SECURITY CONTROL OF ISLANDED MICRO-GRID BASED ON ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM

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In an islanded microgrid, the balance between power generation and consumption is considered as an indicator for assessing its security, if this equilibrium is not created in the micro-grid, In this case, preventive measures such as load shedding and generation tuning in the micro-grid will be required in the shortest time. In this paper, a new strategy is proposed to investigate the dynamic security of the micro-grid in the event of power and load disturbances based on adaptive neuro-fuzzy inference system (ANFIS). Also, other ANFIS has been proposed to predict the application of preventive controller, if the micro-grid is unsafe.

Keywords: Micro-Grid Security, Frequency Droop, Voltage Droop, Load Shedding, Power Electronic Interface Resources, adaptive neuro-fuzzy inference system (ANFIS)

1. Introduction

Today, factors such as economic benefits, concerns about the environmental impact of energy generation, technological advances in distributed generation sources and power electronics, the increasing need for higher quality and reliability, incentives to increase the use of distributed energy sources. This has led to a new concept called micro-grid [1] and [7-10]. A micro-grid is a set of loads and distributed generation resources. There are various categories for energy resources in micro-grids. One of these is the basic classification of how to connect energy sources to the micro-grid. On this basis, one unit is connected to micro-grid via a synchronous machine, and the other is connected to the micro-grid via a power electronic interface. In micro-grids with power electronic interfaces distributed sources for network transient operation or load demand changes, it usually needs to operate an energy storage system (DS), especially when the micro-grid is in islanded mode [11-13]. Micro-grids can be operated in both grid-connected and islanded modes [5-6]. When connected to the main grid, the

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distribution system can be referred to as a slack bus, supplying or absorbing any power difference in the micro-grid [14-15]. But when the grid is slowly shifted to the islanded operating mode due to the effects of voltages droop, faults, shutdowns, etc., the power balance in the island's micro-grid especially when power and load disturbances are a critical issue for continued operation micro-grid is safe. An energy storage system may be utilized in the event of power disturbance or an increase in load consumption, the micro-grid generation resources that are not capable of supply [16] may be required if necessary due to load shedding. But the lowest load shedding rate and the fastest possible power balance in the micro-grid is a subject to be achieved. In the micro-grid, frequency and voltage droop control is used to generation tuning the active and reactive power to realize the desired installation and removal characteristics of the sources. In this method, the contribution of each source with the inverter interface is based on the characteristic of the droop curve, which allows for quick response and allocation of reference to each unit to prevent damage to distributed generation [17-21]. Frequency deviation can be limited by defining the frequency droop characteristic and even returning it to the nominal value using the frequency restoration loop. It is also possible to limit terminal voltage changes by using the voltage droop characteristic [26]. As a result, distributed generation units with power electronic interfaces react to voltage deviations caused by micro-grid or local load variations within the permissible range [3-4]. This method can then adjust the frequency and voltage of the micro-grid to prevent them from dropping. Therefore, unlike traditional systems in micro-grids, frequency and voltage deviations are not considered as indicators for evaluating micro-grid security. Therefore, it is important to find ways to quickly detect the security of the islanded microgrid, especially when it comes to power and load disturbances. Also, if the micro-grid is unsafe, taking immediate action to secure the micro-grid operation is imperative. One of the most precise traditional methods for assessing micro-grid security is to solve a set of nonlinear equations that will be extremely complex and time-consuming. But using artificial intelligence tools would be a good alternative to quickly and accurately describe micro-grid security. In [22], the frequency deviation and performance of storage equipment in the micro-grid have been studied and an indicator has been provided for assessing the safety of the micro-grid in anticipated transmission to the islanded mode when high-voltage network disturbances are available. In this paper, the use of an artificial neural network (ANN) for the reason of computational speed in online performance and its flexibility to predict corrective actions in unsafe operating modes to achieve a smooth transition between connected and islanded performance is emphasized. In [23-24], to evaluate the security of the traditional distribution network, the voltage deviation is also investigated. In this paper, an artificial neural network is used to evaluate the safety of the 9-bus standard network. When a system is designed with only artificial neural networks, the network is a black box that needs to be defined. This is a heavily computationally expensive process. After extensive experience and training on the complexity of the network and the learning algorithm to be used and the degree of accuracy that is acceptable in this application, the designer can achieve a relative satisfaction. Now, if we incorporate fuzzy logic functions into neural networks and learning, and associate neural network classification into fuzzy systems, then the failures and weaknesses of neural networks and fuzzy systems can be covered. The result will be an adaptive neuro-fuzzy inference system (ANFIS). In the adaptive neuro-fuzzy control system, the neural network section is used to learn and classify abilities and transplants and modify the model. The neural network part automatically generates fuzzy logic rules and membership functions during the learning period. Overall, even after learning, the neural network continues to refine membership functions and the rules of fuzzy logic in such a way that it learns more and more of its input signals. On the other hand, fuzzy logic is used to infer and providing a definite or non-fuzzy output (when fuzzy variables are created) [2]. In [27-31] Micro-grid control consisting of distributed generation sources including solar cell and wind turbine in island state based on parameter control using MATLAB software is presented. In this paper, the security of an islanded medium-voltage micro-grid with power electronic interfaces in the presence of power and load disturbances is investigated, and the effect of droop characteristics on frequency and voltage deviation in the presence of these disturbances is observed. The adaptive neuro-fuzzy inference system has been used for the rapid evaluation of the studied micro-grid security in the presence of power and load disturbances. In the case of micro-grid insecurity, other ANFIS systems have also been proposed for projecting the minimum amount of generation tuning and load shedding to achieve faster micro-grid safe mode.

