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Intelligent controller Design based on wind-solar system

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K E Y W O R D S

Wind Turbine Generating System (WTGS), Permanent Magnet Synchronous Generator (PMSG), Maximum Power Point Tracking (MPPT), Artificial Neural Network (ANN)

A B S T R A C T

This paper presents an Intelligent controller designed to mastery the output power flow from the Solar System, the Wind system, the sum of the two systems or from the battery system, according to the Maximum power point tracking algorithm, to ensure the continuity of the output power at fast time response. The proposed controller has been designed using MATLAB m-file and trained with the different number of hidden neurons using two different algorithms to get as fast a response time with minimum Mean Square Error (MSE) as possible which resulted in six hidden neurons using Levenberg-Marquardt training algorithms.

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1. Introduction

The use of renewable energy sources is growing globally, which leads to a variety of sustainable energy, reduces emissions of greenhouse gases, and becomes less dependent on oil[1]. Solar and wind energy are environment-friendly everlasting sources of energy available all over the earth. It an alternative electricity source especially with the consumption of petroleum, natural gas, and other nonrenewable sources [2]. Wind power, the fastest-growing electricity source in the world, is one of the clean energy sources with almost no environmental issues, but the major drawbacks of wind power are fluctuations due to the problem of power distribution in the transmission network, where the structure of grids in distant areas is poor and wind instability is taken into account [3].

Solar energy is commonly used because it is pollution-free and transforms incident sunlight directly into electrical energy by using solar cells[4]. Solar cells depend on a variety of factors, including internal ones, such as the type of metal used in production or manufacturing methods, and external factors such as air temperature, light intensity falling on the cell, and wind strength[5].

Artificial Neural Networks (ANN)are generally known as a technology providing an alternative way of solving complicated problems and have already been effectively implemented in many aspects. ANN helps to simplify the management of non-linear processes[6].

ANN is one of the most critical tools in artificial intelligence. Acquired its role by preparation, consisting of a vast number of basic and intertwined cells called neurons, identical to human brain biological cells[7]. Neurons are arranged in layers; the ones of the same layer usually operate similarly and have a similar activation function. The neurons in any layer can be associated with the neurons in other layers. Network architecture is a concept given to the arrangement of neurons into layers and the nature of the interaction inside and between layers[8].

The ability of training is the most important characteristic of ANN. Training is a process of adjusting the weights of ANNs in response to perform some special tasks[9]. Primarily there are two ways of training unsupervised and supervised. Unsupervised the desired response is unknown and the error can't be generated to modify weight[10]. The only way to stop the training is to observe the response to the inputs. Hebbian and Self-organizing map are types of unsupervised learning methods, but in supervised the desired output is known and the error can be calculating it to modify weight, The BP is a popular type of supervised training in intelligent controller[11].

2. Methodology

The following sections examine the Photovoltaic (Solar) systems, the Wind Turbines systems, and The Artificial Neural Network training theories.

I. Solar System

The light consists of energy packets called photons. The Photons energy depends on the color of the light where each color has a specified range of frequencies as shown in Figure (1)[12]. The photons in the ultraviolet and visible regions had sufficient energy to pump electron charges in semiconducting material and this can be effectively used for a current generation[13].

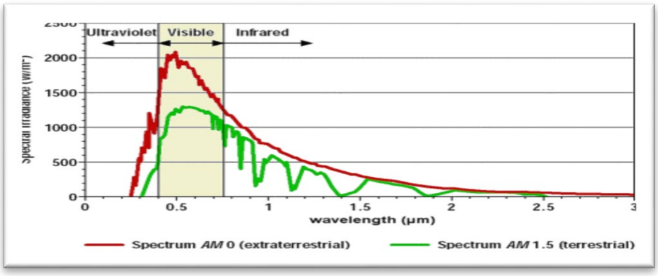

Figure 1: Solar Spectrum[12].

A photovoltaic cell is a semiconductor material that releases an electron charge when the photons hit its surface. Ideally, the number of electrons equals the number of photons in the equivalent circuit of the photovoltaic (PV) cell shown in Figure (2)[14].

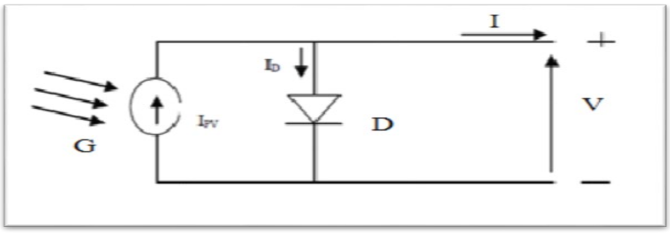

Figure 2: Ideal PV Cell with One Diode[4].

