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Published (to be published) in: Tehran, Iran. Conf. on Smart Electric Grids Technology (SEGT2012)

(Expected) publication date: 2012

Conference on
Smart Electric Grids Technology (SEGT2012)
18-19 December 2012
Iran University of Science and Technology, Tehran, Iran
www.segt.org

Application of Neuro-Fuzzy Controller on Voltage and Frequency Stability in Islanded Microgrids

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Abstract: *This paper presents a new droop control strategy based on neuro-fuzzy technique to minimize voltage and frequency deviations in islanded microgrids (MGs) under severe changes in load. In islanded MGs, due to lack of the backup power, the imbalance between consumption and generation usually leads to violent voltage/frequency fluctuations. Therefore, designing a reliable control structure to prevent the MG instability is needed. The proposed control strategy is designed to maintain the system stability and minimize the voltage/frequency fluctuations regardless of the MG structure. The most important advantage of the proposed controller is independency from the MG structure and operating conditions. The simulation results show the appropriate operation and efficacy of the proposed controller in the presence of severe changes in load.*

Keywords: Microgrid, Distributed Generation, Islanded mode, Droop characteristics, ANFIS, System Stability.

1. Introduction

Nowadays, extensive changes are happening in distribution systems area. Penetration of small renewable energy sources (RESs) such as solar cells, fuel cells is rapidly increased in the distribution levels. This increase leads to making a new structure called Microgrid (MG) [1]. In the last decade, distribution systems have been considered as dependent and passive systems, since their existence was depended on the transmission systems. After appearance of the MGs, distribution systems have been changed to the systems with two aspects: generating and consuming power [2]. The MGs must be able to operate in both connected and disconnected modes, and continue supplying local loads in both modes [3].

A MG is formed by several small power generation sources which their task is supplying power to local loads [4]. In critical places such as industrial buildings and hospitals that generally have a low inertia and their consumption power is less than 1MW, the existence of a backup generation is necessary at blackout times. If the generated power cannot be delivered to the consumer with an appropriate quality for any reason, the protection systems is activated, and the MG is separated from the distribution system, and tries to supply the power of critical and non-critical local loads autonomously [5, 6]. In the islanded operation, the main task of MGs is maintaining the power quality in critical loads. Therefore, the islanded MG is responsible to provide voltage and frequency stability, as well as active and reactive power balance.

The MGs in spite of many advantages such as, reducing the environmental problems, reducing costs of constructing a new power plant, increasing system reliability, increasing efficiency by reducing power transmission losses, reducing load aggregation in distribution feeders, cause some new problems in the power system such as changing of the power flow pattern, increasing high frequency harmonics due to using power electronic devices; and increasing of frequency and voltage fluctuations [6, 7].

A distributed generation (DG) can be micro-turbine, photovoltaic cell, and fuel cell, wind generator, along with energy storage devices such as flywheels, energy capacitors and batteries [8, 9]. There are two main groups of DGs. First group includes DC sources such as solar and fuel cells and the other covers the high frequency AC sources such as microturbines that need rectifying. In both groups, the resultant DC voltage should be converted to an acceptable AC voltage [4]. IEEE STD1547-2003 standard expresses technical requirements to connect distributed generation units to the power system [10]. The DGs capacity are not so much, and do not have significant effects on the main grid. However, due to their increasing penetration on the power networks in future, these effects will be significant [6]. The local DGs have some benefits such as, low cost for consumer and producer, low voltage, high reliability, increasing redundancy and robustness of system and high flexibility [4].

A general structure of MG is shown in Fig. 1. The MG can be connected to the main grid at the point of common coupling (PCC); the DG units can have any arbitrary configuration, but each DG unit is usually interfaced to the MG through a power electronic converter, at the point of coupling (POC) [1].

Disconnecting of a MG from the main grid in stable state and without any problems for consumers is one of the challenges towards the MG designers. Hence, control of the microsources especially in the islanded mode is an important issue to design these systems, so that the resources should control the system voltage and frequency and share the loads among each other. Thus, the MGs should be capable of managing rapid changes of the power and frequency that occur in the network, even when the generated power is less than the power required by consumers. To achieve this goal and control the important network parameters such as voltage and frequency, several central and local controllers are required.

In [11], a droop control method named generalized droop control with a different structure from the previous works is presented. In the generalized droop method, the frequency and voltage is controlled under the severe changes in loads, simultaneously. In other words, both the active and reactive powers are used for voltage/frequency droop control.

