Bitlis Eren Univ J Sci & Technol
5 (1), 42 - 47, 2015

E - ISSN 2146-7706

Research Article

Artificial Neural Network Based Power Flow Analysis for Micro Grids

Serhat Berat Efe [1] *, Mehmet Cebeci [2]

[1] *Bitlis Eren University, Department of Electrical and Electronics Engineering, Bitlis - Turkey*
[2] *Frat University, Department of Electrical and Electronics Engineering, Elazığ - Turkey*
* *Corresponding author: sbefe@beu.edu.tr*

Abstract

This paper proposes a neural network based power flow analysis method that applied on a grid connected and ring-shaped micro grid. As the use of micro grids increasing rapidly, it becomes necessary to analyze them for different operating and loading conditions as large power systems. At the outset, a MG is designed and simulated under MATLAB / Simulink platform. Normal operation data collected and stored. Then, different loading scenarios performed, operational data collected and stored to use for proposed method. Intelligent systems are used to process these data and also for training. After training a fully different scenario is created and the effectiveness of the proposed method is verified through simulation study.

Keywords: Artificial neural networks, micro grid, power flow analysis, renewable energy sources.

1. Introduction

Micro grids (MG) are small power systems that consist of several types of Distributed Generators (DG) such as photovoltaic generation (PV), wind energy systems (WES), fuel cell generation (FC), micro hydroelectric power plant (micro turbine); and storage devices like flywheel. Also a micro grid is defined as a cluster of loads and relatively small energy sources operating as a single controllable power network to supply the local energy needs (Zhang et al. 2010). MGs can be designed either main grid connected or islanded modes of operation.

There are advantages and disadvantages of these operation modes. Uninterruptable energy supplement is the main advantage of main grid connected mode. But in case of any fault that occurs at main grid, MG and also customers affected directly. So, it is recommended to operate MG in islanded mode for sensitive loads. To harness the full benefits of the microgrid, there is a need for mathematical and software tools to manage its resources.

There are many tools to manage the operation of the conventional power systems but most of them are are not appropriate for microgrids. One of basic tools required for microgrid management is to perform load-flow analysis (Elrayyah et al. 2014).

In complex power systems, power transfers from power resources to loads through power transmission network. If power load only increases on a single node and its node voltage lower limit is regarded as the main factor that hinders the load increasing, situation may be that load increases until the node voltage reaches its lower limit. Situations may be similar on other nodes when single node loadability is analysed on them (Sun et al. 2014). This prove the importance of power flow analysis for a network. The focus of this paper is on the power flow analysis of micro grid.

2. Components of Micro Grid

A. *Photovoltaic System*

A solar cell basically is a p-n semiconductor junction. The equivalent circuit of a PV cell is shown in Fig. 1.

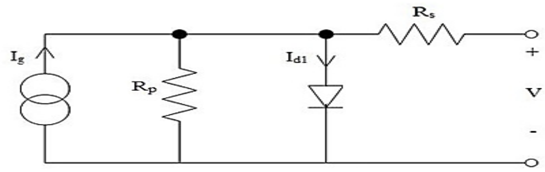


Figure 2. DC equivalent model of solar cell

Mathematical model of the Fig. 1 is given in (1)

$$I_{FV} = I_g - I_{d1}\left[e^{q(V+IR_s)/kT} - 1 \right] - \frac{V+IR_s}{R_p} \qquad (1)$$

In this equation V is terminal voltage of cell, I_{PV} is output current, k is Boltzmann constant, T is absolute ambient temperature in terms of Kelvin and q is electron charge.

Internal structure of a PV panel model that designed under Matlab/Simulink platform is given in Fig. 2.