It consists of a current source IPV that symbolize the current generated by the incident light and a single diode connected in parallel, the output current from the cell is calculated from the following equations[12]:

$$I = I_{PV} - I_D \tag{1}$$

$$I_D = I_0 \left[\exp\left(\frac{V}{AV_T}\right) - 1\right] \quad (2)$$

Substituting eq. (2.2) in eq. (2.1) yields:

$$I = I_{PV} - I_0 \left[\exp\left(\frac{V}{AV_T}\right) - 1\right] \quad (3)$$

Where:
I_{PV} : the current results from the incidence light.
I_0: the reverse saturation current due to diffusion.
V_T: the thermal voltage of a PV module which calculated by $\{V_T = \frac{Ns*k*T}{q}\}$.
Ns: the number of cells connected in series.
q: the charge of electron.
K: Boltzmann constant.
T: the p-n junction temperature.
A: the diode ideality factor.

II. Wind Turbine Generator System

Wind Turbine Generator System (WTGS) is a system that is used to convert the kinetic energy in the winds into mechanical energy that eventually generates electrical power[15]. It's consisted of three parts: Aerodynamic, Mechanical, and Electrical as shown in Figure (3).

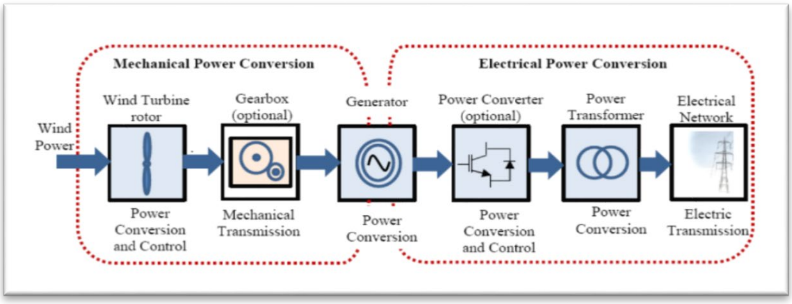

Figure 3: Basic components of wind turbines[16].

There are two types of Wind Turbine Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs)[17].

The basic components of HAWTs are listed as follows[18]:

1) Turbine Blade: This is responsible for transforming the kinetic energy of the wind to the mechanical strength of rotation. It may be constructed of aluminum, carbon-fiber composites, or fiberglass to minimize weight. Wind turbines have various blade numbers, such as single blade, two blades, and three blades.
2) Pitch Controller: it is used as a protection procedure where the attack angle of blades changes depending on to wind to improve the efficiency of the turbine by capturing maximum power.
3) Gearbox: it is used for adapting the low turbine rotor speed to the high shaft speed of the generator.
4) Rotor Mechanical Brake: it is used for turbine stopping during the very high speed of the wind and turbine maintenance.
5) Generator: it is used to perform electrical energy from mechanical energy. Different kinds of generators are used in wind turbine systems such as; Squirrel Cage Induction Generator (SCIG), Doubly Fed Induction Generator (DFIG), and Synchronous Generator (SG).
6) Yaw Drive: generally, it consists of an electric motor drive, yaw gear, and bearing to keep the turbine in the face with the wind.

7) Tower: the major function of towers to provide the necessary support to the nacelle and turbine rotor. Usually, it is made of steel and the tower height increases with the power rating of the turbine and the diameter of the rotor.
8) Wind Sensor (Anemometers): it operates as a data collection of wind speed and wind direction where the control systems need these measurements.

The output power from the WTGS can be evaluated by the following equations [18]:

$$P = \frac{1}{2} \times \rho \times A \times v_v^3 \times C p(\lambda, \beta) \quad (4)$$

Where:
V_v : wind speed, m/s.
A: the swept area by the turbine blades, m^2.
B: the pitch angle of the turbine, degree.
λ: the tip speed ratio.
C_p: the power coefficient.
ρ: the air density, kg/m^3.

The power coefficient represents the function of tip speed ratio (λ) and blade pitch angle (β) in this model we take β as zero so the tip speed ratio will be [19]:

$$C_p = -0.2121\lambda^3 + 0.0856\lambda^2 + 0.2539\lambda \quad (5)$$

the ratio of tip speed of the turbine blade to the wind speed as given by Equation (6).

$$\lambda = \frac{\omega \times R}{V_v} \quad (6)$$

ω: the rotor angular speed, *rad/s*.
R: blade radius of wind turbine, m.

III. Artificial Neural Networks ANN

In 1986, Rumelhart, Hinton, and Williams proposed the Back Propagation (BP) algorithm, the most popular supervised learning technique in the ANN for training MLP [6]. BP learning consists mainly of two passes through the different layers of the network, a forward pass, and a backward pass. The synaptic weights of the network are all set during the forward pass [20]. During the backward pass, the synaptic weights are all modified in compliance with the error-correction algorithm. Throughout the training cycle, the learning rate and momentum are modified to get the network out of its local minima and to promote network convergence. A small learning rate leads to slow convergence of algorithms, whereas a too high rate can lead to failure[18].