2. Investigation of frequency and voltage deviation in micro-grid with power electronic interface

In traditional distribution networks, especially in isolated cases, it is critical to evaluate system security, maximizing frequency and voltage deviations from the nominal value under different operating conditions (presence of power and load disturbances). But in a micro-grid with electronic interfaces, the power-loss strategy used to manage power prevents them from going out of value by limiting the frequency and voltage. It is also possible to recover the frequency and voltage to the nominal value using the frequency and voltage restoration loop. Fig. 1 shows the block diagram of the frequency-active power controller.

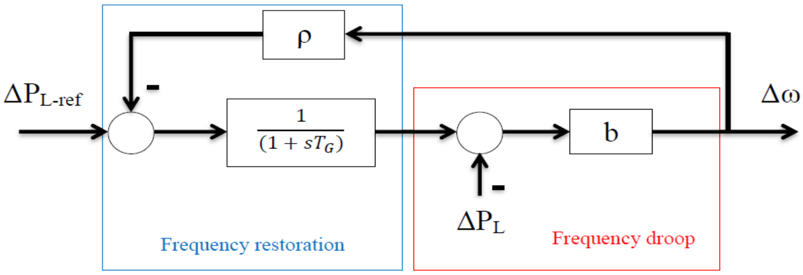

Fig. 1. Frequency-active power controller block diagram for a distributed generation unit with power electronic interfaces [25]

For a distributed generation unit with power electronic interfaces connected to the micro-grid, the relationship between frequency deviation and load change is:

$$\Delta\omega(s) = -\Delta P_L(s)\left[\frac{b}{1+\rho\left(\frac{1}{1+sT_G}\right)b}\right] + \Delta P_{L-ref}(s)\left[\frac{b}{(1+sT_G)+\rho b}\right] \quad (1)$$

In Equation (1), the frequency-active power controller droop is modeled by (b) gain. Also, the frequency restoration loop with (ρ) gain and a post-phase first-order function with T_G time constant modeled. Meanwhile, the ΔP_L of the load variations and the $\Delta P_{L\text{-}ref}$ of the load reference set point, for the reference frequency allocation, are considered at each output power point [25]. The deviation in the frequency response of the transient mode for the controller is obtained by setting 1/s = 0 from Equation (2):

$$\Delta\omega = -b\Delta P_L \quad (2)$$

The deviation in the frequency response of the stable mode for the controller is obtained by settings = 0 from Equation (3): [25]

$$\Delta\omega = \left(-\Delta P_L + \Delta P_{L-ref}\right)\left(\frac{1}{\frac{1}{b}+\rho}\right) \quad (3)$$

Fig. 2 shows the block diagram of the voltage-reactive power controller. Voltage regulation in the voltage-reactive power controller consists of a voltage restoration loop. This loop with (ρ) gain for the voltage error and T_G time constant is modeled. Meanwhile, the ΔQ_L load variations and the ΔQ_{L-ref} of the load reference set point, for the reference voltage allocation, are considered at each output power point [25].

The reactive loads are dependent on the voltage, while the reactive power of a distributed generation unit differs with the power electronic interface based on the deviation in the bus voltage. As a result, a distributed generation unit with power electronic interfaces react to the deviation caused by micro-grid or local load changes. Thus, the distributed generation unit can provide a reactive load.