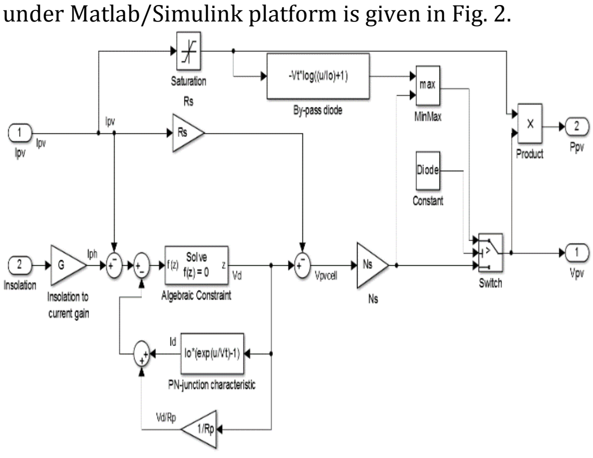


Figure 2. Matlab/Simulink model of PV module

Received 21 June 2015
Available online June 2015

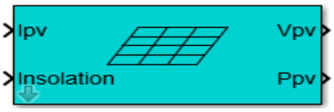


Figure 3. PV block

Figure 4. PV block parameters

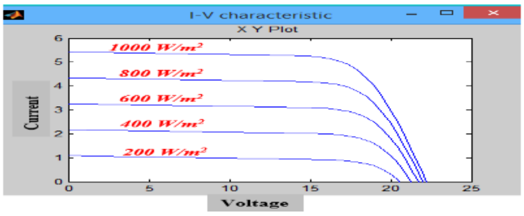


Figure 5. Current-Voltage relation curves

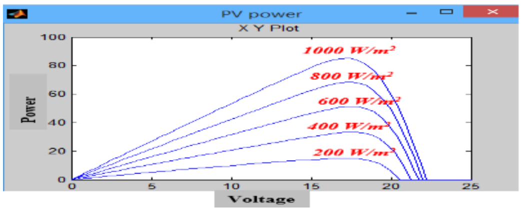


Figure 6. Power-Voltage relation curves

Block representation of this model which is designed for theoretical applications is given in Fig. 3 and also Fig. 4 represents the parameters of this block. Current (I) and voltage (V) relation of module is given in Fig. 5; power and voltage relation of module is given in Fig. 6. PV generation system is designed by using 24 of blocks that is given in Fig. 3. This system is given in Fig.7. As it can be seen from Fig. 7, output voltage of the system is 412.8 V and output power is 2043 W.

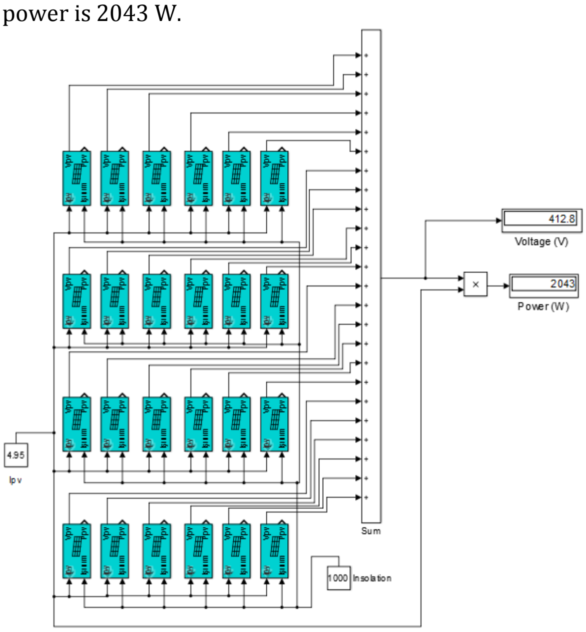


Figure 7. PV generation system

Obtained 412.8 V DC voltage is inverted to 3 phase AC by 6-pulse inverter and connected to busbar over 380/380 V transformer to avoid reverse effects of pulses on voltage waveforms.

B. Wind Energy System

The power extracted from the wind can be given as the relation as follows:

$$P_m = \frac{1}{2}\rho A V^3 C_p(\lambda,\beta) \quad (2)$$

where ρ is air density (kg/m³), *A* is swept area (m²), *V* is wind speed (m/s), C_p is power transform coefficient, λ tip-speed ration, β is the pitch angle, which is the angle between the plane of rotation and blade in terms of radians. Power transform coefficient can be detailed as;

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \quad (3)$$

Proposed c coefficients are c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21 and c_6 = 0.0068.

Other parameters of the equation can be given as follows:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0,08\beta} - \frac{0,035}{\beta^3 + 1} \quad (4)$$

$$\lambda = \frac{\omega r}{V} \quad (5)$$

$$A = \pi r^2 \quad (6)$$

where ω is turbine rotor speed (rad/s) and r is Radius of the turbine blade (m).

