Proposing an Artificial Neural Network Based Controller for a Stand-Alone MicroGrid

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Abstract— **This paper is concerned with the generation control in small stand-alone MicroGrids consisting of inverter interfaced Distributed Generation (DG) units. An intelligent and on-line Microgrid Management System (MGMS) using Artificial Neural Network (ANN) controller is proposed in this study for MicroGrid control. It determines the amount of power produced from generation units in a stand-alone MicroGrid. The ANN trained with a data generated from a Genetic Algorithm (GA) solved optimal power flow problem, which defines generation unit's power in order to have a minimum power loss in the system, considering normal buses voltage and rating of generation units.**

Keywords-MicroGrid, State Estimation, Genetic Algorithm, Artificial Neural Network, Load Sharing, Distributed Generation

I. INTRODUCTION

Nowadays environmental concerns, electricity market liberalization, the need to decrease CO2 emission and climatic change as well as fuel price and availability have been motivating the interconnection of small modular generations like photovoltaic arrays, Fuel Cells, Microturbines, small wind generators and storage devices into LV distribution network [1]- [3]. This new type of generation cause development of MicroGrids which are predicted to play an important role in future power systems. A Microgrid (MG) can be a flexible section of the power system if it is controlled through management and control systems in generation units and loads [4]-[6].

The main challenge in an islanded MicroGrid, which is caused after a fault or preplanned utility outage, is coordination of the numerous generators for sharing power output and control of system frequency and voltage. In [7]-[10] a concept has been developed and improved using "reactive power/voltage" and "active power/frequency" droops for the power control of the inverters similar to conventional power systems. The main advantage of this method is that it uses local variables for controlling the generation units. However, as frequency will deviate after any load change a secondary control loop is needed for stable and accurate frequency controls. In addition, load sharing between generation units will not be performed in order to have optimal condition in the network and maintain all constraints in the system.

In order to increase penetration level of DG units and to facilitate flexible planning and operation of distribution system, interconnected systems with large amount of DG units require on-line and intelligent system control tools as stated in [11]. These tools should be able to make prediction of electrical system dynamic behavior following the occurrence of disturbances or changes in power production, and based on these predictions, it provides optimal and proper control signal to generation units and preventive control actions if undesired conditions are detected like AGC operation in conventional power system. Since optimization is a time consuming process and cannot be used on-line, an Artificial Neural Network (ANN) based approach can be designed to emulate a set of optimized condition following a disturbance that provokes the system state and applies in on-line control. In this paper, according to any change and load demands, optimal control signals will be generated with Genetic Algorithm (GA) and then the ANN system will be trained with these data and finally manages the islanded Microgrid in optimal, accurate, and on-line condition.

II. MICROGRID MANAGEMENT SYSTEM (MGMS)

Active management is a form of centralized control for distribution networks and is proposed as a mean of enhancing connectable capacity [11]. Taking a similar approach to that used in conventional power systems, a distribution management system controller would be used for wide area voltage and frequency control and also active and reactive power management.

Three control levels are suggested for a distribution system consisting of several MicroGrids [11]-[14] as seen in Figure 1 :

- Distribution Management System (DMS) and Market Operator (MO) at the level of the Medium Voltage that are responsible for the technical and economical operation in a medium and low voltage area.
- MicroGrid Management System (MGMS) at any MicroGrid systems which control and manage individual MicroGrid in the system.
- Local Controllers (LC), those which exist in some controllable part of the distribution system in order to firstly avoid abnormal condition and fault for each equipment and secondly to performe control commands which come from MGMS.

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The main and critical equipments used in this structure are communication devices among all levels of controller. With recent advances in the filed of communication technology, using this structure is applicable and the connection can be reliable enough. Also there are several projects all around the world investigating the practical and technical issues of applying the active management to distribution networks [14]-[17].