The voltage droop characteristic can be obtained by the relationship between the voltage deviation and load change in the Equation (4):

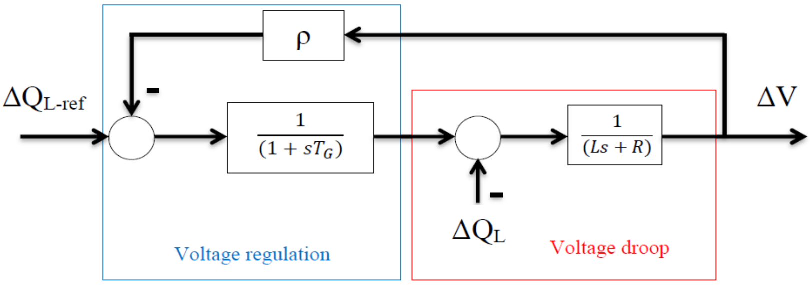

Fig. 2. Voltage-reactive power controller block diagram for a distributed generation unit with power electronic interfaces [25]

$$\Delta V(s) = \left[\frac{\frac{-\Delta Q_L(s)}{Ls+R}}{1+\rho\left(\frac{1}{1+sT_G}\right)\left(\frac{1}{Ls+R}\right)}\right] + \left[\frac{\frac{\Delta Q_{L-ref}(s)}{Ls+R}}{(1+sT_G)+\rho\left(\frac{1}{Ls+R}\right)}\right] \tag{4}$$

In Equation (4), Similar to the frequency governor of the real power-frequency control described earlier, a voltage regulator consisting of a voltage restoring loop is included in the reactive power controller. This loop is modeled by a gain ρ for the voltage error and a time-constant T_G. It is noted that the voltage droop as well as the voltage restoration loop are programmed in a DSP controller, and any load governing that may take place because of voltage-dependent reactive loads is a natural occurrence. In Figure 2, the input labeled $\Delta Q_{L\text{-}ref}$ is the load reference set point that is the control input to shift the generator's voltage regulator characteristic to give the reference voltage at any desired reactive power output [25]. The deviation in the frequency response of the stable mode for the voltage-reactive power controller is obtained by settings s = 0 in Equation (4). The steady-state change in voltage is:

$$\Delta V = \frac{-\Delta Q_L}{R+\rho} + \frac{\Delta Q_{L-ref}}{R+\rho} \tag{5}$$

Here is the ΔQ_G, the deviation in the reactive power produced by the source with the power electronic interface, which is provided by the change in the reactive load, by the change in productive output, so we have [25]:

$$\Delta V = \frac{-\Delta Q_G}{R+\rho} + \frac{\Delta Q_{L-ref}}{R+\rho} \tag{6}$$

In Equation (6), the Value of Q_{L_ref} corresponding to a load reference setpoint of zero is $Q_{L\_ref} = 0$. A positive value of load reference setpoint would refer to $Q_{L\_ref} > 0$, and a negative value would refer to $Q_{L\_ref} < 0$. By changing Q_{L_ref}, the controller can be set to give nominal voltage at any desired reactive load condition. According to the convention, the load is inductive when it draws a positive reactive power and capacitive when it draws a negative reactive power.

3. System understudy

Fig. 3 shows a single-line diagram of the medium-voltage micro-grid. Here it is assumed that the micro-grid would be in island mode operation. Each distributed generation unit can supply a certain amount of active/ reactive power, depending on the limitations of predetermined. The characteristics of the micro-grid studied are listed in Table.1.