As the torque (T_m) and power (P_m) relation of a turbine is

$$T_m = \frac{P_m}{\omega} \quad (7)$$

the amount of aerodynamic torque in N.m can be given in detailed form as follows;

$$T_m = \frac{1}{2\omega}\rho\pi r^5 C_p(\beta,\lambda)V^3 \quad (8)$$

By using these equations, the model of the wind turbine implemented in Matlab/Simulink is shown in Fig. 8(a). Also the block form of the model is given in Fig. 8(b).

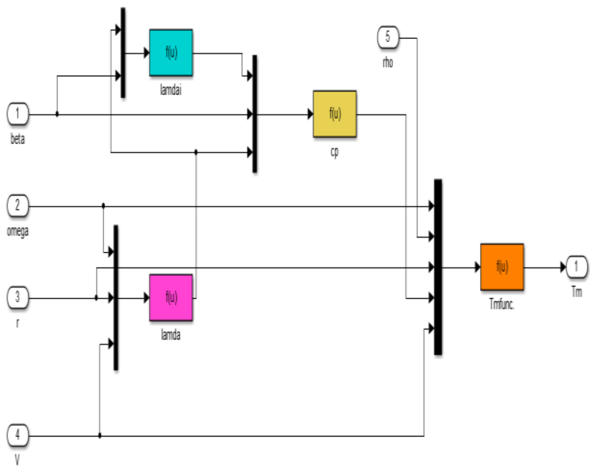


Figure 8(a). Wind turbine Matlab/Simulink model

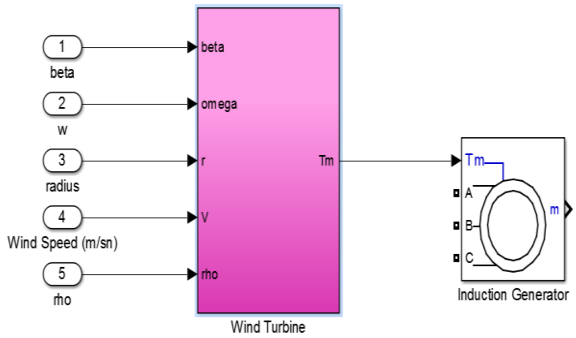


Figure 8(b). Wind turbine block

A squirrel-cage induction generator is used in system. Parameters of the generator is given in Fig. 9.

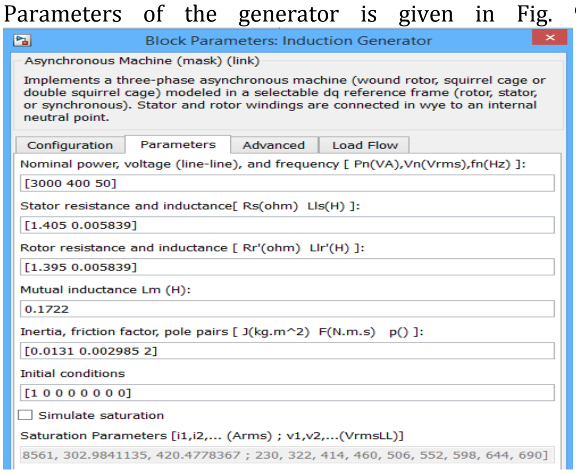


Figure 9. Parameters of induction generator.

C. *Fuel Cell System*

A fuel cell is an electrochemical system that converts chemical energy of a fuel directly into electrical energy without combustion. The fuel cell that is connected to micro grid is designed to produce 500 W power. As it is applied in PV system, obtained 382,5 V DC voltage is inverted to 3 phase AC by 6-pulse inverter and connected to busbar over 380/380 V transformer to avoid reverse effects of pulses on voltage waveforms. Internal structure of designed fuel cell is given in Fig. 10 (a) where block model is given in Fig. 10 (b).