The BP algorithm starts by determining the output (y) of each neuron in the network and then evaluates the Mean Square Error (E). The gradient (g) is then determined to change the weights as shown below [21].

$$E = \frac{1}{2}\sum_k (d - y)^2 \quad (7)$$

$$g = \frac{\partial E}{\partial W} \quad (8)$$

Where:
k: No. of output neuron.
d: Output target vector.
W: Weight of network.

3. The Proposed System Design

The system consists of Solar System that provides DC output voltage, a Wind System also with DC output voltage at the same rating as the Solar System output, A Summing Circuit with a Voltage Regulator System to provide the output DC voltage when the wind speed or solar irradiation of the sun is not high enough to provide the rated voltage to the user, also to charge the Battery System in the meantime, An Intelligent Controller (Artificial Neural Network) that designed with MPPT algorithm to determine the best system to supply the user, finally, Battery System so when the previous sources have no sufficient output to supply the user it will be providing the user with the desired output until any of the previous systems start to deliver the required output. Figure (4) shows the proposed system.

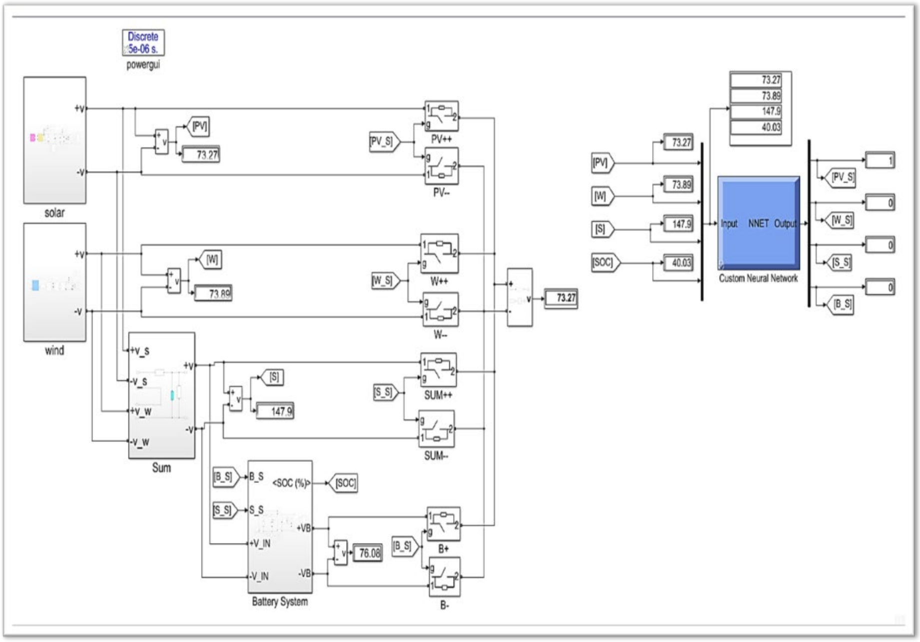

Figure 4: Simulink Model of the System.

I. Solar System

The Solar System consists of a Solar Panel and DC-DC Boost converter used to boost the output current while maintaining the output of the solar system as smooth as possible as shown in Figure (5).

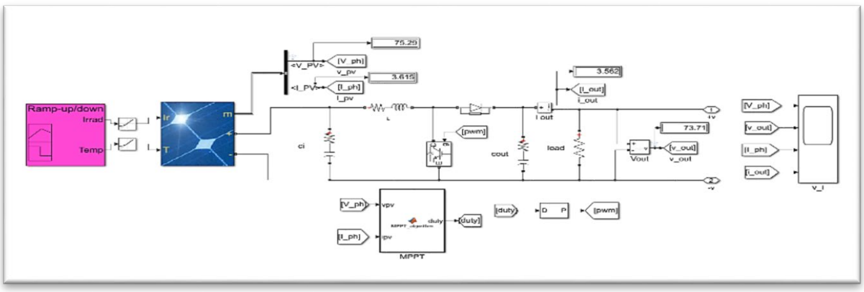

Figure 5: Solar System.

The duty cycle of the boost converter is controlled by Pulse Width Modulator PWM block. It is very important to operate Solar System to a maximum power point to obtain maximum power output from Solar System. the incremental conductance MPPT algorithm has been used to find the duty for the PWM Block.