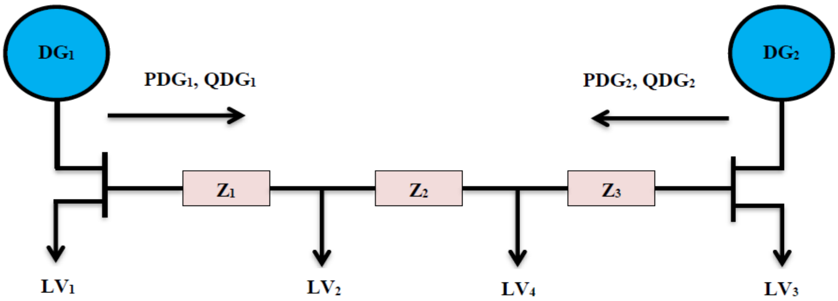

Fig. 3. Micro-grid understudy

Table 1

Micro-grid characteristics

Parameters	Explanation	Values
$P_{max\ DG1}$	Maximum active power DG_1	1.75 MW
$P_{max\ DG2}$	Maximum active power DG_2	3.2 MW
m_{DG1}	F-P DG_1 droop coefficient	0.57 Hz/ MW
m_{DG2}	F-P DG_2 droop coefficient	0.3125 Hz/ MW
$Q_{max\ DG1}$	Maximum reactive power DG_1	0.75 MVAr
$Q_{max\ DG2}$	Maximum reactive power DG_2	1.8 MVAr
n_{DG1}	V-Q DG_1 droop coefficient	0.032 kV/ MVAr
n_{DG2}	V-Q DG_2 droop coefficient	0.016 kV/ MVAr
f	System Frequency	50 Hz
Z_1	Line impedance 1	0.0331+ j 0.02
Z_2	Line impedance 2	0.0188+ j 0.0068
Z_3	Line impedance 3	0.0251+ j 0.0035
L_{f1},L_{f2}	VSC series filter inductance	0.0004 H
R_{f1},R_{f2}	VSC series filter resistance	0.002 Ω
C_{f1},C_{f2}	Load parallel filter capacitor	2500 μF
V_{L-L}	Line voltage	20 kV

4. Adaptive Neuro-Fuzzy Inference System for Evaluating Micro-Grid Security

To assess the security of the island micro-grid, have a high level of data due to the dynamic behavior of large sets of data to be extracted. Therefore, the data set is initially generated and then an adaptive neuro-fuzzy inference system will be designed to check the micro-grid security. Designed to offer preventive control if a micro-grid is detected if the network is unsafe.

4.1. Generate a dataset

The dataset contains examples of system behavior that is dependent on various system performance conditions. When selecting inputs for the ANFIS system, it should be noted that this dataset can easily express the behavior of the system while avoiding a large number of indicators for the ANFIS system. The ANFIS system inputs also contain a set of monitoring and control variables to run preventive controls if unsafe operating modes are detected. To generate knowledge about the dynamic behavior of the micro-grid, the data set includes distributed generation power supply and micro-grid consumption power supply for power and load disturbances with off-line simulated using EMTDC/PSCAD software and evaluating micro-grid security with MATLAB software will be reviewed.

4.1.1. Normalize the dataset

Because the training process for each characteristic on a scale can increase the speed of training, it should, therefore, normalize the data set. The data set was normalized using the minimum-maximum [23] method and all the characteristics were scaled to 0-1 on the new scale.

$$x_i' = \frac{x_i - Min_{value}}{Max_{value} - Min_{value}}\left(Max_{target} - Min_{target}\right) + Min_{target} \tag{7}$$

Where, x: The dataset, $x^{/}$: The normalized dataset, Max_{value}: Maximum initial value of x, Min_{value}: Minimum initial value of x, Max_{target}: Maximum value for scale range, Min_{target}: Minimum value for scale range.

The normalized data set is divided into two groups: network training and health. The training set is used for ANFIS training and the health set is used to evaluate the network output.

4.2. Proposed design to investigate the security of the micro-grid with the ANFIS system

To evaluate the security of the island's micro-grid, the use of the ANFIS system is suggested. Fig. 4 shows the fuzzy inference system. Fig. 5 shows the ANFIS system for assessing the security of a micro-grid. The inputs of this network include a set of active and reactive power generation and consumption in the micro-grid. The output is also 0 and 1 in binary characters.

$$Pgen = \sum_{k=1}^{n} Pgen_k \tag{8}$$

$$Qgen = \sum_{k=1}^{n} Qgen_k \quad (9)$$
$$Pcon = \sum_{h=1}^{m} Pcon_h \quad (10)$$
$$Qcon = \sum_{h=1}^{m} Qcon_h \quad (11)$$

Mark 0 for unsuccessful island and mark 1 for successful island. When in the micro-grid of the island, the power consumption is higher than power productive, the island is unsuccessful and otherwise successful. Fig. 6 shows the mean square error in each category for the network designed in Fig. 5. However, if the ANFIS1 network detects the micro-grid to be unsafe, urgent measures are needed to balance the power in the micro-grid such as load shedding and generation tuning. It is possible to predict the minimum load shedding and the minimum storage capacity using ANFIS2 and ANFIS3 networks. This will be discussed further below.