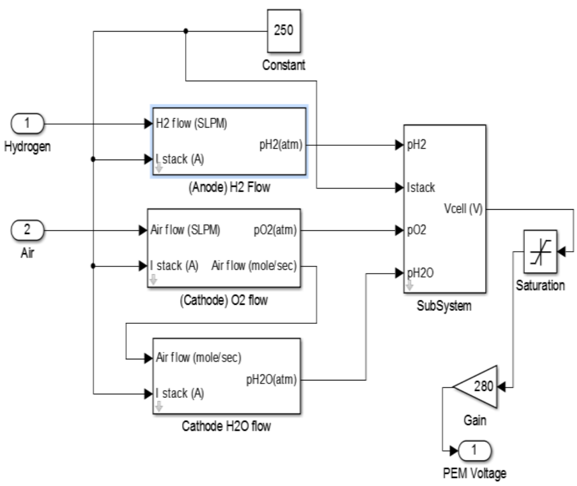


Figure 10 (a). Internal structure of PEM fuel cell

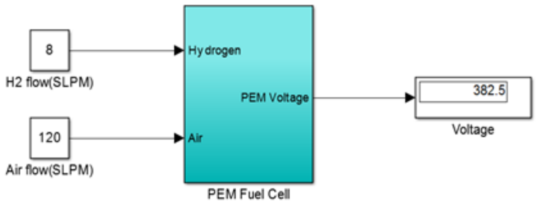


Figure 10 (b). Block model of PEM fuel cell

D. *Micro Turbine*

Micro turbine is supposed as the biggest power source of micro grid. It has a power of 10 kW. Output of the plant is connected to micro grid with a value of 380 V. Three Phase Source Block is used as micro hydro power plant in designed micro grid. Properties of this source is given in Fig. 11.

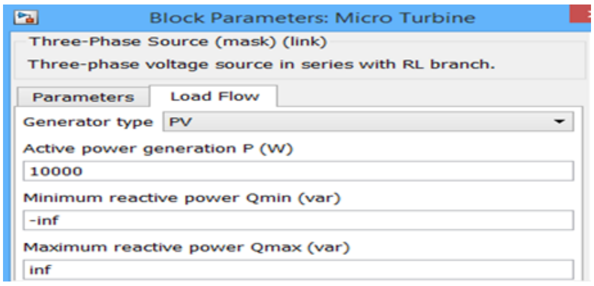


Figure 11. Block properties

Bus loading values of the designed microgrid are given in Table 1. These values are obtained from simulation of designed microgrid.

Table 1. Bus Loading Values

BUSBAR	*P (pu)*	*Q (pu)*
PV	0.1597	1.524
Micro Turbine	1.347	0.3766
PEM	0.0244	0.4564
WES	1.383	0.1708
Load	1.721	0.9936

Table 2 shows the line parameters of designed micro grid.

Table 2. Line Parameters

Source Busbar	*Target Busbar*	*R*	*X*	*B*
PV	**Micro Turbine**	0.01273	0.0093	0.002
PV	**WES**	0.01273	0.0093	0.002
Micro Turbine	**PEM**	0.01273	0.0093	0.002
PEM	**Load**	0.02546	0.0186	0.004
WES	**Load**	0.00636	0.000465	0.001

3. Forming Bus Admittance Matrix

Line parameters that are given in Table III are defined to the software. Bus admittance matrix can be obtained as given in 9:

$$Y = \begin{bmatrix} 1.0244 - 0.7483i & -0.5122 + 0.3742i & 0.0000 + 0.0000i & -0.5122 + 0.3742i & 0.0000 + 0.0000i \\ -0.5122 + 0.3742i & 1.0244 - 0.7483i & -0.5122 + 0.3742i & 0.0000 + 0.0000i & 0.0000 + 0.0000i \\ 0.0000 + 0.0000i & -0.5122 + 0.3742i & 0.7683 - 0.5612i & 0.0000 + 0.0000i & -0.2561 + 0.1871i \\ -0.5122 + 0.3742i & 0.0000 + 0.0000i & 0.0000 + 0.0000i & 2.0762 - 0.4885i & -1.5640 + 0.1143i \\ 0.0000 + 0.0000i & 0.0000 + 0.0000i & -0.2561 + 0.1871i & -1.5640 + 0.1143i & 1.8201 - 0.3014i \end{bmatrix} \quad (9)$$

4. Power Flow Analysis of Micro Grid by Using Gauss-Seidel Method

This technique is perhaps the best known of all methods of power flow analysis. One of the challenges (Dugan 2008) considering DG in the analysis and design of distribution systems, is the power flow solution taking into account the proper modeling of embedded DGs. Teng (Teng 2008) has proposed three types of mathematical models of DGs for load flow analysis i.e a) constant power factor model for synchronous generator and power electronics based DGs b) variable reactive power model for induction generator based DGs and c) constant voltage model for large scale controllable DGs. The micro grid is analyzed by Gauss – Seidel power flow analysis method (Kumar et al. 1995). Bus loading values that given in Table II are defined. Positive signed values represent that busbar is supplying the grid and negative signed values represent that busbar is supplied from grid. Gauss-Seidel method uses cartesian coordinates for analysis. Therefore, amplitude and angle values have to be converted to cartesian coordinates form from polar form. By completing the steps given above, a designed algorithm is used for power flow analysis of the micro grid by Gauss-Seidel Method. Table 3 shows the results of analysis after executing software with all algorithms.