II. Wind Turbine Generation System

The WTGS consists of Wind Turbine, Permanent Magnet Synchronous Generator PMSG, AC-DC Rectifier, and DC-DC Boost converter, the Wind System stages is shown in Figure (6).

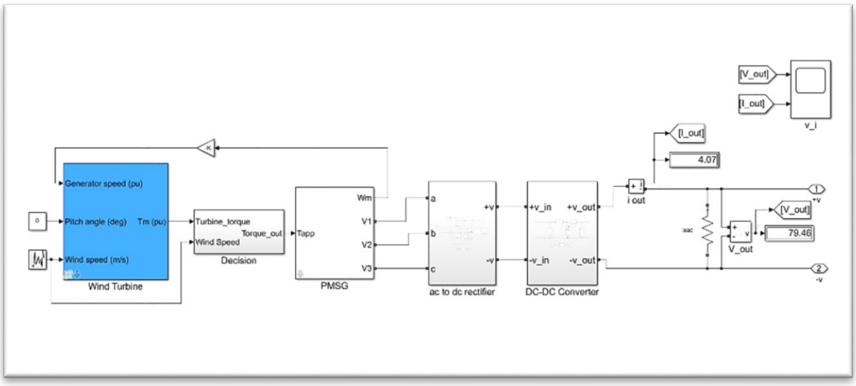

Figure 6: Wind System.

The internal parameters of the wind turbine block have been changed according to equations (1,2,3), also the main parameters of the Wind Turbine were set to zero pitch angle and 9 m/s base wind speed.

The decision block used to decide whether the wind speed enough to turn the turbine ON or not by comparing it to the base torque that needed so the PMSG start converting the output torque of the wind turbine converted into three phases Ac supply the Thyristor Bridge Rectifier to transform it to DC form then finally, the output signal has been refined with the DC-DC converter.

III. Sum Circuit

The third part of the inputs to the intelligent controller is the sum of both systems which will be used to supply the output in case the wind and the solar are not producing the desired output. This circuit is designed by connecting the two systems in series and the terminals of the systems are connected to R_L series impedance with the same value of the boost converter of the wind and solar to maintain the current at the same level during charging of the battery system, Figure (7) show Sum Block internal Connection.

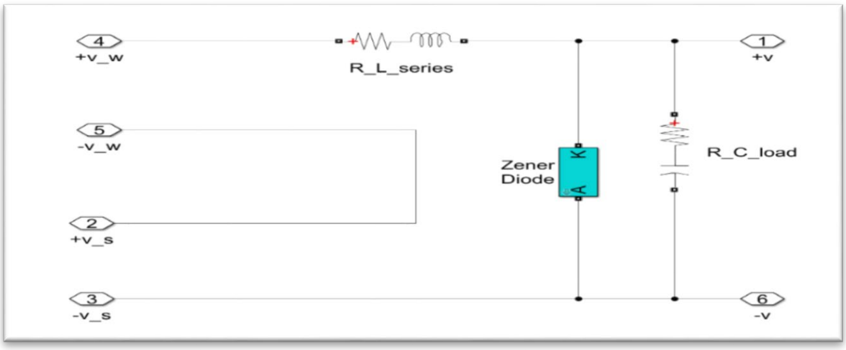

Figure 7: Sum Circuit.

IV. Battery System

The Battery System Block is connected to the Summing Circuit to be charged through DC-DC Converter to provide a constant level of current and voltage to charge the Battery. The battery nominal voltage was set at 70 volts and the initial state of charge to 40%.

The converter is controlled by two PI controllers which provide the PWM generator with the duty cycle that fulfill the right output from the PWM to turn the MOSFETs gate on and off Figure (8) shows the internal connections of the Battery System Block.

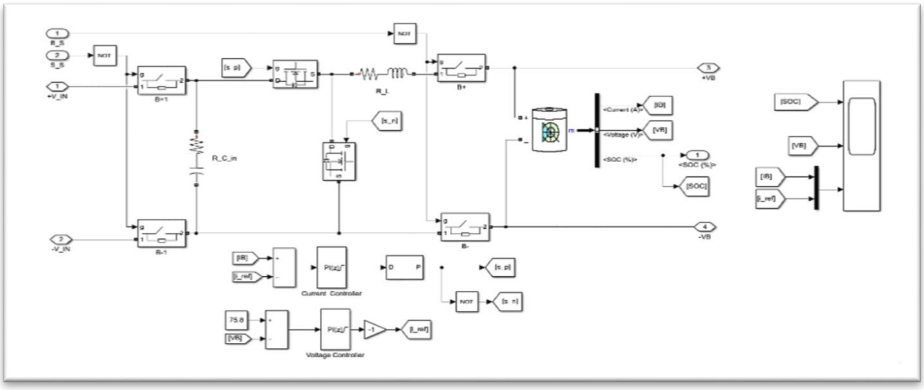

Figure 8: Battery System.