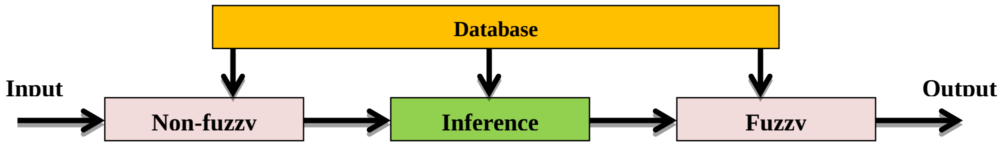

Fig. 4. Fuzzy inference system

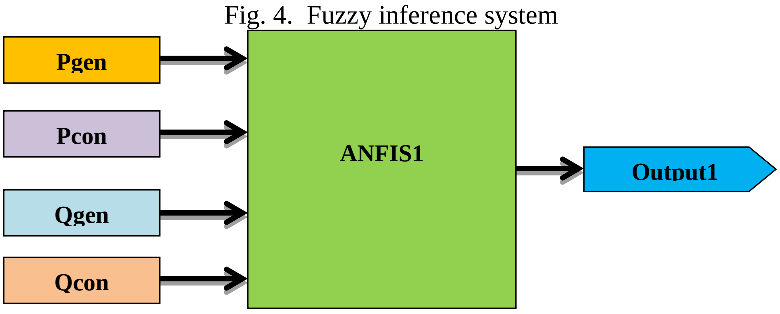

Fig. 5. ANFIS system for assessing micro-grid security

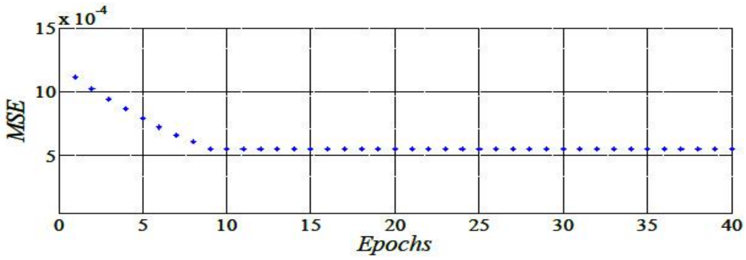

Fig. 6. Mean square error (MSE) per category for ANFIS1

4.2.1. Proposed control scheme for unsafe micro-grid

As mentioned earlier, the imbalance in the micro-grid is expressed as a criterion for detecting system security. If the micro-grid is unsafe then a plan is needed to coordinate the generation and consumption of the micro-grid. For this purpose, the distance between the operating point and the boundary of safety can be used for the amount of load shedding and generation tuning (if available with limited storage capacity or network connection). If it is not possible to connect to the network or use a storage device, it should only be achieved by limiting the safety of the micro-grid using load shedding.

To illustrate this control scheme, as shown in Fig. 7, the horizontal axis is assigned to the total consumption power and the vertical axis to the sum of the generation capacity in the micro-grid. Three points in Fig. 7 that have been considered include:

Point A, B, x_n, A($S_{con\_t\_A}$, S_{gen_t}), B(S_{con_t}, $S_{gen\_t\_B}$), x_n($S_{con\_t\_n}$, $S_{gen\_t\_n}$).

Where x_n is the point between A and B on the boundary of the safe zone. So for the generation, we will have:

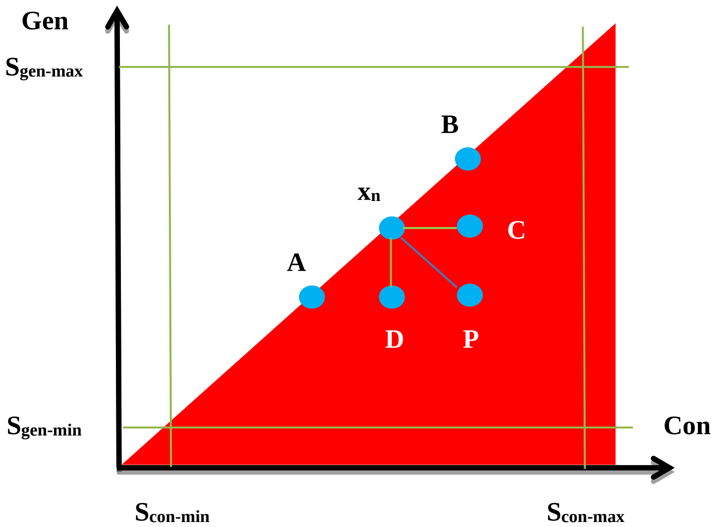

Fig. 7. Calculate the shortest distance from the boundary of safety

$$S_{gen\_t} \in [\, S_{gen\_min}, S_{gen\_max}] \tag{12}$$

And for consumption we will have:

$$S_{con\_t} \in [\, S_{con\_min}, S_{con\_max}] \tag{13}$$

At moment t, at point P, the system is outside the safety zone of the micro-grid but is still operating in the natural range of voltage and frequency. (Due to the use of distributed generation sources with power electronic interfaces and the droop method for power management, frequency, and voltage regulation, they do not go beyond the permissible range).

