

Research Article

Controlling Output Voltage of Photovoltaic Cells using ANFIS and Interfacing it with Closed Loop Boost Converter

Rikesh Singh^{*a} and Moumi Pandit^b^aDepartment of Electrical and Electronics, Sikkim Manipal Institute of Technology, India.^bDepartment of Electrical and Electronics, Faculty of Electrical and Electronics, Sikkim Manipal Institute of Technology, India.

Accepted 24 April 2013, Available online 1 June 2013, Vol.3, No.2 (June 2013)

Abstract

Photovoltaic system has become one of the most promising renewable sources of energy due to its ability to produce electric power by directly converting solar radiation into electric power. However the output power delivered by Photovoltaic system is very less and is varying with respect to solar radiation. Thus we have proposed a system of Photovoltaic array interfaced with closed loop dc-dc boost converter which considerably steps up the output voltage. ANFIS has been applied to control the uncontrolled output voltage of PV array and remove its disturbances. This disturbance free controlled voltage is fed as input to the closed loop dc-dc boost converter.

Keywords : Renewable source, Photovoltaic cells, solar energy, closed loop dc-dc boost converter, ANFIS.

1. Introduction

Conventional energy sources such as coal, natural gases and oil are the major energy sources but these are non-renewable energy sources therefore these sources of energy are decreasing day by day and are not able to meet the increasing demand of energy. These conventional sources of energy have lead to serious environmental issues like green house effect, air pollution, water pollution etc which has lead to global warming. Hence there has been a major increase in demand for renewable sources of energy. Non conventional energy sources or renewable energy sources are continuously replenished by nature. Most of the renewable energy comes either directly or indirectly from sun and wind and can never be exhausted, and therefore they are called renewable (Application of non-conventional & renewable energy sources, Bureau of Energy Efficiency). Hydropower, wind energy, solar energy is some of the Non conventional energy sources. Photovoltaic (PV) energy appears quite attractive for electricity generation because of its noiseless, pollution-free, scale flexibility, and little maintenance (Farzam Nejabatkhah May 2012). Photovoltaic can convert sunlight directly into electricity. 174 petawatts (PW) of incoming solar radiation is received by earth at the upper atmosphere. 89 pw is absorbed by oceans and land masses and approximately 30% is reflected back to space. The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 EJ per year

(http://en.wikipedia.org/wiki/Solar_power). The spectrum of solar light at the Earth's surface is generally spread across the visible and near-infrared region with a small part in the near-ultraviolet.

Photovoltaic systems (PV system) use solar panels to convert sunlight into electricity (http://en.wikipedia.org/wiki/Photovoltaic_system). Solar panels use light energy (photons) from the sun to generate electricity through the photovoltaic effect (http://en.wikipedia.org/wiki/Solar_panel). The photovoltaic systems has two main disadvantages which are the output voltage produced by photovoltaic system varies with varying sunlight and the voltage produced by photovoltaic system is very less. Thus in this paper we have proposed a simulink model to control the output voltage produced by photovoltaic systems and step up the controlled output voltage so that photovoltaic system can produce a constant and stepped up high voltage to meet the required voltage of the load. ANFIS has been applied to control the varying output voltage of PV system and make it constant. The boost converter can increase the dc input voltage (Ned Mohan). The constant output voltage is then stepped up using a closed loop DC-DC Boost converter.

This paper is organised as follows, section 1 includes introduction. In section 2 the design of closed loop dc-dc boost converter is discussed. In section 3 design of PV cells is discussed in detail. In section 4 simulink model is presented and discussed. In section 5 application of neural network to remove harmonics and disturbances has been discussed followed by section 6 where design of neural network is discussed. Section 7 includes results and

*Corresponding author: Rikesh Singh

discussion followed by section 8 which includes the conclusion. Section 9 includes the future works.

2. Design of closed loop dc-dc boost converter

In this paper boost converter is designed to step up 6 volts of DC voltage to 22 volts. The boost converter also known as the step-up converter is the basic dc-dc converter configuration with an output voltage higher than its input voltage (Rong-Jong Wai, Li-Chung Shih, April 2012). For the design purpose load R of 10kΩ and inductor of 3.3mH has been used. Mosfet has been used as a switch. Pulse with duty cycle of 72% and switching frequency of 300 kHz is supplied to the switch. Capacitor of 100 μF is used.