In this paper, a simultaneous droop control by the Neuro-Fuzzy technique is proposed to stabilize the voltage and frequency of the islanded MGs. The generalized droop control structure is modeled by the neuro-nuzzy method and is trained to simulating the dynamic generalized droop control behavior regardless the MG structure and its DGs. The Simulation results by MATLAB and the defined indexes towards the control structure validity express the high accuracy of the trained model. Final results show high performance of the proposed method under the severe changes in loads.

2. Coordination between Voltage and Frequency Control

Different classifications for MGs are defined. These classifications can be based on capacity, voltage level, load sensitivity, control method and etc. Nonetheless, another classification is defined based on the structure MGs and how to connect between generation and consumption. The DGs are connected to the local loads by the lines. The lines can be resistive or inductive. Hence, the MGs are divided into resistive MGs and inductive MGs. In the inductive MGs, active power-frequency (P/f) and reactive power-voltage (Q/V) droop characteristics and in the resistive MGs active power-voltage (P/V) and reactive power-frequency (Q/f) droop characteristics are used [12-25]. For example, P/f and Q/V characteristics are shown in Fig. 2. However, if the resistivity and inductivity of MG lines do not have significant difference with each other, the above mentioned methods do not have required accurate performance.

In [11], a control structure for coordination between voltage and frequency regulation based on droop control is presented. The participation percentage of the active and reactive power in the voltage/frequency droop control has been determined by the lines inductivity/resistivity index. Index K_R has been presented to determine the lines inductivity or resistivity. The generalized droop control structure is shown in Fig. 3. The load changes effect on the voltage and frequency simultaneously. The main problem of this method is dependency on the line parameters. So that, in MGs including several DG units and loads, due to the existence of several lines in the system, the virtual line parameters should be used. Then, for optimal estimation of these parameters, evolutionary algorithms such as particle swarm optimization (PSO) can be used. Evolutionary algorithms can be efficient for optimal estimation of line parameters needed in generalized droop control method.

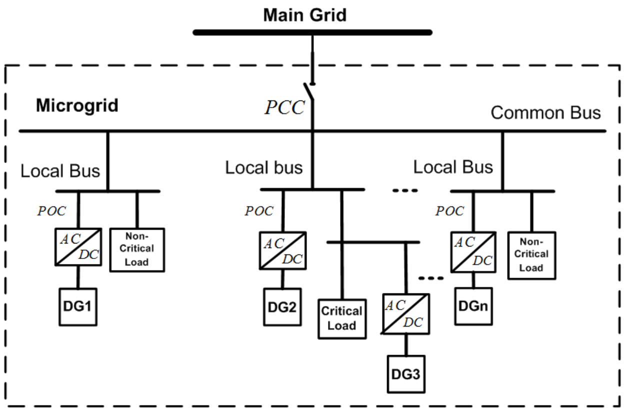

Fig. 1: Typical structure of a MG

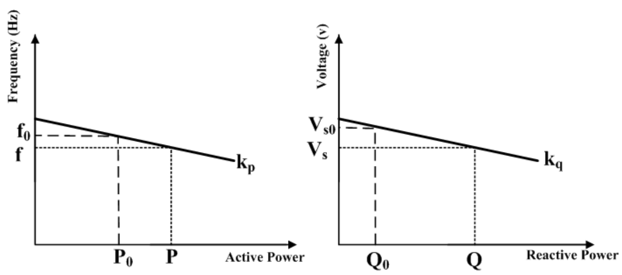

Fig. 2: Characteristic curve of the inductive MGs

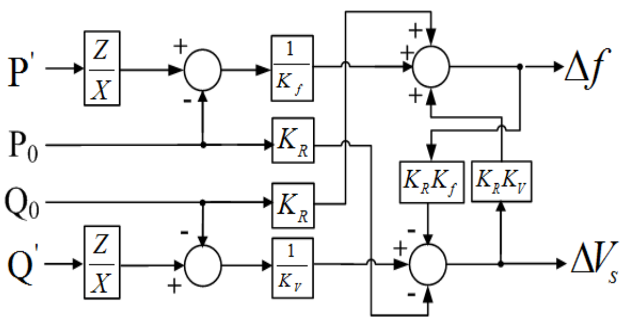

Fig. 3: Block diagram of generalized droop control method [11]

But if the MG scales is adequately large, the number of parameters, calculation time and also the possibility of stranding evolutionary algorithm in the local minimum is more. Here, to solve this problem, the adaptive neuro-fuzzy inference system (ANFIS) is used instead of the generalized droop control with same accuracy and also without dependency to the MG structure.