Table 3. Voltage Amplitude and Angle Values Obtained by Algorithm

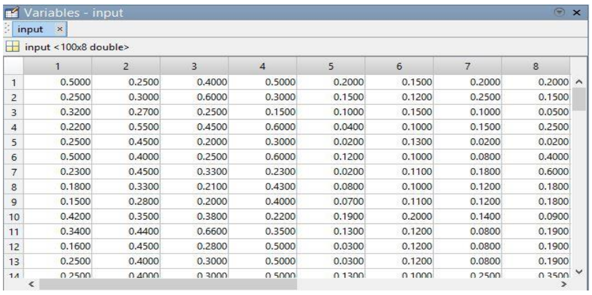
BUSBAR	AMPLITUDE	ANGLE
Micro Turbine	0.9500	-0.3317
PEM	0.9498	-1.1934
WES	0.9494	-2.0993
Load	0.9609	-2.1979

5. Power Flow Analysis Of Micro Grid By Artificial Neural Network

ANN is a powerful tool for the simulation and prediction of nonlinear problems. A neural network comprises many highly interconnected processing units called neurons. Each neuron sums weighted inputs and then applies a linear or nonlinear function to the resulting sum to determine the output, and all of them are arranged in layers and combined through excessive connectivity (Shi et al. 2010).

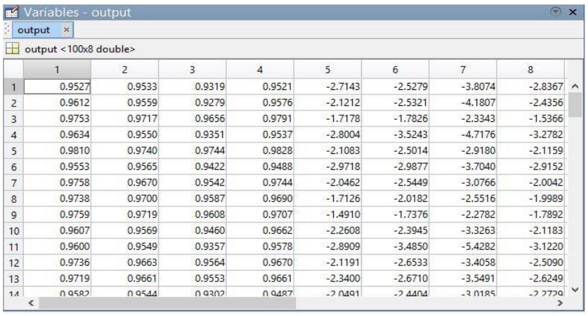
This section proposes the configuration steps of artificial neural network (ANN) that designed for power flow analysis of micro grid. ANN is designed due to various busbar loading values. It consist of one input layer, one hidden layer and one output layer. Input parameters are created by writing active and reactive power values of busbars in single line matrix form. Busbar voltages and angles are obtained as result.

Creating input data is the first step to design ANN. Various loading values, which are determined for designed microgrid, are taken from measurement blocks and provided to ANN as input data. Each busbar voltage amplitude and angle are defined as output. ANN is trained by 100 different loading scenarios. As the different training algorithms are tested, system reach to the best results by proposed algorithm. A total of 100 line and 8 column data is defined as input for this algorithm, where the first 4 columns are active power values (P) and the last 4 columns are reactive power values (Q). Also output data is defined by 8 column data where the first 4 columns are voltage amplitudes (V) and last 4 columns are angle (δ) values. As the system trained by 100 different scenarios and therefore there are 100 lines for input data, output data is consist of 100 lines. Fig. 12 represents the input parameters and Fig. 13 represents the output parameters of training process.