$$S_{gen\_t\_n} \in [\, S_{gen\_t}, S_{gen\_t\_B}] \tag{14}$$

$$S_{con\_t\_n} \in [\, S_{con\_t\_A}, S_{con\_t}] \tag{15}$$

It is assumed that, if generation and consumption are equal, the bisector is the safe zone boundary of the island. Otherwise, the red area is the non-secure area of the micro-grid, which should be considered as a plan for coordinating the micro-grid in this area. The shortest distance from the operating point to the safety boundary is the vertical line drawn on the safety boundary. This line's distance is:

$$\overline{PX_n} = \sqrt{(PD)^2 + (PC)^2} \quad (16)$$

$$PD = S_{con\_t} - S_{con\_t\_n} \quad (17)$$

$$PC = S_{gen\_t\_n} - S_{gen\_t} \quad (18)$$

Where PD indicates minimum load shedding and PC minimum generation tuning as predicted by ANFIS2 and ANFIS3 in the proposed method. If it is not possible to generation tuning, and only by load shedding to reach the safety limit, this value is:

$$\overline{PA} = S_{con\ t} - S_{con\ t\ A} \quad (19)$$

If it is possible to generation tuning and we do not want to make it load shedding:

$$\overline{PB} = S_{gen\_t\_B} - S_{gen\_t} \quad (20)$$

4.2.2. Design of ANFIS systems for control operations in unsafe micro-grid

In this paper, ANFIS systems have been used for the design of micro-grid synchronization. The inputs of the ANFIS system as shown in Fig. 8 include the sum of the power generated by the power electronic interface sources, the total consumption power of the feeders, the 0 or 1 indication for safe detection of the micro-grid. The ANFIS2 output can the amount of load shedding and the ANFIS3 output the generation tuning rate. The two ANFIS networks are considered in parallel, each having an input number of 5 and an output of 1. The step by step design is summarized as follows:

1) The training set collected for the ANFIS controller is obtained under changes in the generation and consumption of active and reactive power.

2) The dataset was normalized using the minimum-maximum method and all the characteristics were scaled to a new scale of 0-1.

3) After obtaining the dataset, the ANFIS structure is complete.

4) After creating the controller structure, trained ANFIS, with mean square error (MSE) trained in Fig. 6, Fig. 9 and Fig. 10.

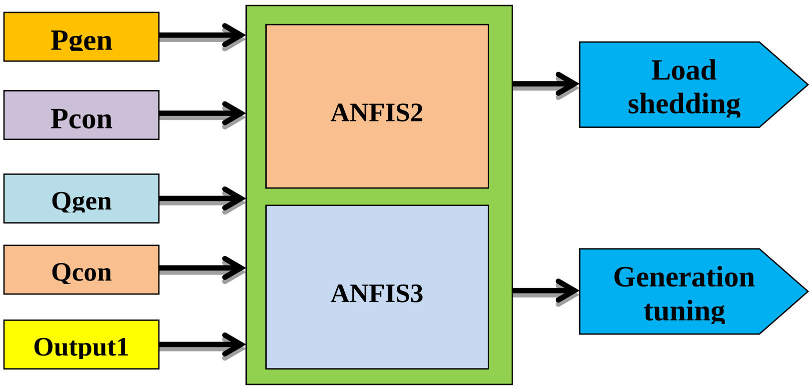

Fig. 8. Unsafe micro-grid synchronization scheme

Fig. 9 shows the mean square error in each category for the designed grid to predict the minimum load shedding. Fig. 10 shows the mean square error in each category for the designed grid to predict the minimum generation tuning.

5. Simulation results on the studied micro-grid

Two tests were performed to evaluate the security of the micro-grid under different conditions. In the first experiment, occurred a static load increase in feeder 1 at the time of 2 s, and at the time of 2.2 s, the distributed generation 2 (DG_2) is disconnected. Fig. 11 shows the distributed generation active power during power and load disturbances.