3. Design of PV cells

The solar cell is the building block of PV arrays, which is basically a p-n junction that directly converts solar energy into electricity:

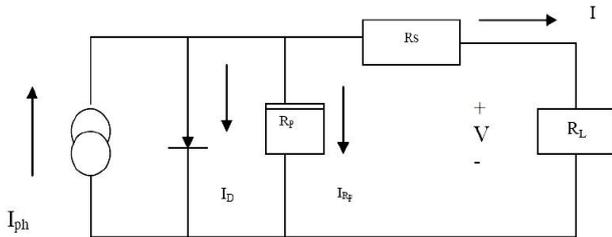


Fig.A.1. Equivalent circuit of a PV cell

Modelling of an ideal PV cell is done by a current source in parallel with a diode. Since no solar cell is ideal therefore series and shunt resistances are added to the model as shown in FigA.1. RS is the intrinsic series resistance whose value is very small. RP is the equivalent shunt resistance which has a very high value (Md. Rabiul Islam, Youguang Guo, Jian Guo Zhu, M.G Rabbani, December 2010).

Applying Kirchoff's law to the node where I_{ph}, diode, R_p and R_s meet, we get

$$I_{ph} = I_D + I_{Rp} + I \tag{A.1}$$

Following equation is obtained for the photovoltaic current:

$$I = I_{ph} - I_{Rp} - I_D \tag{A.2}$$

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V + IR_s}{V_T}\right) - 1 \right] - \left[\frac{V + IR_s}{R_p} \right] \tag{A.3}$$

Where, R_p is the Parallel resistance, I_{ph} is the Insolation current, I is the Cell current, I₀ is the Reverse saturation current, V is the Cell voltage, R_s is the Series resistance, q is the Charge of an electron, VT is the Thermal voltage, K is the Boltzman constant, T is the Temperature in Kelvin.

Equivalent circuit of PV cell is shown in Figure A.2 (K.H. Hussein, I. Muta, T. Hoshino, M. Osakada, January 1995). An ideal solar cell is modelled by a current source in parallel with a diode. However no solar cells are ideal and therefore shunt and series resistances are added to the model. R_j represents the nonlinear impedance of the p-n junction, the current source I_{ph} represents the cell

photocurrent, R_j represents the nonlinear impedance of the p-n junction, R_{sh} and R_s are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis.

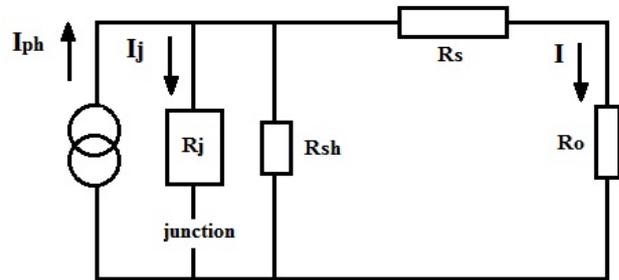


Fig A.2. Equivalent circuit of a PV cell.

To simulate the PV array, a PV mathematical model was used according to the following set of equations:

$$I = n_p I_{ph} - n_p I_{rs} \left[\exp\left(\frac{q}{kTA} \frac{V}{n_s}\right) - 1 \right] \tag{A.4}$$

where V is the PV array output voltage (V), I is the PV array output current (A), q is the charge of an electron, n_s is the number of cells connected in series, n_p is the number of modules connected in parallel, k is Boltzmann's constant, A is the p-n junction ideality factor, I_{rs} is the cell reverse saturation current, T is the cell temperature (K); The factor A in equ.(A.4) determines the cell deviation from the ideal p-n junction characteristics; it ranges between 1 and 5, 1 being the ideal value (I.H Atlas, A.M Sharaf, 2007). In our case we have A = 2.46.

The cell reverse saturation current I_{rs} varies with temperature according to the following equation:

$$I_{rs} = I_{rr} \left[\frac{T}{T_r} \right]^3 \exp\left(\frac{qE_G}{kA} \left[\frac{1}{T_r} - \frac{1}{T} \right]\right) \tag{A.5}$$

Where E_G is the band-gap energy of the semiconductor used in the cell, T is the cell reference temperature and I_{rr} is the reverse saturation current at T_r and

The temperature dependence of the energy gap of the semiconductor is given by (<http://ecee.colorado.edu/~bart/book/eband5.htm>).

$$E_G = E_G(0) - \frac{\alpha T^2}{T + \beta} \tag{A.6}$$

The photocurrent I_{ph} depends on the solar radiation and the cell temperature as follows (Md. Rabiul Islam, Youguang Guo, Jian Guo Zhu, M.G Rabbani, December 2010):

$$I_{ph} = [I_{scr} + k_i (T - T_r)] \frac{S}{100} \tag{A.7}$$

Where I_{scr} is the cells short-circuit current at reference temperature and radiation, k_i is the short circuit current temperature coefficient, and S is the solar radiation in mW/cm².