Variables - input
input <100x8 double>

	1	2	3	4	5	6	7	8
1	0.5000	0.2500	0.4000	0.5000	0.2000	0.1500	0.2000	0.2000
2	0.2500	0.3000	0.6000	0.3000	0.1500	0.1200	0.2500	0.1500
3	0.3200	0.2700	0.2500	0.1500	0.1000	0.1500	0.1000	0.0500
4	0.2200	0.5500	0.4500	0.6000	0.0400	0.1000	0.1500	0.2500
5	0.2500	0.4500	0.2000	0.3000	0.0200	0.1300	0.0200	0.0200
6	0.5000	0.4000	0.2500	0.6000	0.1200	0.1000	0.0800	0.4000
7	0.2300	0.4500	0.3300	0.2300	0.0200	0.1100	0.1800	0.6000
8	0.1800	0.3300	0.2100	0.4300	0.0800	0.1000	0.1200	0.1800
9	0.1500	0.2800	0.2000	0.4000	0.0700	0.1100	0.1200	0.1800
10	0.4200	0.3500	0.3800	0.2200	0.1900	0.2000	0.1400	0.0900
11	0.3400	0.4400	0.6600	0.3500	0.1300	0.1200	0.0800	0.1900
12	0.1600	0.4500	0.2800	0.5000	0.0300	0.1200	0.0800	0.1900
13	0.2500	0.4000	0.3000	0.5000	0.0300	0.1200	0.0800	0.1900
14	0.2500	0.4000	0.3000	0.5000	0.1300	0.1000	0.2500	0.3500

Figure 12. Input parameters for training process


Variables - output
output <100x8 double>

	1	2	3	4	5	6	7	8
1	0.9527	0.9533	0.9319	0.9521	-2.7143	-2.5279	-3.8074	-2.8367
2	0.9612	0.9559	0.9279	0.9576	-2.1212	-2.5321	-4.1807	-2.4356
3	0.9753	0.9717	0.9656	0.9791	-1.7178	-1.7826	-2.3343	-1.5366
4	0.9634	0.9550	0.9351	0.9537	-2.8004	-3.5243	-4.7176	-3.2782
5	0.9810	0.9740	0.9744	0.9828	-2.1083	-2.5014	-2.9180	-2.1159
6	0.9553	0.9565	0.9422	0.9488	-2.9718	-2.9877	-3.7040	-2.9152
7	0.9758	0.9670	0.9542	0.9744	-2.0462	-2.5449	-3.0766	-2.0042
8	0.9738	0.9700	0.9587	0.9690	-1.7126	-2.0182	-2.5516	-1.9989
9	0.9759	0.9719	0.9608	0.9707	-1.4910	-1.7376	-2.2782	-1.7892
10	0.9607	0.9569	0.9460	0.9662	-2.2608	-2.3945	-3.3263	-2.1183
11	0.9600	0.9549	0.9357	0.9578	-2.8909	-3.4850	-5.4282	-3.1220
12	0.9736	0.9663	0.9564	0.9670	-2.1191	-2.6533	-3.4058	-2.5090
13	0.9719	0.9661	0.9553	0.9661	-2.3400	-2.6710	-3.5491	-2.6249
14	0.9582	0.9544	0.9302	0.9487	-2.0491	-2.4404	-3.0185	-2.2729

Figure 13. Output parameters for training process

Algorithm executed for training of ANN and this it is completed after 279 iterations. This process is given in Fig. 14.

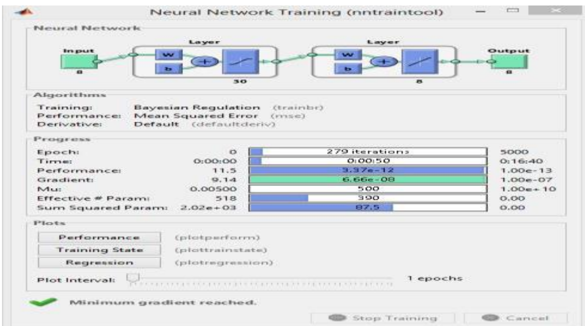


Figure 14. ANN training process

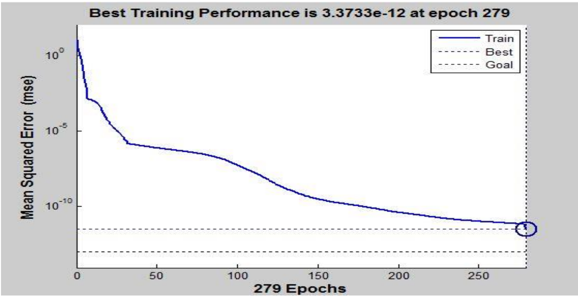


Figure 15. ANN training performance curve.

Regression curve of the training process is given in Fig. 16. It is clear from figure that curve is precisely close to convergence value and training process is successful.