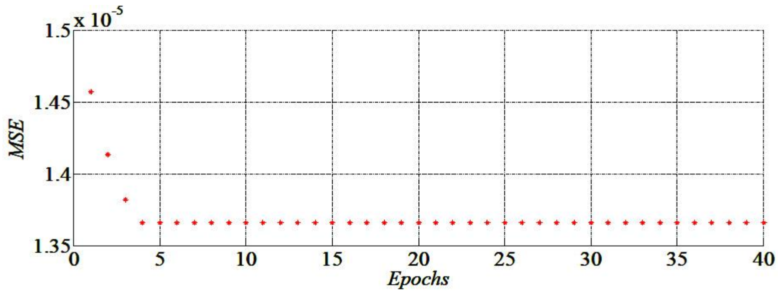

Fig. 9. MSE per category for ANFIS2

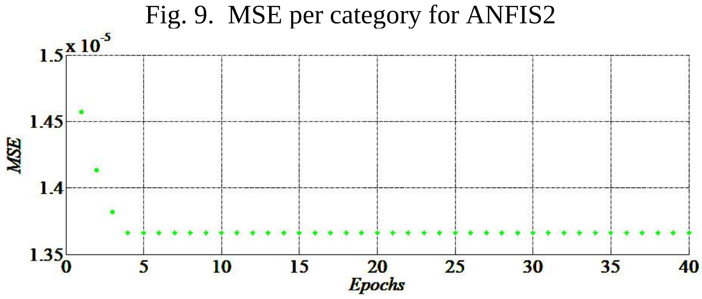

Fig. 10. MSE per category for ANFIS3

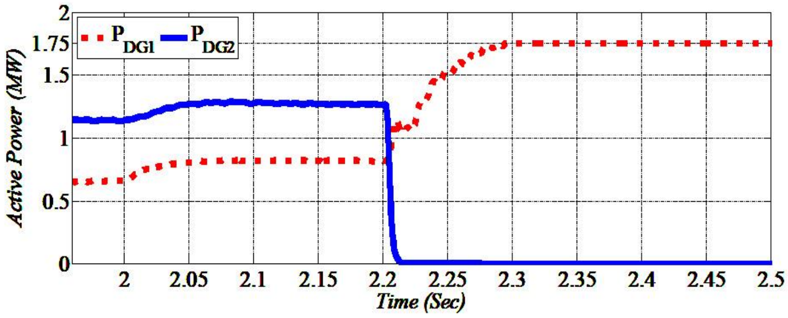

Fig. 11. Injection active power rate of distributed generation to the Micro-grid during power and load disturbances

With the increasing demand for power in 2 seconds, this demand is shared by the droop method in distributed generations. But when, in the 2.2 second, because of problems, suddenly, distributed generation 2 interrupted, distributed generation 1 responds to the load demands of the micro-grid, increasing its generation active power capacity to a maximum, but unable to supply the demands of micro-grid loads. Fig. 12 shows the reactive power of distributed generation in the micro-grid during power and load disturbances.

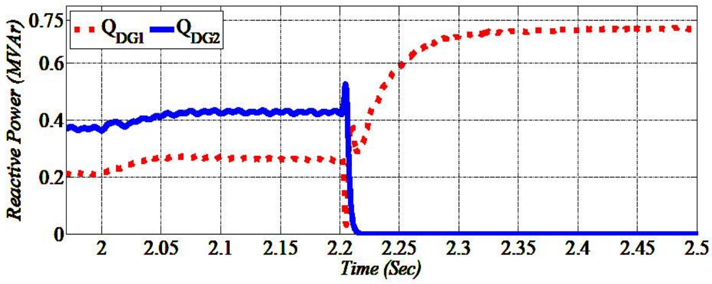

Fig. 12. Injection reactive power rate of distributed generation to the micro-grid during power and load disturbances

In an island micro-grid according to Equation (5) and Equation (6), the load change will be provided by the distributed generations. Also, when distributed generation 2 is interrupted, distributed generation 1 provides reactive power to the micro-grid by increasing power. At these disturbances, the frequency and voltage deviation rate of the micro-grid is obtained in Fig. 13 and Fig. 14.

As a result of the power and load changes in the micro-grid studied, the frequency of the micro-grid has changed, which is limited by the use of the droop characteristic of these changes. Frequency variations are about 0.5 Hz. The voltage of the micro-grid has also changed, which is limited to 0.9 (pu) due to the use of the droop characteristic. Therefore, the deviation of frequency and voltage cannot be considered as an indicator for assessing the security of the micro-grid.

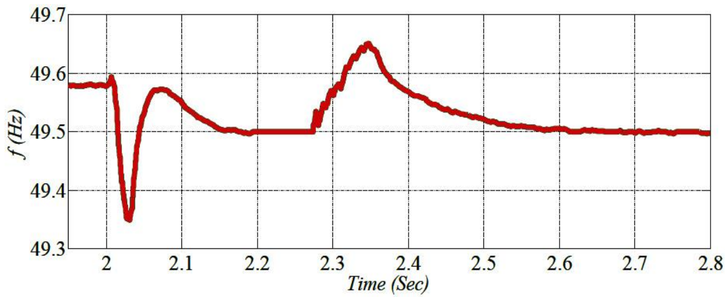

Fig. 13. Frequency deviation rate of the studied micro-grid during power and load disturbances

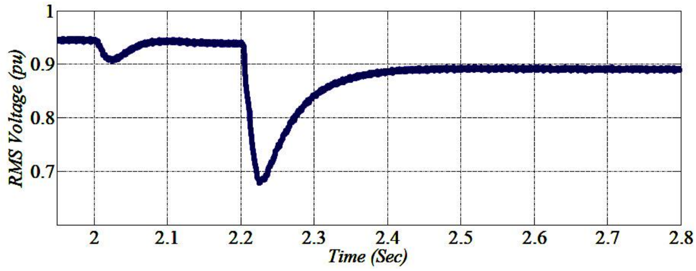

Fig. 14. Voltage deviation rate of the studied micro-grid during power and load disturbances

Fig. 15 shows the proposed method for assessing the security of a micro-grid using the ANFIS system.