4. THE INTELLIGENT CONTROLLER

According to the weather in Iraq and the long hours of solar irradiation as we proposed previously the Solar System will be the main source then the Wind System, the Sum, and finally the Battery System, the Artificial Neural Network will decide the suitable output. The flow chart in figure (9) Describes the proposed controller.

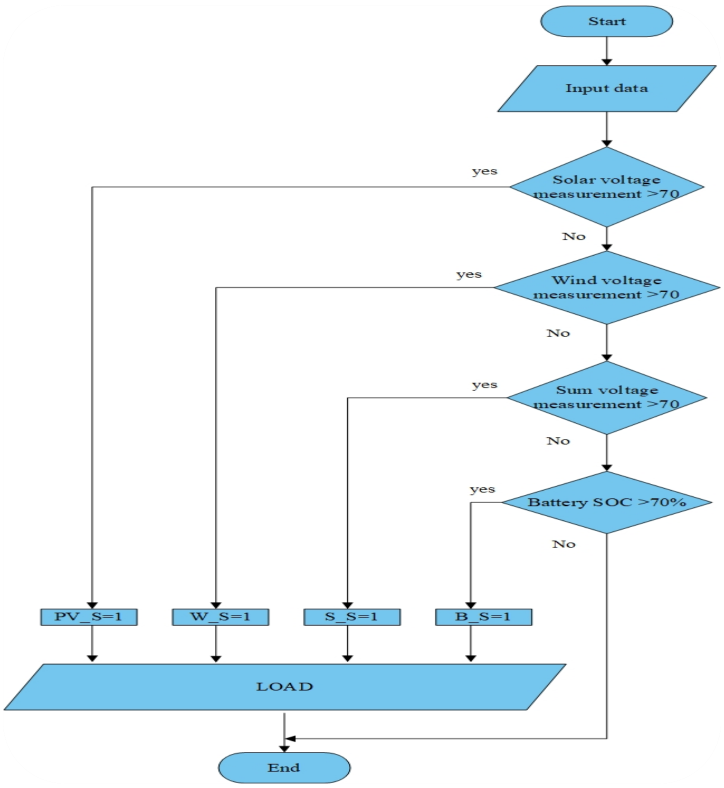

Figure 9: The Proposed Controller Flow Chart.

Multilayer Neural Network with four inputs, four outputs, and one hidden layer were designed with activation function Satlin at the hidden layer and Satlins at the output layer. The number of hidden layer neurons was taken (4,6,9) and the mean square error was calculated for each training algorithm.

5. Simulation Results

The output V_I Characteristics of the Solar System and Wind Turbine Generation System are in Figures (10,11) respectively.

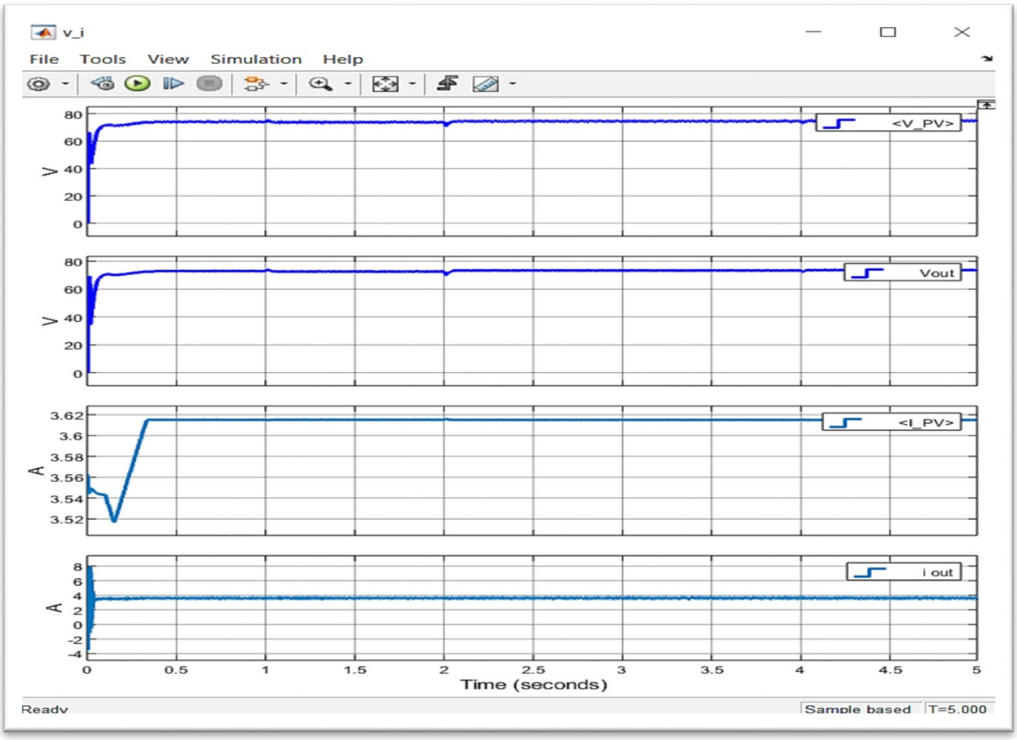

Figure 10: V_I characteristic of Solar System.