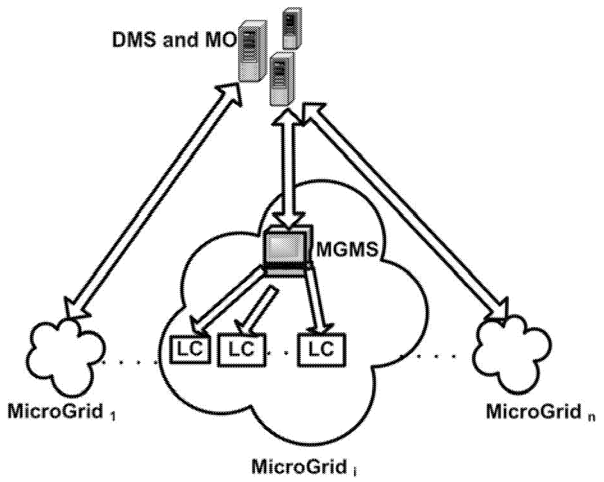

Figure 1: Active Management Scheme for a Distribution Network

This energy management system has been developed by several companies and implemented in some European countries such as Germany and Spain [15], [16] and it seems that in near future this system will take place in all distribution networks. Figure 2 shows a possible structure for the MGMS.

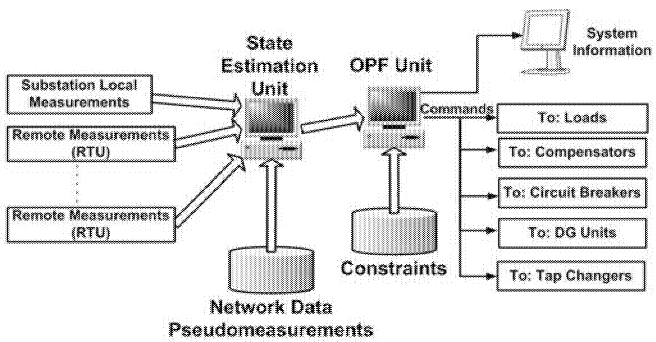

Figure 2: Structure of MGMS

In MicroGrid designs, special consideration should be given to the MGMS. This MGMS uses the information based on local electrical and thermal needs, power quality requirements, electricity and fuel costs, etc to compute the amount of produced power for each Distributed Generation (DG) units and control commands for other controllable components.

The ultimate goal of this paper is to propose a control strategy for stand-alone MicroGrid in order to cause its normal and optimal operation. So any equipment in the system should have a controller and the coordination among all parts and managing the system is performed with MGMS. Following subsections focuses on discussion and modeling of different parts of MGMS in an island mode of operation.

A. State Estimation Unit

Today with the development of automation in Distribution systems, SCADA (Supervisory Control And Data Acquisition) has been installed on the distribution system which can measure the voltage magnitude, active power, reactive power and other values at a certain node or line. SCADA can transmit all this data back to the control center [18], [19].

In modern distribution system, state estimation (SE) plays a critical role in estimating the real-time system states that are unable to be obtained from the limited and sometime unreliable measuring instruments at the distribution system level. Moreover, distribution systems have huge number of nodes and pseudo measurements are used for distribution system state estimators. The load modeling procedure can provide estimates of real-time customer load profiles, which can be treated as the pseudo measurements for state estimation [19], [20].

The algorithm used in this paper is based on classical power system state estimator algorithms that use weighted least squares formulation [19], [20] of equation (1).

$$Min \quad J(x) = \sum_{i=1}^{M} \frac{[z_i - h_i(x)]^2}{\sigma_i^2} \tag{1}$$

where:

x: vector containing all the state variables (Buses voltages amplitude and angle)
M: Number of real measurements and pseudo-measurements
zi: Measured value of measurement i
hi: Expression of the measurements in function of state variables
σi: variance of the distribution of measurement i
The functions h are not linear, and it is necessary to apply Newton's iterative technique. More precisely, the gradient of J(x) is calculated and then forced to zero using Newton's method. This will lead to the following equation to be solved iteratively:

$$\begin{aligned} x_{k+1} &= x_k + G(x_k)H^T(x_k)W[z - h(x_k)] \\ G(x_k) &= [H^T(x_k)WH(x_k)]^{-1} \\ H(x) &= \frac{\partial h(x)}{\partial x} \end{aligned} \tag{2}$$

The State Estimation (SE) unit uses real time measurements from the system,pseudo measurements and system configurations such as switch status, and then calculate the current state of the system. The state estimation unit output is all buses voltage, values of load demand, power loss, generation level, and lines power [20].