The PV array power P can be calculated using equ.A.1 as follows:

$$P = IV = n_p I_{ph} V - n_p I_{rs} V \left[\exp\left(\frac{q}{kTA} \frac{V}{n_s}\right) - 1 \right] \tag{A.8}$$

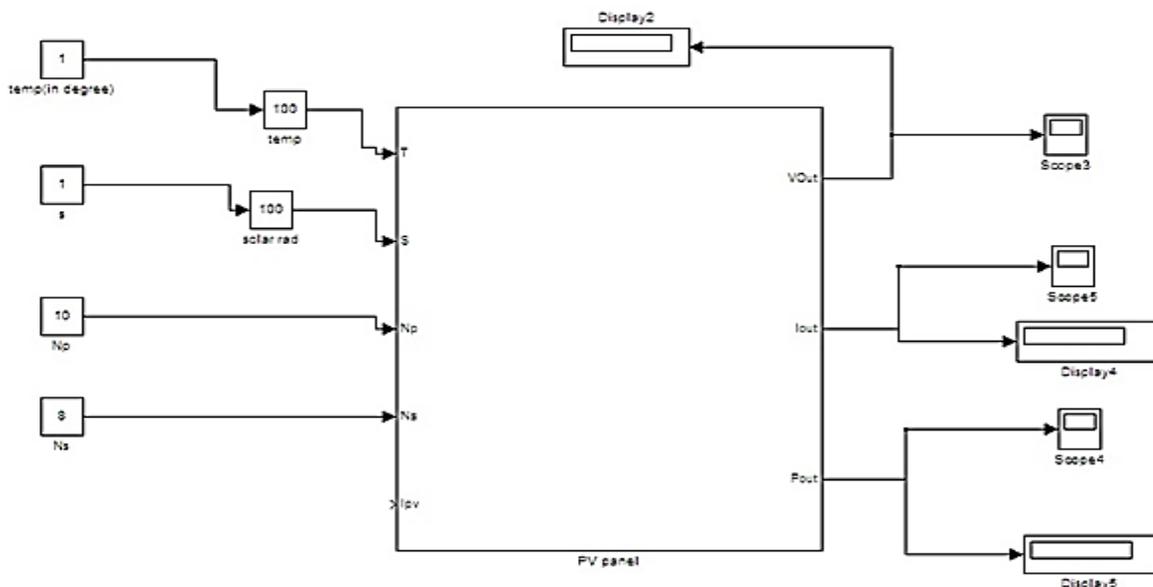


Fig A.3. Simulink model of PV array

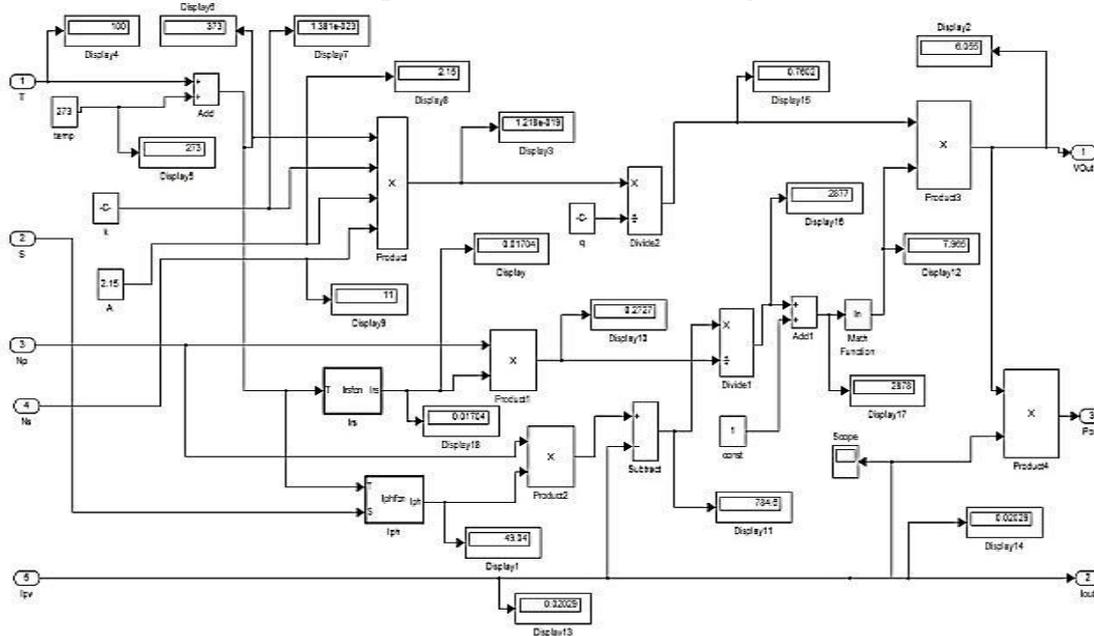


Fig.A.4. Internal model of PV subsystem

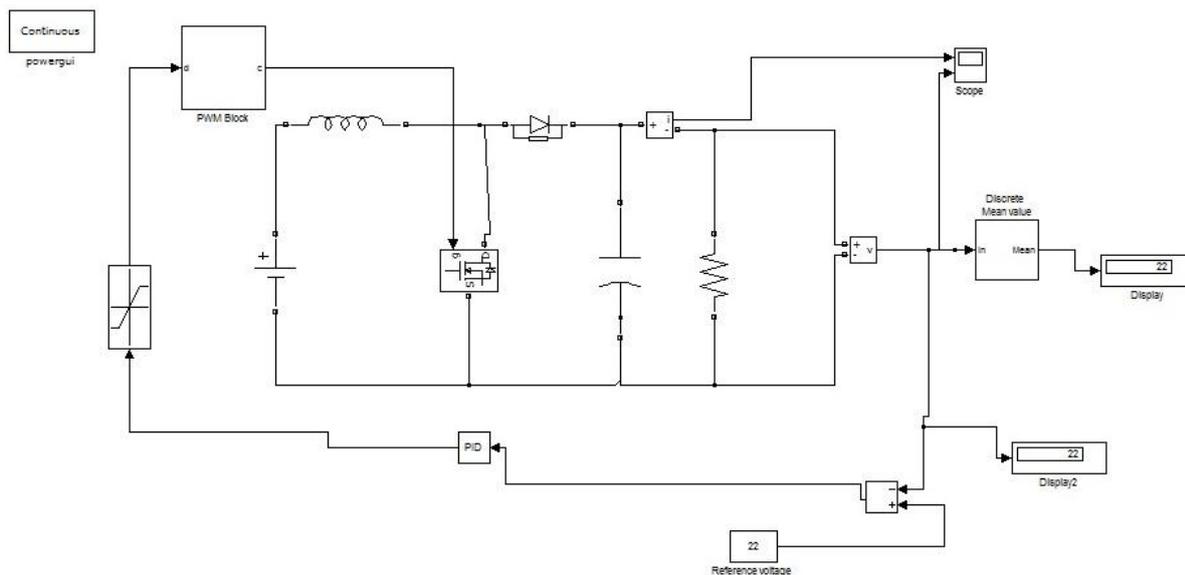
4. Simulink model

Simulink model of PV array has been shown in figure A.3. Five parameters have been considered while designing PV array. Irradiance(S), Temperature(T), number of PV cells connected in series(Ns), number of PV cells connected in parallel (Np), and the inductor current of closed loop boost converter