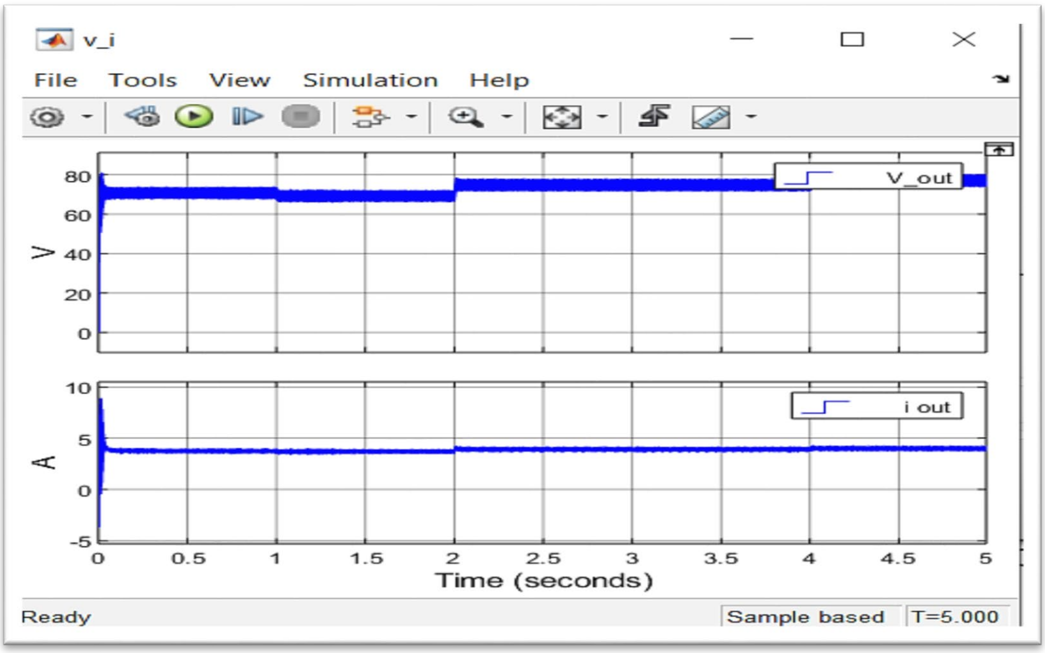

Figure 11: V_I Characteristics of the WTGS.

the output Voltage, Current curves of the Battery system as well as the battery State of Charge for Charging and Discharging States are in Figure (12,13) respectively.

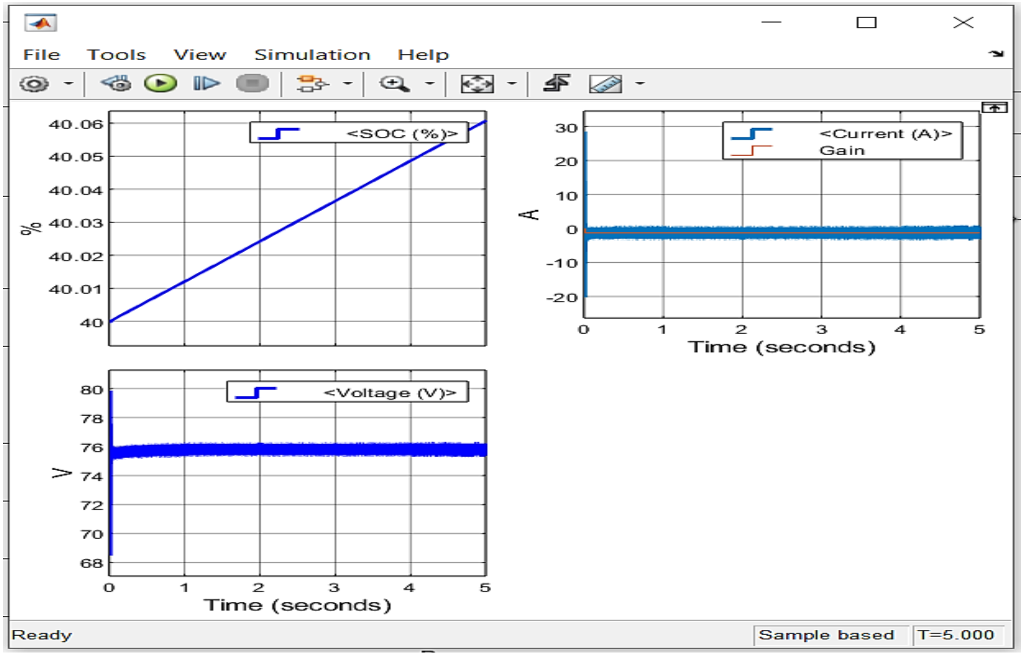

Figure 12: Battery System Charging.