B. Optimal Power Flow unit

The aim of this unit is to determine each DG unit's values of generation in order to have optimal operation and also normal voltage in all buses, normal current in lines, considering inverter's rating, considering DG unit rating and time delay for responding to changed parameter.

In this study the OPF unit in modeled as a problem of finding each DG units active and reactive power in order to minimize active power loss of the system with constraints of normal voltage magnitude, DG units rating, and lines power rating. The problem formulation is as equation (3).

$$Minimize \quad P_{Loss} = f(|v|, \delta)$$

Subject to:

$$\begin{aligned} &Load\ Flow\ Equation\ (it\ mean \sum_{i=1}^{ngen} P_{G_i} = \sum_{i=1}^{nload} P_{D_i} + P_{Loss}) \\ &V_i^{\min} \le V_i \le V_i^{\max} \quad for\ i = 1\ to\ no.\ of\ Buses \\ &P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad for\ i = 1\ to\ no.\ of\ DG\ units \\ &Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad for\ i = 1\ to\ no.\ of\ DG\ units \\ &S_{Line-i} < S_{Max-i} \quad for\ i = 1\ to\ no.\ of\ Lines \end{aligned} \tag{3}$$

In this equation the power loss (P_{Loss}) in the system can be found as a function of voltages magnitude ($|v|$) and angle (δ) which is derived in appendix A1. Also P_G and Q_G are output active and reactive power of the generation units, P_D is demand of loads, V_i is bus voltage and S_{Line} is distribution line apparent power.

An efficient and accurate solution to this problem depends not only on the size of the problem in terms of the number of constraints and design variables, but also on characteristics of the objective function and constraints. Since this problem has nonlinear objective function and constraints, Genetic Algorithm (GA) is suitable for off-line optimization of the function and is used in this study.

C. Local Controller (LC) of Interface Inverters

In a MicroGrid the local controller can be active and reactive power control of the DG units, tap position of the transformers, status of circuit breakers, amount of reactive power compensation and also command for load shedding in controllable loads. This study focuses only on DG units that connect to MG with an inverter and other controllable equipments are not considered. Also the type and dynamic of generation unit which can be Fuel cell, wind turbine, photovoltaic array,… have effect on the system's performance. In this paper the generation units with its DC-DC converter and storage is considered as a constant DC source. Therefore with this assumption the main factor is interfaced inverter control and is described in this section.

The active and reactive power which is supplied by DG unit can be controlled independently with parameter of the interfaced inverter. PQ mode (which inverter injects reference values of active and reactive power to system) and Vf mode (which inverter produce voltage with desired magnitude and frequency) are the common schemes which are applied for inverter interfaced DG units [7]-[10], [22].

III. OPTIMIZATION WITH GENETIC ALGORITHM

Genetic Algorithm (GA) as a powerful and broadly applicable stochastic search and optimization techniques is perhaps the most widely known types of evolutionary computation methods in many complex optimization problems nowadays.

Genetic Algorithm (GA) solves optimization problems by exploitation of random search. When searching a large space, GA may offer significant benefits over the traditional optimization techniques such as (i) work on encoding of control variables rather than variables themselves, (ii) search from one population of solution to another rather than from individual to individual, and (iii) use only objective functions, not derivatives; hence they are derivative free optimization techniques, and they don't rely on the detailed model of the system to be optimized [21]. Figure 3 shows flowchart of optimization process with GA.