which is same as the load current (I_{pv}) of the PV system is used as feedback for designing the PV array. Here V_{out} is the output voltage of PV array, I_{out} is the output current of PV array and P_{out} is the output power of PV array. PV panel in the simulink model is the subsystem whose internal model is shown in figure A.4.

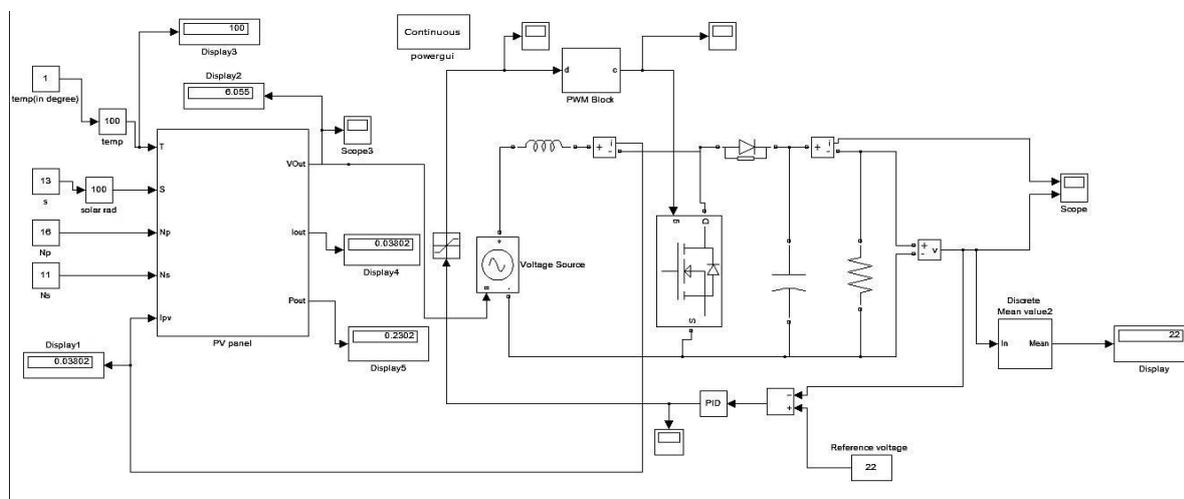
Figure A.4 shows the internal model of PV subsystem. The PV array has been modelled using equations (A.1) to

(A.8). The M-file for I_{rs} function has been developed using equation (A.5) and that of I_{ph} function using equation (A.7). Thus the output of PV array is with respect to the equations provided from (A.1) to (A.8).