3. Neuro-Fuzzy Technique

Artificial neural network (ANN) is one of the intelligent algorithms that can be used in both identification and control. The neural networks have the ability to learn systems behaviors. In non-linear systems can be used to diagnose the accurate systems behaviors. Recently, ANNs, due to their ability in accurate estimation of the non-linear systems behavior, is being used to identify non-linear dynamic systems [26].

Fuzzy logic (FL) is a useful tool in control engineering, which can be used to control the variable parameters in the real-time systems [27]. Combining FL and ANNs leads to useful and valuable results. ANNs can be trained by data, but the FL has no ability for training [26]. In the early 90s, Jang [28] combined these two methods.

Adding the training ability of ANN to FL creates a new hybrid technique, known as ANFIS [26]. ANFIS sets an adaptive modelling procedure to memorize data set information. It produces an appropriate input/output (I/O) mapping with membership functions (MFs) based on fuzzy if-then rules to generate the I/O pairs. The MFs parameters can be changed through the learning process. To adjust these parameters, the back-propagation (BP) or hybrid learning algorithm can be implemented.

The ANFIS is a technique based on data processing. Therefore, to guarantee ANFIS controller performance, the I/O data must be involved the vast operational range. Otherwise, the designed controller will not be accurate. Design process of an ANFIS controller consists of two steps: constructing and training. In the constructing step, type and number of I/O MFs is determined. Several MFs such as Gaussian and triangular can be used as input MF. Number of input MFs can be chosen as 3, 5, and so on. Selecting proper number of input MFs decreases the rule number and increases the learning speed. Output MFs can be chosen as a constant or in linear form.

After the constructing step, learning algorithm and training parameters are selected. To determine the parameters, BP algorithm is used in this study. In this algorithm, the network output is compared with the desired output. The obtained error is used to update weights in order to reduce the error. After several training epochs, the final network error is expected to be reduced to an acceptable value. Then, the ANFIS has learned how to solve the problem by training data.

In this method, the fuzzy rules correction is possible when the system is being trained, and by setting the ANN appropriately, does not require any previous knowledge about the MFs and rules, and the optimum MFs are sufficient for obtaining the I/O data. The configuration of MFs depends on their parameters. The ANFIS selects these parameters automatically, and does not need a human to obtain these parameters, as a fuzzy inference system (FIS) is built by using the appropriate I/O data, which the parameters of MF are set by means of a back-propagation (BP) algorithm and the least square error (LSE) [29].

Typical structure of an ANFIS with five layers is shown in the Fig. 4. This network is equivalent to Sugeno fuzzy inference system [29]. In the first layer, which is known as MF layer, MFs Weights are analyzed. In this layer, the input variables are applied to obtain the fuzzy sets proportional to the inputs variables. The second layer output is the multiplication of the input signals. The input signals are equivalent to the IF parts of rules. In the third layer, which is known as rule base layer, the activity level of each rule is calculated. The number on layers is equal to the number of fuzzy rules. This layer output is a normalized form of the previous layer. The forth layer produces the output values. This layer is known as the defuzzification layer. Finally, the ANFIS output is obtained from the output layer.

4. ANFIS Controller Design

If the ANFIS trains properly, it can be useful in control applications. Therefore, to design the ANFIS controller, first the generalized droop control structure, which is used in the simplest MG (Fig. 5), should be modeled by the ANFIS. Then after ensuring about the model validity, the modeled ANFIS could be used instead of equivalent block diagram shown in Fig. 4. In designing and testing the ANFIS controller, the fuzzy logic toolbox of MATLAB is used [30]. Design steps can be summarized as follows:

1. By applying and testing the generalized droop control on the system shown in Fig. 5, and saving the controller inputs/outputs, the training data to synthesis the ANFIS controller are collected. To obtain an accurate model, the training data under violent changes of active and reactive loads are considered.
2. After obtaining the training data set, the ANFIS structure to be formed. MFs of input and output are considered as linear form and Gaussian functions.