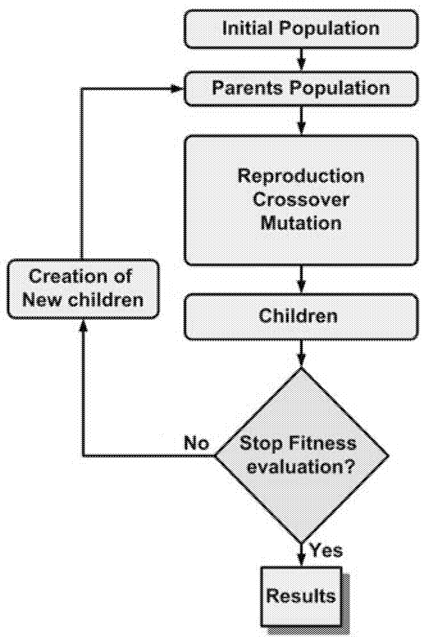

Figure 3: Optimization procedure with Genetic Algorithm

GA starts with random creating the initial population of binary strings called chromosomes. Each chromosome represents a possible solution to the optimization problem which is evaluated according to the fitness function. GA performs following operations to create a new generation:

- Reproduction: Reproduction creates new generations of chromosomes
- Crossover: Crossover allows information to be exchanged among individuals in the population. Two parent strings are selected randomly, and a new child string is created by combining random sub-string from two parent strings.
- Mutation: Mutation is random alteration of bits in a string that flips a bit from 1 to 0 or vice versa.

By the end of mutation, the new generation is completed and the process is repeated for evaluation of new fitness untill the optimized solution gained..

In this study, GA is used to optimize the active and reactive power set points of DG units in the system with the goal of minimizing the power loss (Fitness Function) and satisfying system constraints. Therefore any chromosome is defined as Figure 4 consists of active and reactive output power of DG units.

$P_{DG\,1}$	$Q_{DG\,1}$	…	$P_{DG\,m}$	$Q_{DG\,m}$

Figure 4: Structure of used chromosomes

As the digital coding is used in chromosome, the values of powers are normalized according to their maximum and minimum and then convert to string of 0 and 1. Finally after optimization real power can be obtained according to nominal values.

In this paper, fitness proportionate reproduction is achieved through roulette wheel selection. Fitness is 1/PLoss which is defined in equation (3). Also Two cut-point crossover with Mutation Probability o.2 percent is used for each chromosome. Two cut-point crossover is employed to prevent local optimal solutions.

IV. NEURAL NETWORK BASED MGMS (NN-MGMS)

The optimal operation of a MicroGrid with an MGMS has been recently achieved by using Economic Dispatch which is a well-known technique for solving the optimal scheduling of generation. But it is not easily adoptable for on-line applications due to variable nature of loads, distributed generation units, and also computational time requirement [23].

The main contribution in this study is to propose a strategy to manage an islanded MicroGrid with variable loads and generation units in an on-line and optimal situation. For this aim the controller response to any change in an on-line, quich and optimal manner by using an ANN based decision center. The approch have many advantages in comparision to the method explained in introduction. This method can manage a MG in any situation in an on-line and optimal condition (Minimum loss) while satisfying the system limit (buses voltage, lines currents, generation units rating,…).

The NN based MGMS is designed according to the following steps in this study.

A. Stand-Alone MicroGrid Control Strategy

In a stand-alone distribution network, there are two major problems. The former is the presence of some low response and inertia-less generation units which necessitates putting some storage devices on dc link to realize fast load tracking. The latter is the lack of frequency and voltage reference and so one or perhaps more than one of the DG units should play such a role and be a reference for voltage and frequency. Therefore the reference DG unit should be suitably sized so that such desired regulation on power and voltage could be performed. The suitably sized storage included on the DC bus of this unit ensures fast response to any change in power demand (fast load tracking) and stable AC voltage. The other DG units may work in constant power control scheme (PQ mode) to have contribution in stable load balance. Such reference unit is called the Master DG unit in this study. This configuration is used in the study and the remaining part of controller is based on this strategy.

The proposed strategy for controlling power sharing among DG units in this paper is as flowchart in Figure 5.