Figure A.5 shows the Simulink Model of closed loop Boost Converter. Here 6 volts of DC voltage is given as input voltage. Capacitor of 100µF, inductor of 3.3mH, load R of 10kΩ, mosfet and a diode is used. The output voltage of boost converter is subtracted with the reference voltage of 22 volts which gives the error voltage. This error voltage is fed to the PID block for reduction of error whose output is given to the saturation block which limits the input signal. This saturated signal is given to the PWM block with switching frequency of 300 kHz which gives the required output pulse having duty cycle of 72%.



FigA.5.Simulink Model of closed loop Boost Converter



FigA.6.The complete simulink circuit model showing interfacing of PV array with the closed-loop boost converter.

Finally this pulse is fed to the switch of the boost converter.

Figure A.6 shows that five parameters have been taken into consideration for the simulink model of PV array. These parameters are temperature, number of PV cells in series, number of PV cells in parallel, inductor current of closed loop boost converter and solar irradiation. Thus by varying the values of these parameters the output voltage of PV array can be varied respectively. The PV array is interfaced with closed loop boost converter using a controlled voltage source. The output voltage produced by PV array is fed as input voltage to closed loop boost converter. Therefore output voltage of 6volts produced by PV array is stepped up to 22 volts using closed loop boost converter.

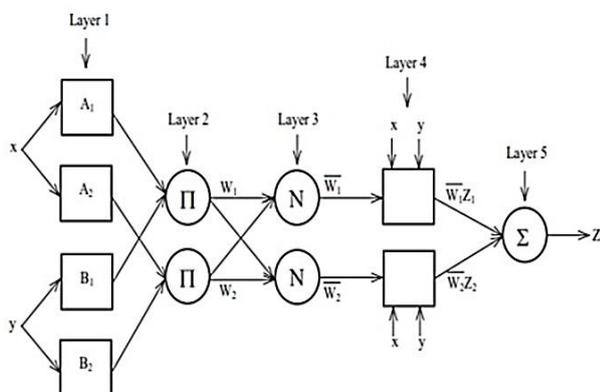
5. Application of neural network to remove harmonics and disturbances.

Various techniques based on Artificial Intelligence are being invented to model and enable solutions to real world problems. These problems are typically associated with fuzzy, complex, and dynamical systems, with uncertain parameters. These systems are the ones that model the real world and are of most interest to the modern science. These models based on artificial intelligence are efficient enough to replace the costly devices and long time consuming mathematical calculations. In this paper a model is proposed, developed and tested based on artificial intelligence to control the output voltage of PV cells. The performance goal is set to be 10^{-5} and epochs are set to be 1000. The models are trained with a input matrix having data received from the PV cells and the output matrix with expected voltage. After a proper training the model is tested with the output data of PV cells received from the simulink model created in the matlab platform. The output voltage of the PV cells is retrieved from the simulink

model and given to the model for testing. The model takes in the input from the PV cells and gives a controlled output of desired value. The same process can be implemented for real data which can be given to the network with the help of parallel ports and the controlled output can be derived from the model and fed to the boost converter using parallel port.

6. Design of neural network

The ANFIS is a FIS implemented in the framework of an adaptive fuzzy neural network, and is a very powerful approach for building complex and nonlinear relationship between a set of input and output data years (J.-S.R. Jang,1993), (J.-S.R. Jang, C. T. Sun, and E. Mizutani,1997). It combines the explicit knowledge representation of FIS with the learning power of ANNs. Usually, the transformation of human knowledge into a fuzzy system (in the form of rules and membership functions) does not give exactly the target response. So, the optimum values of the FIS parameters should be found. The main objective of the ANFIS is to determine the optimum values of the equivalent FIS parameters by applying a learning algorithm using input-output data sets.



FigA.7. Architecture of ANFIS

The parameter optimization is done in such a way that the error between the target and the actual output is minimized. The ANFIS architecture consists of fuzzy layer, product layer, normalized layer, de-fuzzy layer, and summation layer. A typical ANFIS architecture is shown in Figure A.7, in which a circle indicates a fixed node, whereas a square indicates an adaptive node. For simplicity, we assume that the FIS under consideration has two inputs x and y and one output z. The ANFIS used in this work implements a firstorder Sugeno fuzzy model. Among many FIS models, the Sugeno fuzzy model is the most widely applied one for its high interpretability and computational efficiency, and built-in optimal and adaptive techniques.