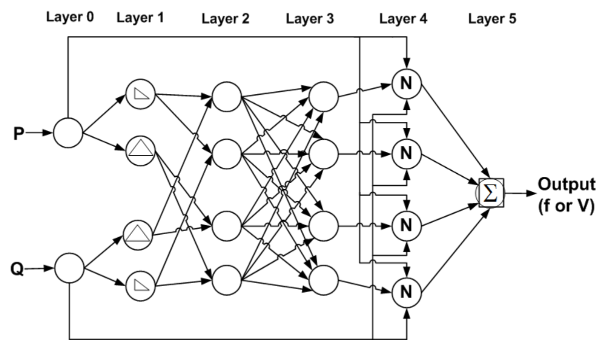

Fig. 4: Overall construction of an ANFIS

3. After creating the controller structure, using the optimal hybrid method (combination of LSE and BP), the ANFIS is trained for 5 epochs (iterations) with a small error tolerance about 0.00001ms. Total output of the system is determined using the Sugeno FIS by means of combining the output of all rules.

4.1 Validity Examination

After designing the ANFIS controller, the model validity should be investigated in view point of dynamic behavior similarity to the generalized droop controller. For this purpose, the I/O data set of $K_R=1$ is used for training the ANFIS. As shown in Fig. 3, the generalized droop control consists of two inputs and two outputs that are active/reactive power and frequency/voltage amplitude, respectively.

Since the ANFIS is a multi-input-single-output (MISO) system, two ANFIS structures should be separately used for two outputs of frequency and voltage outputs. These controllers including two inputs and one output are shown in Fig. 6. Since, it is expected that the designed ANFIS controllers should simulate the generalized droop control behaviour as far as possible; the input data (active and reactive power) should include a wide range of load changes.

After generating the I/O data set and applying to the MATLAB ANFIS toolbox, the ANFIS models are trained. Due to the high switching frequency of inverter (4000 Hz), the sampling time is considered as 100000 samples per second until the ANFIS controllers could be able to simulate the system behavior, accurately.

To evaluate the designed ANFIS performance, both real and training data sets are considered as the test data. The real and training data are compared together. Fig. 7 shows the ANFIS network outputs versus the real outputs. Also, in Fig. 8, both data sets are drawn together. Comparing real and network data shows that the training process is accurately done, and the ANFIS controllers have effectively simulated the system behavior.

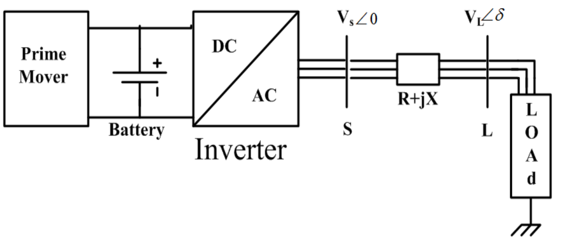

Fig. 5: A simple MG

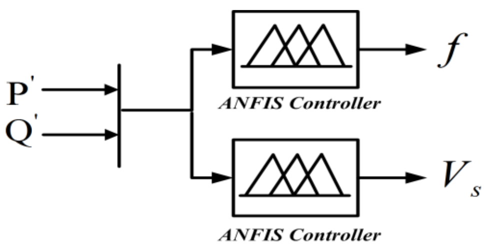

Fig. 6: The inputs and outputs of the designed ANFIS controller

Now, as shown in Fig. 9, the two ANFIS trained controllers are replaced with the generalized droop control. Then, under the violent changes of active and reactive loads, the system voltage and frequency are compared to the previous structure. The active and reactive power changes are considered as shown in Fig. 10. Fig. 11 shows that the high validity of the ANFIS controllers.

4.2 Applying the controller to the system

The designed ANFIS controller has some benefits such as lack of necessity to the line parameters, independency to the MG structure and operating conditions. According to the above mentioned benefits of ANFIS, the controller is experimented (Fig. 12) on the second test system [11] and their results are compared with the obtained results from the PSO. The active and reactive load changes are shown in Table I. The system response including voltage and frequency profiles is shown in Fig. 13. Fig. 13 shows that the steady state voltage and frequency are normal. As regards in the proposed control structure, only primary control (droop control) is applied and secondary control loop of voltage and frequency is not considered, existence of a steady state error for voltage and frequency seems reasonable. Therefore, returning frequency to nominal value is one of the presented control methodology advantages and lack of returning voltage to primary value after load change is not disadvantage and is customary. But with adding a secondary voltage control loop to suggested VSI control, the voltage steady state error can be returned to nominal value after a load change.