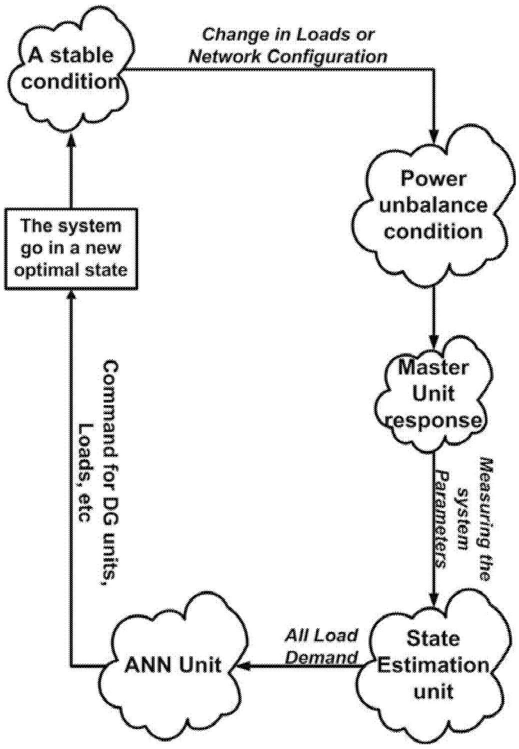

Figure 5: Proposed Control Strategy for a stand-alone MicroGrid

At first it is assumed that all the units in the stand-alone system operate below their ratings in order to have selection of power change. After any change in the system, firstly the Master DG unit will response and injects or absorbs some power to the system to meet the requirements of the loads, whereas the other DG units in the system continues to supply the same power as scheduled. In constant intervals, the measurement units measure the system parameters and send them to MGMS. The state estimation unit uses the measured and virtual measurement data and estimates the system state and calculate amount of generation and demand powers and also buses voltage and line current.

Next step will be dividing the power among other units with consideration of their rating and guide system to work in optimal and normal condition. The ANN unit can reply real-time to this change and produce the optimal commands since it is trained with the genetic algorithm optimized fitness function. The communication links will transmit new reference of power to the DG units. Finally the system will reach to a new stable point.

It is obvious that the Master DG unit should be able to produce extra load demand in the interval of load change and receiving new set point to other DG units and so the of storage device should be determined with consideration of the amount of the load change, speed of controller, and DG units' response time. Authors in [24],[25] have described how much storage is suitable and how it should be designed.

B. Identification of the input and output of ANN

Neural Network (NN) approach can overcome limitations in optimizing the big systems due to their high computational skill, low complexity, easiness of implementation, and short processing time (particularly useful for real-time control) [26]. On the other hand, the NNs require to be trained and it is necessary to create a suitable training set of the problem inputs and outputs. However, the training process of the NN is an off-line procedure that can be made only periodically, to test the NN performance, or when significant variations in the microgrid characteristics (e.g. load demand, DG capability, network topology, etc.) happend.

ANN inputs should be selected so that they would be able to conveniently characterize system's behaviour and be small enough to avoid a large number of ANN parameters. The ANN inputs should also contain a set of monitorable and controllable variables. In this study NN-MGMS inputs are the active and reactive power demand which come from State Estimation unit and the network configuration (e.g. if some lines are out of service for maintenance).

The NN-MGMS output is the non-master DG units active and reactive power production set points. Because as described in control strategy, the duty of Master unit is to produce regulating power and compensate difference between demand and generation according to error in all controller and time delay for other units. The input and output of the ANN unit is shown in Figure 5.

C. Data set generation

After estimating the total demand of MG, the OPF unit with optimization process will return the optimal solution by minimizing the global power loss, under technical constraints related to the load flow equations, the maximum allowed overvoltage, the minimum voltage drop, maximum Lines power, and the maximum/minimum DG power production.

The data set generation procedure consists of a data set of samples which reflects the dependency of the system behaviour with variations in its operating conditions.

In this study data set generation is as follow:

- Assuming several values for load demand. in this study for decreasing the data set number, three levels of load for each bus (Minimum, Medim, and Maximum) is considered and the loads combination is chosen among these levels .
- Considering several network configuration
- Solving genetic algorithm based optimization method to determine the optimal value of generation for each DG unit in order to minimize the power loss and maintain the constraints.