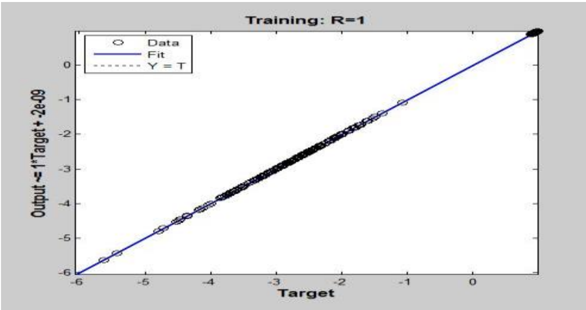


Figure 16. Regression curve

Micro grid loading values are determined as input data to ANN and voltage amplitudes and angles are obtained as it is done in Gauss-Seidel analysis method. Results are given in Table 4. PV busbar is recognized as swing bus at Gauss-Seidel analysis. This busbar is also not been considered for appropriate comparison.

Table 4. Voltage Amplitude and Angle Values Obtained by ANN

BUSBAR	AMPLITUDE	BUSBAR
Micro Hyd.	0.9503	-0.3313
PEM	0.9500	-1.1934
WES	0.9490	-2.0989
Load	0.9611	-2.1976

Comparison of Gauss-Seidel analysis and ANN analysis results are given in Table 5. As the values are so close to each other, the table prove that ANN works properly and can be used instead of classic iterative power flow analysis methods like Gauss-Seidel Method.

Table 5. Comparison Of Results

Bus	Gauss-Seidel Analysis		ANN Analysis		Convergence	
	Ampl.	Angle	Ampl.	Angle	Ampl.	Angle
Micro Turbine	0.9500	-0.3317	0.9503	-0.3313	0.0003	0.0004
PEM	0.9498	-1.1934	0.9500	-1.1934	0.0002	0
WES	0.9494	-2.0993	0.9494	-2.0989	0	0.0004
Load	0.9609	-2.1979	0.9611	-2.1976	0.0002	0.0003

6. Power Flow Analysis in case of Single Fault Condition

In an islanding micro grid, there is no single generator that can keep the balance of the increasing demand of the whole system. This means there is no swinging bus in the power flow calculation of an islanding micro grid system which is essentially different from the traditional power flow calculation of large power systems (Liu et al. 2009). While the microgrid is operating in islanded mode, a fault which occurs at load busbar has been applied to the system to determine ANN based power flow analysis results. System values are supplied to ANN online and instant results are obtained. As the ANN based power flow analysis system operating online, it results too much power flow analysis data at output. Therefore, values are taken at the beginning, in the middle and at the end of fault which are given in Table 6. ANN block which is given in Fig. 17 is used for online analysis where P variables are represent active power and Q variables represent reactive power values of each busbar.

Table 6. Power Flow Analysis Result During Load Busbar Fault

BUSBAR	Beginning of Fault		Middle of Fault		End of Fault	
	Amplitude	Angle	Amplitude	Angle	Amplitude	Angle
PV	1.3122	-3.462	0.9813	-0.2105	0.9493	-1.1726
Micro Hyd.	1.3312	-2.216	0.9826	-0.1912	0.9501	-1.1832
PEM	1.2703	-2.897	0.9816	-0.2034	0.9608	-1.2103
WES	1.3233	-3.0154	0.9809	-0.1989	0.9496	-1.1912
Load	1.4373	-0.1847	0	0	0.9619	-1.2462

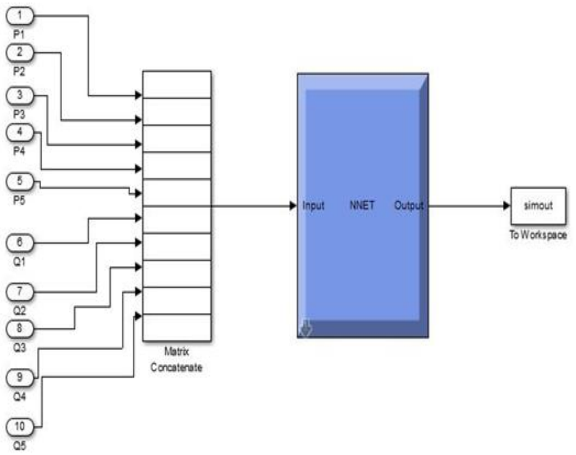


Figure 17. ANN block for online operation

Main advantage of ANN based power flow analysis is no necessity to determine slack bus. Therefore, analysis results for all busbars can be obtained, as none of them are slack busbar. As an example, PV busbar's voltage and current waveforms are given in Fig. 18.