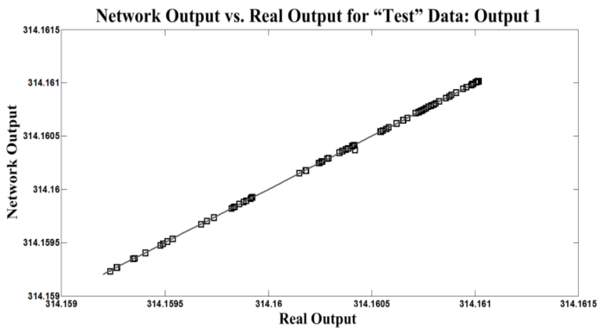

Fig. 7: Trained network output versus real output

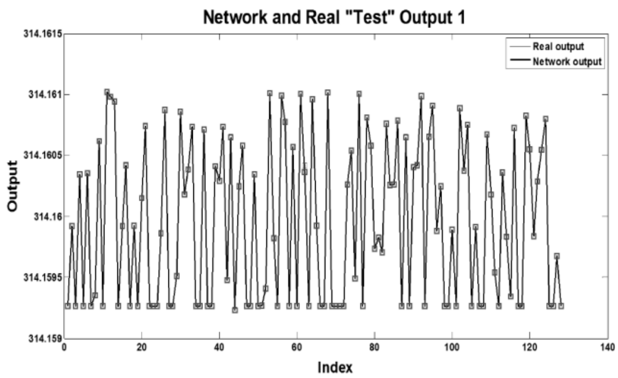

Fig. 8: Trained network output and real output together

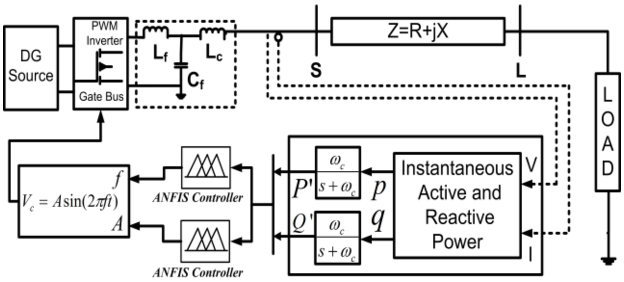

Fig. 9: Control structure of VSI inverter, presented in [11], by replacing the ANFIS controller with generalized droop control