After this steps the input and output of the control system is known and can be used for the learning stage of an ANN.

D. ANN Design

The simple feed-forward NN with one hidden layer, may be advantageously used in this application provided that the greatest attention is paid to reduce the number of input variables. It is worth considering that the number of hidden neurons has to be carefully chosen with an accurate optimisation aiming at exalting the NN generalization capability (the capability to give reasonable response to inputs never seen during the training).

According to ANN inputs and outputs described in section 4.2, the NN configuration is as Figure 6. Input layer consists of bus loads, active and reactive powers and output layer has generation powers for m non-master DG units.

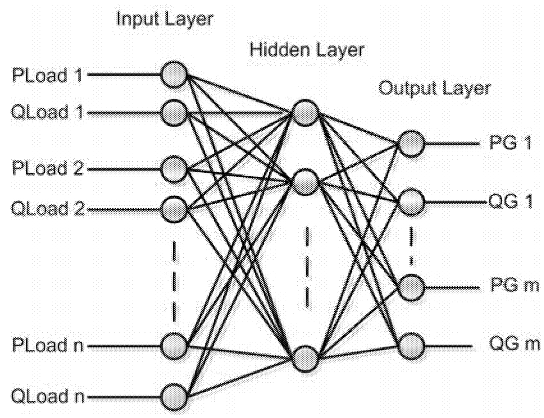

Figure 6: Structure of the ANN

E. Training

The MatLab Neural Network Toolbox has been used to create, train and validate the NN. The backpropagation algorithm has been employed to train the NN using a suitable set of training parameters achieved by resorting to off-line Optimal Power Flow (OPF) calculations.

After the training process, the performance of the ANN was evaluated with other data sets that can be obtained by solving the GA optimization problem with a new set of load demands.

F. Using ANN in on-line controller

All previous steps are to be performed in an off-line mode. The final products of the procedure are to be used in an on-line environment as a software module of the MGMS to obtain physical interpretation of the system behaviour. Figure 7 shows a general overview of control strategy proposed in this paper for controlling power sharing among DG units.

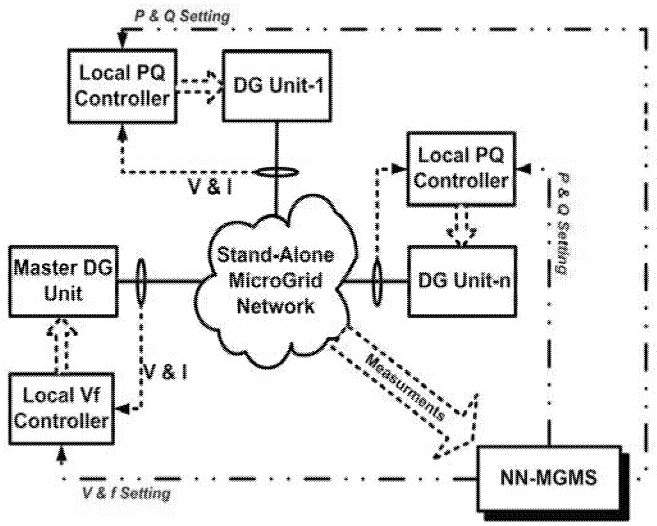

Figure 7: General Overview of propsed control Strategy

V. Conclusion

This paper proposed a control and management strategy for optimal and reliable operation of a MicroGrid in stand-alone mode. The scheme uses communication facility to send the data of systems to central controller. The optimal generation value for each DG unit is determined by a Genetic Alogorithm optimization method with several situations in load and system configuration and an ANN is trained with this data off-line. Finally the ANN is used in on-line system controller to define the suitable control command of system immediately after any change.

When the utility isn't available in a part of distribution network with some DG sources, the proposed scheme can control the system in such case that the available DG units supply the loads in the system and ensure continuity of power to the loads.

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