The model in this paper is developed using a hybrid learning algorithm years (J.-S.R. Jang,1993), (J.-S.R. Jang, C. T. Sun, and E. Mizutani,1997), which combines the least-square method and the backpropagation algorithm. The model is trained with 100 sets of input/output data,

which are obtained from the PV cells. The model is trained for giving a controlled output of desired value.

The network is trained with least square algorithm, which has 5 member functions whose performance goal was taken as 10^{-5} and number of epochs 10000. For 100 input/output training samples, the network requires only 1 minute for training.

The training procedure consists of the following steps:

- Developing training patterns: Using the output voltage of PV cells the input layer of the training data is prepared over a long period of time under different irradiance level whereas the output layer consists of the expected voltage. An input pattern and an output target give a training pattern together. All the training patterns form the training set.

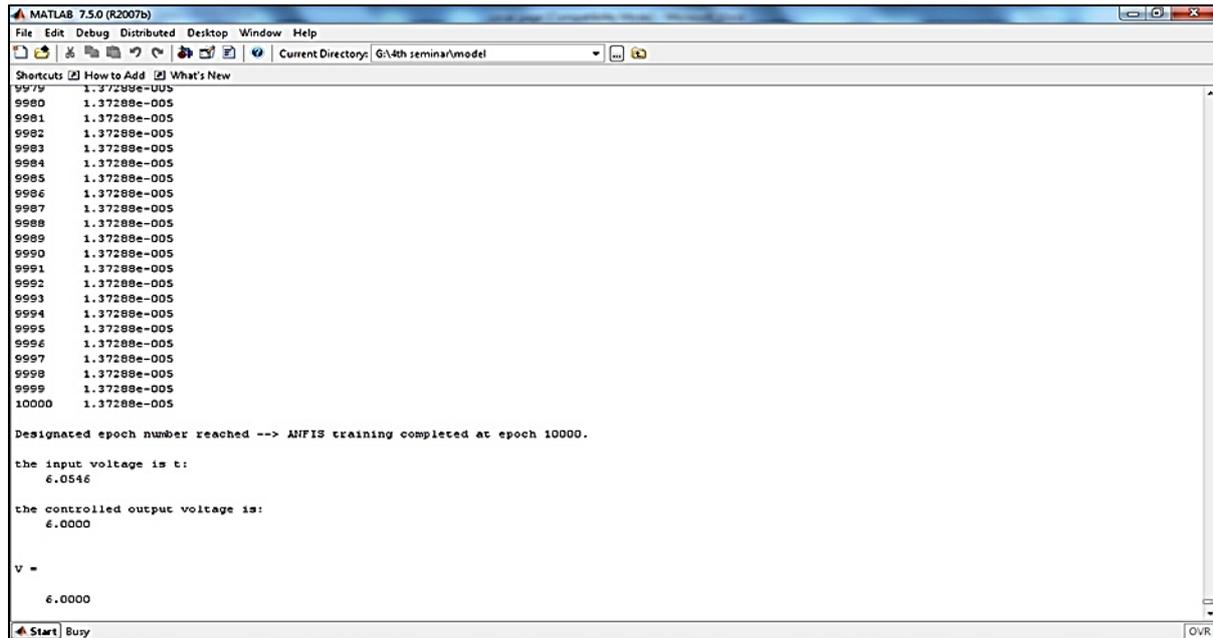
- Formation of ANFIS model: We create a network consisting of an estimated number of layers and of an estimated number of neurons in the layers. The ANFIS architecture consists of fuzzy layer, product layer, normalized layer, de-fuzzy layer, and summation layer. A typical ANFIS architecture is shown in Figure A.2, in which a circle indicates a fixed node, whereas a square indicates an adaptive node. For simplicity, we assume that the FIS under consideration has two inputs x and y and one output z. The ANFIS used in this work implements a first order Sugeno fuzzy model. Among many FIS models, the Sugeno fuzzy model is the most widely applied one for its high interpretability and computational efficiency, and built-in optimal and adaptive techniques. The number of resonant frequencies for which the network is trained gives the number of neurons in the input layer and the number of computed parameters determines the number of neurons in the output layer. The number of hidden layers and hidden neurons has to be estimated. Initial synaptic weights and biases are set randomly.

- Training ANFIS model: During the training, input patterns are successively introduced into the inputs of the network, and synaptic weights are changed to reach desired output responses. The training is completed when the network reacts properly to all input patterns from the training set.