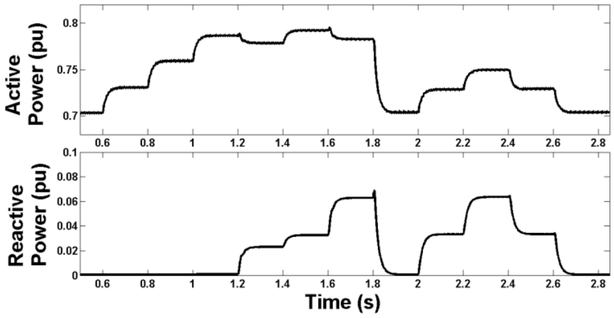

Fig. 10: Changing of the active and reactive power

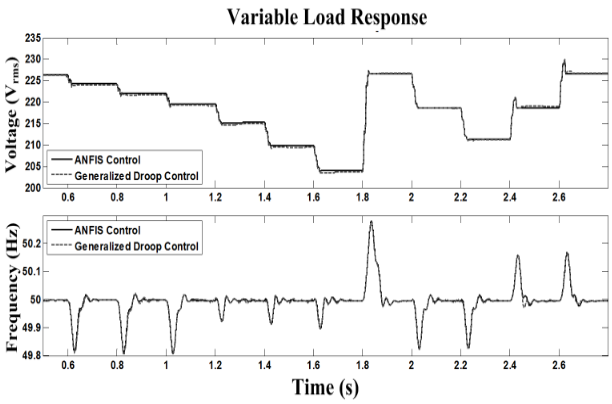

Fig. 11: Voltage and frequency under the violent changes of the load

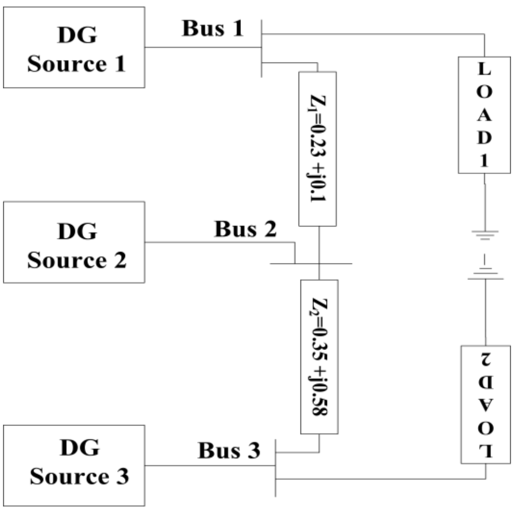

Fig. 12: Test case 2: a MG with three DGs and two load banks

TABLE I: load change scenario

Time Duration[s]	Load 1[kVA]	Load 2 [kVA]
0-0.3	30	10
0.3-0.5	30	j40
0.5-0.7	30 +j10	10
0.7-0.9	30	j10
0.9-1.1	0	10
1.1-1.3	30	10

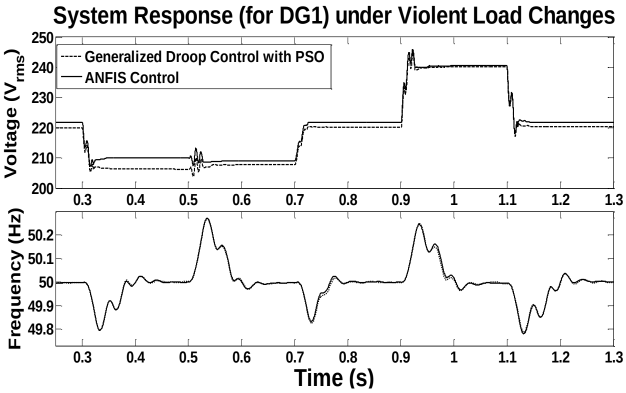

Fig. 13: Voltage and frequency profile under violent load changes.

5. Conclusion

In this Paper, a new droop control structure based on the adaptive neuro-fuzzy inference system has been presented. Basis of this controller is coordination between voltage and frequency control in the MGs under severe changes in loads. This controller has been trained by the desired input and output data set, and has capable to apply to islanded MGs, and under the different working conditions can keep system, and prevents the voltage and frequency collapse.

Acknowledgements

The authors would like to thank Iranian Oil Pipelines and Telecommunications Company (IOPTC) and University of Kurdistan (UOK) to support this research work.

References

[1] H. Bevrani, and T. Hiyama, *Intelligent Automatic Generation Control*, 1st ed. New York: CRC Press, 2011.

[2] J. Driesen, G. Deconinck, W. D'haeseleer, and R. Belmans, "Active User Participation in Energy Markets Through Activation of Distributed Energy Resources,'' , *IEEE Power Engineering Society general Meeting*, pp. 1-4, 2007.

[3] R. H. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A. Meliopoulous, and R. J. Yinger, "The CERTS Microgrid Concept," *White paper for transmission reliability program, Office of Power Technologies, U.S. Dept. Energy*, Apr. 2002.

[4] R. H. Lasseter, "Microgrids," in proc. *IEEE PES'02 Winter Meeting, 2002, Power Engineering Society Winter Meeting*, pp. 305- 308, 2002.

[5] F. Katiraei, M. R. Iravani, P. W. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *IEEE Trans. Power Del*., vol. 20, no. 1, pp. 248-257, Jan. 2005.

[6] A. A. Salam, A. Mohamed, and M. A. Hannan, "Technical challenges on Microgrids," *Asian Research Publishing Network (ARPN)*, vol. 3, no. 6, pp. 64-69, Dec. 2008.

[7] S. Diaf, G. Notton, M. Belhamel, M. Haddadi, and A. Louche, "Design and techno-economical optimization for hybrid PV/wind system under various metrological conditions," *Applied energy 85*, pp. 968-987, 2008.

[8] T. Ackermann, G. Andersson, and L. Soder, "Distributed generation: a definition," *International Journal of ElectricPower Systems Research*., vol. 57, no. 3, pp. 195-204, 2001.

[9] H. Bevrani, A. Ghosh, and G. Ledwich, "Renewable energy resources and frequency regulation: survey and new perspectives," *IET Renewable Power Generation*., pp.438-457, 2009.

[10] *IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems*, IEEE Std 1547-2003, 2003, pp. 0_1-16.