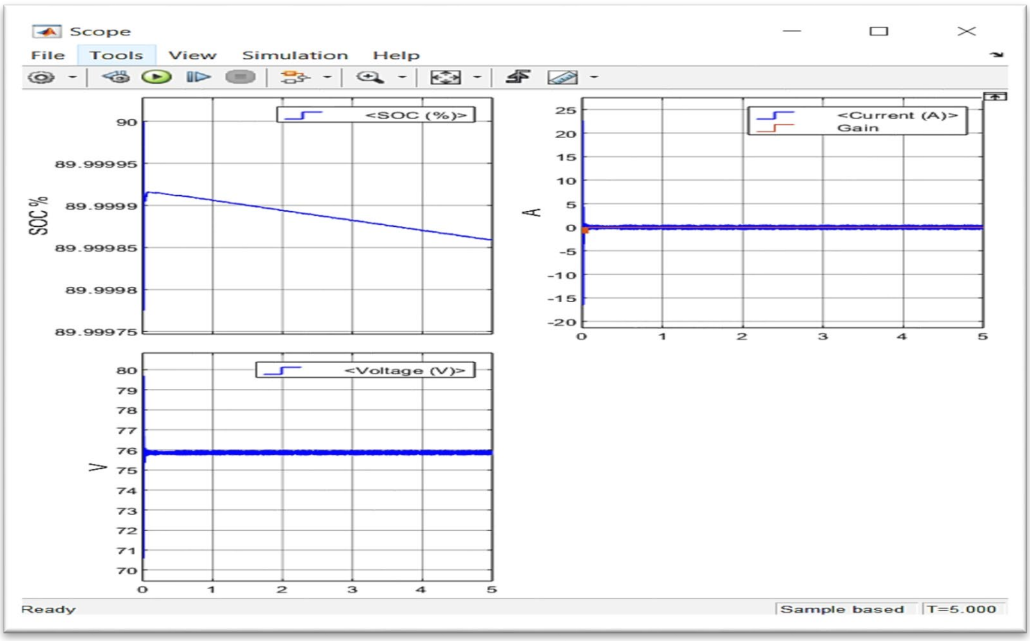

Figure 13: Battery System Discharging.

The results of training the Artificial Neural Network showed that the best training algorithm for the Artificial Neural Network is the Levenberg-Marquardt with a single hidden layer that consists of six neurons as shown in figure (14), Table (1) shows compression of training the ANN with (4,6,9) hidden neurons.

