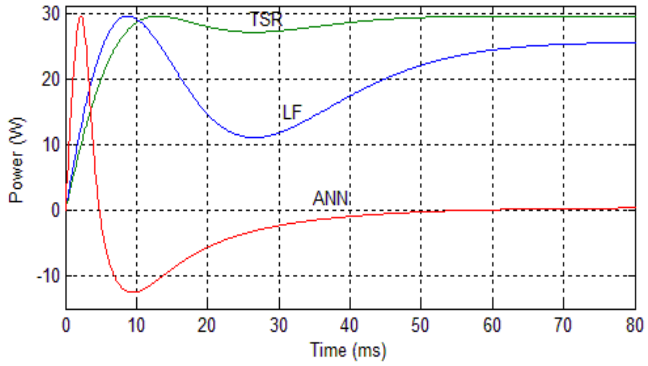

Fig. 12: MPPT performances of Fuzzy Logic Controller and ANN Controller Type number 3.

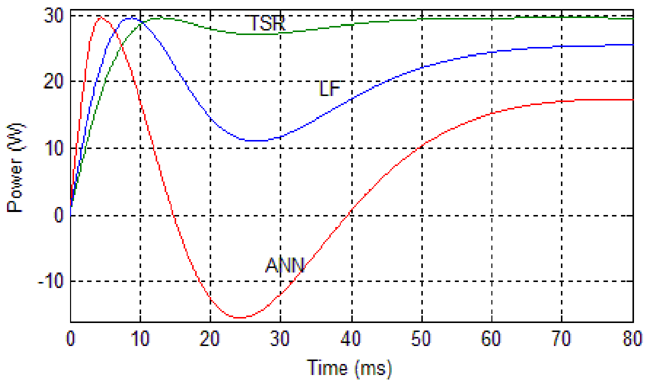

Fig. 13: MPPT performances of Fuzzy Logic Controller and ANN Controller Type number 4.

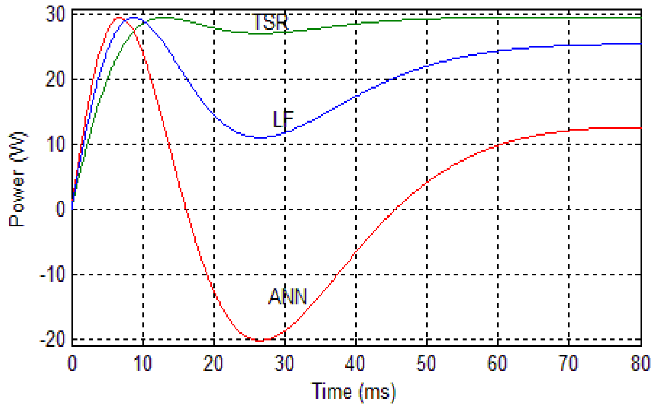

Fig. 14: MPPT performances of Fuzzy Logic Controller and ANN Controller Type number 5.

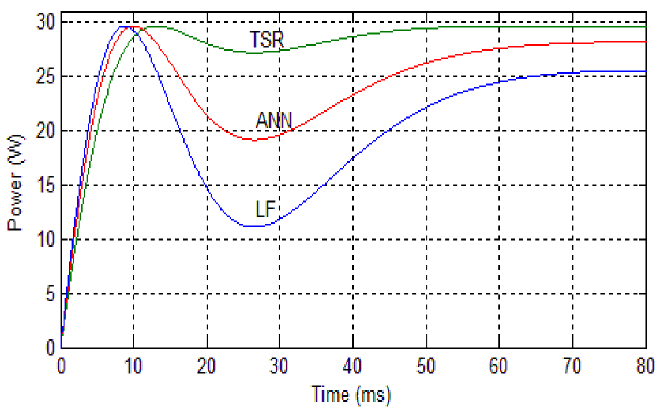

Fig. 15: MPPT performances of Fuzzy Logic Controller and ANN Controller Type number 6.

In the six figures the MPP achieving time of ANN controller and Fuzzy controller are shorter as the achieving time of TSR controller.

In Fig. 10 and Fig. 11 the MPP achieving time of ANN and Fuzzy controllers are almost the same.

In Fig. 13 and Fig. 14 the MPP achieving time of ANN controller is a little bit faster than the achieving time of Fuzzy controller.

The only case, who the achieving time of Fuzzy controller is a little bit faster than the achieving time of ANN controller is the case of Fig.15

The case number 3 (Fig. 12) present the perfect performance assessment, the achieving time of ANN controller is 1.5ms.

V. CONCLUSION

In general, the MPP achieving time of ANN Controller is shorter as the achieving time of Fuzzy controller. For the analyzed cases it is about 8 ms.

When the ANN Controller is used, the MPP achieving time is a little bit faster only in two of analyzed cases (5 ms and 7.5ms, in 4th and 5th cases respectively) .

The ideal structure of ANN controller is 10 sigmoid neuron in first layer and one sigmoid neuron in the second layer (1.5ms in the 3^{rd} case)

REFERENCES

[1] J. Singh Thongam and M. Ouhrouche, " MPPT Control Methods in Wind Energy Conversion Systems",INTECH, Fundamental and Advanced Topics in Wind Power, ISBN: 978-953-307-508-2,2011,pp.340-360.

[2] Kazmi, S.M.R.; Goto, H.; Guo, H.J.; Ichinokura, O. A novel algorithm for fast and efficient speed-sensorless maximum power point tracking in wind energy conversion systems. IEEE Trans. Ind. Electron. 2011, 58, 29–36. 12.

[3] Hohm, D.P.; Ropp, M.E. Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed. In Proceedings of Photovoltaic Specialists, Anchorage, AK, USA, 15–22 September 2000; pp. 1699–1702.

[4] Tse, K.K.; Ho, B.M.T.; Chung, H.S.-H.; Hui, S.Y.R. A comparative study of maximum-power-point trackers for photovoltaic panels using switching-frequency modulation scheme. IEEE Trans. Ind. Electron. 2004, 51, 410–418. 16.

[5] Hilloowala, R.M.; Sharaf, A.M. A rule-based fuzzy logic controller for a PWM inverter in a stand alone wind energy conversion scheme. IEEE Trans. Ind. Appl. 1996, 31, 57–65.

[6] Johnson, K.; Fingersh, L.; Balas, M.; Pao, L. Methods for increasing region 2 power capture on a variable

speed wind turbine. J. Sol. Energy Eng. 2004, 126, 1092–1100.

[7] Z. Ons, J. Aymen, A. Craciunescu and M. Popescu, “Comparison of Hill-Climbing and Artificial Neural Network Maximum Power Point Tracking Techniques for Photovoltaic Modules”, *the Second International Conference on Mathematics and Computers in Sciences and in Industry (MCSI-2015*), (2015), pp. 19-23.

[8] Ahmadi, Hamed, and Hassan Ghasemi (2011). "Probabilistic optimal power flow incorporating wind power using point estimate methods." Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on. IEEE.

[9] Koutroulis E, Kalaitzakis K. (2006). Design of a maximum power tracking system for windenergy-conversion applications. IEEE Transactions on Industrial Electronics; 53:486– 94.

[10] Brahmi J, Krichen L, Ouali A. (2009). A comparative study between three sensorless control strategies for PMSG in wind energy conversion system. Applied Energy; 86:1565– 73.

[11] Mahdi AJ, Tang WH, Jiang L. (2010). A Comparative study on variable-speed operations of a wind generation system using vector control. In: In: The 10th international conference on renewable energies and power quality. Granada, Spain: University of Granada; p. 1–6.