[11] S. Shokoohi, J. Moshtagh, and H. Bevrani, "Transient Stability Enhancement in Microgrids with Iinverter-based DGs (in Persian)," *2nd Iranian Conf. Smart Grids-ICSG 2012*, [online] Available: http://www.bevrani.com/ICSG.pdf, Tehran, Iran, 2012.

[12] M. C. Chandorkar, D. M. Divan, and R. Adapa, "Control of parallel connected inverters in standalone ac supply systems," *IEEE Trans. Industrial Applications.*, vol. 29, no. 1, pp. 136-143, Jan/Feb. 1993.

[13] Yun Wei Li and Ching-Nan Kao, "An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid," *IEEE Trans. Power Electronics*, vol. 24, no. 12, pp. 2977-2988, Dec. 2009.

[14] J. M. Guerrero, L. G. de Vicuna, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," *IEEE Trans. Power Electronics*, vol. 19, no. 5, pp. 1205- 1213, Sept. 2004.

[15] H. Laaksonen, P. Saari, and R. Komulainen, "Voltage and frequency control of inverter based weak LV network microgrid," *Int. Conf. Future Power Systems*, vol., no., pp.6 pp.-6, 18-18 Nov. 2005.

[16] A. Engler, O. Osika, M. Barnes, and N. Hatziargyriou, *DB2 evaluation of the local controller strategies*, [Online] Available: www.microgrids.eu-/micro2000 , 2005.

[17] R. Lasseter, and P. Paigi, "Microgrid: a conceptual solution," *PESC'04, IEEE conf*. vol.6, no., pp. 4285- 4290, 20-25 June. 2004.

[18] J. M. Guerrero, J. Matas, L. G. de Vicuna, M. Castilla, and J. Miret, "Wireless-control strategy for parallel operation of distributed-generation inverters," *IEEE Trans. Industrial Electronics*, vol. 53, no. 5, pp. 1461-1470, Oct. 2006.

[19] T. L. Vandoorn, B. Renders, L. Degroote, B. Meersman, and L. Vandevelde, "Active load control in islanded microgrids based on the grid voltage," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 139-151, March. 2011.

[20] R. Majmuder, "Modeling, stability, analysis and control of microgrid," *Ph.D. Thesis*, Queensland University of Technology, Queensland, Australia, 2010.

[21] E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo, and T. C. Green, "Energy management in autonomous microgrid using stability-constrained droop control of inverters," *IEEE Trans. Power Electronics*, vol. 23, no. 5, pp. 2346-2352, Sept. 2008.

[22] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical control of droop-controlled ac and dc microgrids—a general approach toward standardization," *IEEE Trans. Industrial Electronics*, vol. 58, no. 1, pp. 158-172, Jan. 2011.

[23] G. Diaz, C. Gonzalez-Moran, J. Gomez-Aleixandre, and A. Diez, "Scheduling of droop coefficients for frequency and voltage regulation in isolated microgrids," *IEEE Trans. Power Systems*, vol. 25, no. 1, pp. 489-496, Feb. 2010.

[24] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen, and R. Belmans, "A voltage and frequency droop control method for parallel inverters," *IEEE Trans. Power Electronics*, vol. 22, no. 4, pp. 1107-1115, July. 2007.

[25] T. L. Vandoorn, B. Meersman, L. Degroote, B. Renders, and L. Vandevelde, "A control strategy for islanded microgrids with dc-link voltage control," *IEEE Trans. Power Delivery*, vol. 26, no. 2, pp. 703-713, April. 2011.

[26] F. Rashidi, "Sensorless speed control of induction motor derives using a robust and adaptive neuro-fuzzy based intelligent controller," *IEEE International Conference an Industrial Technology (ICIT)*, PP. 617-627, 2004.

[27] A. Kusagur, S. F. Kodad, and B. V. Sankar Ram, "Modeling, design & simulation of an adaptive neuro-fuzzy inference system (ANFIS) for speed control of induction motor," *International Journal of Computer Applications*, vol. 6, no. 12, pp. 29-44, Sept. 2010.

[28] J. Roger Jang, "ANFIS: adaptive-network-based fuzzy inference system," *IEEE Trans. Systems*, Man, and Cybernetics, vol. 23, no. 3, pp. 665- 685, May/June. 1993.

[29] L. Wang, C. Singh, and A. Kusiak, *Wind power systems, applications of computational intelligencel*, New York: Springer, 2010.

[30] MATLAB/SIMULINK^{TM}**,** [online] Available: http://www.mathworks.com