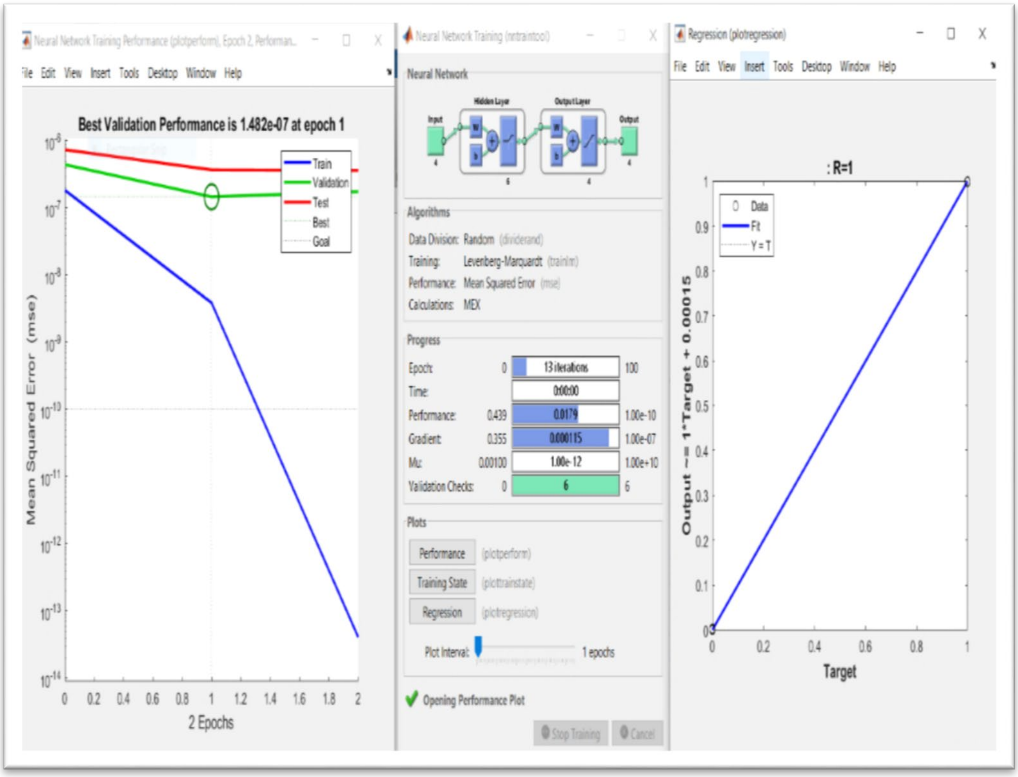

Figure 14: ANN Training results.

TABLE I: Training the ANN with LM algorithm

No. of Hidden Neurons	MSE	Epochs
4	0.00052176	5
6	1.482e-07	1
9	0.0021661	5

The output signal from the Controller is shown in Figure (15) where the transaction time between the output signals has been found $5\mu\ seconds$ which is the best result than other surveys as presented in Table (2).

TABLE II: Comparison with other Surveys results

Reference No.	ANN Structure	Training	Time
Proposed	6 neurons on the Hidden layer, Satlin Activation function	ANN-LM	5µs
[19]	20 neurons on the Hidden layer, Sigmiod Activation function	ANN-BP	0.4s
[20]	10 neurons on the Hidden layer, Sigmiod Activation function	NARX	0.3s
[15]	17 neurons and 9 neurons on the first and second Hidden layers, Sigmiod Activation function	ANN-GA	0.45s

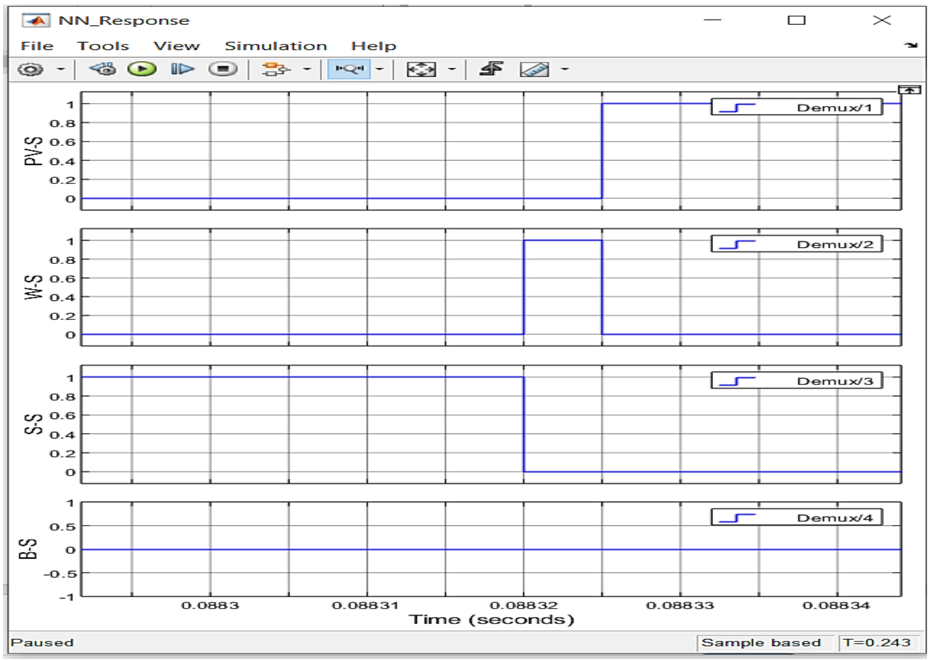

Figure 15: NN Response.

6. Conclusions

MATLAB/Simulink is the best program to simulate the solar-wind energy system and testing the algorithms to verify building the system and avoiding any modeling problems that might appear in the hardware model. Each system has been designed separately with the same power ratings taking in concerned the fluctuations of the solar irradiation and the wind speed then their output terminal connected to switch network controlled with the Intelligent controller which turns the switch network ON and OFF according to the MPPT algorithm to supply the consumer. Satlin activation function provides the fast response for its linear characteristic as well as its appropriate to be implemented on the FPGA card for further investigations in the future.

The Intelligent Controller provides a fast response to the change in weather (5µs). A single hidden layer with six neurons artificial neural network is selected where the mean square error is (1.482e-7) with one epoch.

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