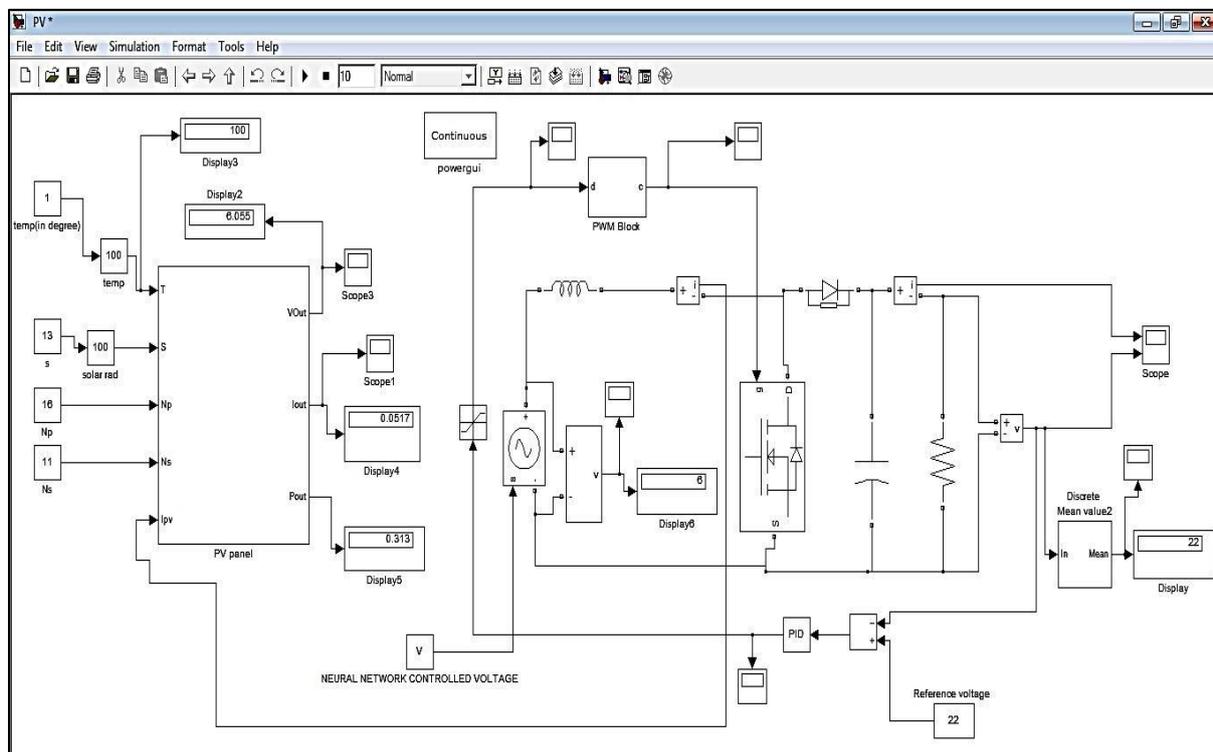
- Verifying neural model: We introduce such patterns to the inputs of the model, which differ from the input patterns of the training set. Exploiting the numerical model, correctness of the response of the network is verified. If the response is incorrect, additional training patterns have to be prepared, and training is repeated over a larger training set.

- Using ANFIS model. The trained neural network produces output responses with a sufficient accuracy both for training patterns and for interlaying input patterns.

The trained neural network provides a special approximation where the exact results of the numerical analysis, which are hidden in the training patterns, are used for neural computation and give us directly all the required designing parameter of an antenna for a desired frequency. That way, a computationally modest network model can replace a numerical analysis for parameters differing from training patterns.



FigA.8. ANFIS controlled output voltage of PV array.



FigA.9. Simulation model with ANFIS controlled voltage of PV Array.

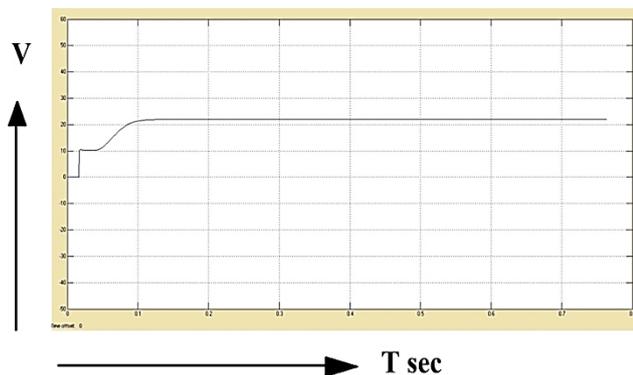
7. Results and discussion

After a proper training, the ANFIS model is presented with various test data which does not belong to training data. The model is accurate enough to give controlled output which is then fed to the boost converter for further processing. The ANFIS model is implemented in the simulink model by taking the output voltage of PV cells

and feeding it to the ANFIS model. The ANFIS model gives controlled output voltage which is then fed to the boost converter.

Figure A.8 shows the ANFIS controlled output voltage of PV array. The ANFIS program automatically take the uncontrolled output voltage of PV array of the simulink model as input voltage and gives out a controlled output voltage of 6 volts.