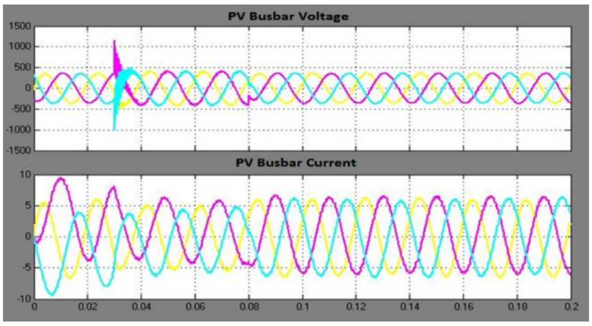


Figure 18. PV busbar voltage and current waveforms

7. Power Flow Analysis for Grid Connected Mode of Operation

Power flow analysis of micro grid is performed by using Table 7 values for grid connected mode of operation. Analysis is performed under fault conditions to determine the validity of online ANN design. Analysis results are given in Table 8. Voltage and current waveforms of PV busbar at fault duration is given in Fig. 19 for comparison.

Table 7. Properties Of Sources And Loads For Grid Connected Mode Of Operation

System Component	Connected Busbar	Power
Main Grid	PEM Busbar	35000 VA
PV System	PV Busbar	2000 W
WES	WES Busbar	3000 VA
PEM	PEM Busbar	500 W
Micro Turbine	Micro Turbine Busbar	10000 W
Load 1	PV Busbar	2000 W, 600 VAR
Load 2	HES Busbar	12000 W
Load 3	RES Busbar	6000 W
Load 4	Load Busbar	12000 W
Load 5	Load Busbar	8000 W
Load 6	Load Busbar	10000 W

Table 8. ANN Based Power Flow Analysis Results

BUSBAR	Beginning of Fault		Middle of Fault		End of Fault	
	Amp	Angle	Amp	Angle	Amp	Angle
PV	0.9388	-1.1462	0.9313	-1.1210	0.9463	-1.1613
Micro Hyd.	1.3619	-2.2216	1.3626	-2.2193	0.9401	-1.1723
PEM	0.9407	-1.1397	0.9379	-1.1334	0.9408	-1.1381
WES	0.9495	-1.1154	0.9486	-1.1124	0.9496	-1.1143
Load	0.9554	-1.1847	0.9532	-1.1798	0.9579	-1.1922

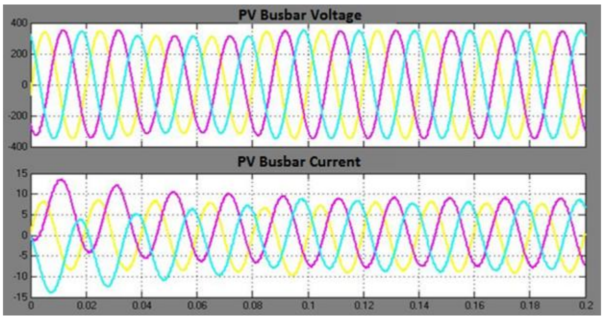


Figure 19. PV busbar voltage and current waveforms during micro turbine busbar fault

It should be noted that fault scenario is based on a fault at micro hydro power plant busbar. As this busbar includes a generating unit, voltage value can be measured from this busbar although the current value is zero. Waveforms are appropriate by power flow analysis results and this prove the ANN based power flow analysis method works properly.

8. Conclusion

In this paper, a novel power flow analysis method, which is a vital analysis for design of microgrids that consist of renewable energy sources is proposed. Performing the power flow analysis without necessity of iterations is the major advantage of proposed method. ANN is used instead of iterative methods and allows online power flow analysis. Also proposed method allows faster power flow analysis for grids which particularly consist of distributed generation units and number of busbars. It is tested on some cases; islanded mode and normal operation, islanded mode with fault and grid-connected mode with fault. Results show that proposed algorithm works properly. Proposed method differ from conventional power flow analysis methods with its ability to analyze system without an assigned slack busbar. This situation plays a vital role to keep power system planners from wrong estimation of initial conditions.

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