Figure A.9 shows the Simulation model with ANFIS controlled voltage of PV Array. The ANFIS controlled output voltage of PV array is fed as input voltage of closed loop boost converter with the help of a variable V .



FigA.10. Output voltage of closed loop boost converter with ANFIS controlled input voltage.

Figure A.10 represents the output voltage of closed loop boost converter with ANFIS controlled input voltage. Here the output voltage goes to transient state and then steady state. The output voltage obtained is 22 V.

8. Conclusions

In this paper we have proposed a system which overcomes the disadvantages of PV cells i.e low voltage and uncontrolled voltage with disturbances. In the proposed system we have interfaced PV cell with closed loop boost converter such that the output voltage produced by PV cell is fed as input voltage to closed loop boost converter which steps up the given input voltage to a considerably high output voltage to meet the voltage requirement of load. ANFIS has been applied to control and remove the disturbance of output voltage of PV array. The ANFIS controlled output voltage is fed as input voltage to closed loop boost converter.

9. Future work

The proposed work can be improved by applying the concept of Maximum power point tracking. Hardware implementation of the proposed method of controlling voltage using ANFIS can be applied by interfacing matlab with PV cells and closed loop boost converter by using parallel ports.

References

K.H. Hussein, I. Muta, T. Hoshino, M. Osakada, (January 1995) Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric condition, *IEE Proc.-Gener. Trans. Distrib.*, Vol. 142, No. 1,

- KHALLAT, M.A., and RAHMAN,(1986) A probabilistic approach to photo voltaic generator performance prediction, *IEEE Trans.*, , EC-1, (3), pp. 34-40
- VACHTSEVANOS, G., and KALAITZAKIS,(1987) A hybrid photovoltaic simulator for utility interactive studies, *IEEE Trans*, EC-2, (2), pp. 227-231
- W. Xiao, W. G. Dunford, and A. Capel, (2004) A novel modeling method for photovoltaic cells, in Proc. IEEE 35th Annu. Power Electron. Spec. Conf. (PESC), vol. 3, pp. 1950–1956
- Modelling and Control design for DC-DC converter, Power Management group, AVLSI Lab, IIT-Kharagpur.
- I.H Atlas, A.M Sharaf,(2007) A photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment, Proce. of IEEE International Conference on Clean Electrical Power, ICCEP, Capri, Italy.
- Md. Rabiul Islam, Youguang Guo, Jian Guo Zhu, M.G Rabbani,(December 2010) Simulation of PV Array Characteristics and Fabrication of Microcontroller Based MPPT, Faculty of Engineering and Information technology, University of Technology Sydney, Australia, 6th International Conference on Electrical and Computer Engineering ICECE 2010, 18-20, Dhaka, Bangladesh.
- Muhammad H. Rashid, Power Electronics Circuits, Devices and Applications, Third Edition.
- Nielsen, R. 2005, 'Solar Radiation', <http://home.iprimus.com.au/nielsens/www.earthscan.co.uk/Portals/>
- Oliva Mah NSPRI, (1998) Fundamentals of Photovoltaic Materials, National Solar power institute, Inc. 12/21/98. Application of non-conventional & renewable energy sources, Bureau of Energy Efficiency.
- http://en.wikipedia.org/wiki/Solar_power.
- http://en.wikipedia.org/wiki/Photovoltaic_system.
- http://en.wikipedia.org/wiki/Solar_panel
- <http://ecee.colorado.edu/~bart/book/eband5.htm>.
- Rong-Jong Wai, Li-Chung Shih, (April 2012), Adaptive Fuzzy-Neural-Network Design for Voltage Tracking Control of a DC–DC Boost Converter , IEEE transactions on power electronics, VOL. 27, NO. 4.
- Farzam Nejabatkhah, Saeed Danyali, Seyed Hossein Hosseini, Mehran Sabahi, and Seyedabdolkhalegh Mozaffari Niapour, (May 2012), Modeling and Control of a New Three-Input DC–DC Boost Converter for Hybrid PV/FC/Battery Power System, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 27, NO. 5.
- Riad Kadri, Jean-Paul Gaubert, and Gerard Champenois,(March 2012), Nondissipative String Current Divter for Solving the Cascaded DC–DC Converter Connection Problem in Photovoltaic Power Generation System, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 27, NO. 3.
- Mitra Sarhangzadeh, Seyed Hossein Hosseini, Mohammad Bagher Bannae Sharifian, and Gevorg B. Gharehpetian,(June 2011), Multiinput Direct DC–AC Converter With High-Frequency Link for Clean Power-Generation Systems, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 26, NO. 6.
- Ned Mohan, Undeland, Riobbins, power electronics converters, applications and design, Third edition book.