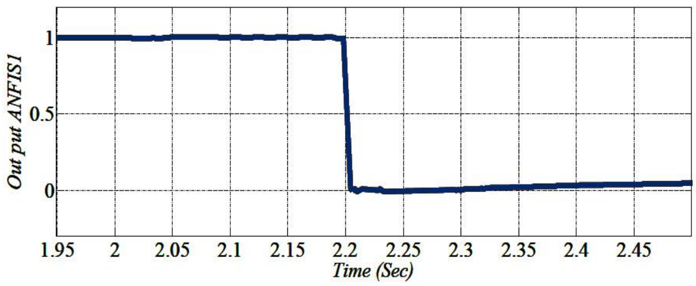

Fig. 15. Evaluation of micro-grid security during power and load disturbances using ANFIS1

As shown in Fig. 15, the load demand in the micro-grid is increased in 2 seconds, but for the reason of being able to supply the power demand by the distributed generations, the micro-grid is safe that the 1 output of the ANFIS1 network acknowledges this. But when the distributed generation 2 is interrupted in 2.2 seconds, the distributed generation 1 alone will not be able to supply the load demand in the micro-grid, and this power imbalance will result in the micro-grid being unsafe, which results in the 0 output of the ANFIS1 network acknowledges this. However, due to the occurrence of power disturbances, the micro-grid has become unsafe for safe operation of the micro-grid, and the proposed synchronization scheme must achieve the minimum load shedding and minimum generation tuning for the micro-grid security. Fig. 16 illustrates the minimum load shedding required for the safety of the micro-grid during power disturbances using the ANFIS2 network.

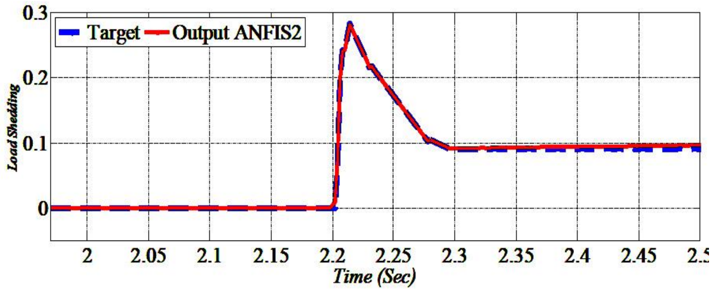

Fig. 16. Predicting the minimum load shedding using ANFIS2

Also, the minimum load shedding exact rates obtained by the Equation (16) are shown in Fig. 16. A comparison of these two results is indicative of the high accuracy of the ANFIS2 network for the predictions of at least the rate of load shedding during disturbances.

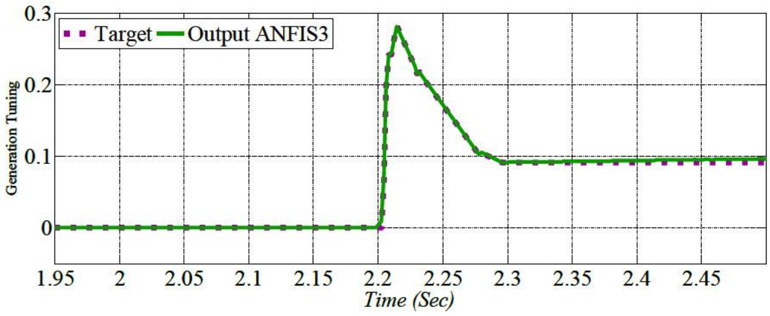

Fig. 17. Predicting the minimum generation tuning using ANFIS3

Given the possibility of using the storage in the micro-grid during power and load disturbances, Fig. 17 shows the prediction of the minimum generation tuning rate using the ANFIS3 network. The minimum generation tuning exact rate obtained from the Equation (16) are also shown in Fig. 17. A comparison of these two results indicates the high precision of the ANFIS3 network for the predictions of at least the rate of generation tuning during disturbances. At moment 2.2 seconds, due to the sudden interrupt of the distributed generation 2, it needs more power, but after a few hundred seconds for the reason of increasing distributed generation 1 output power, this value is adjusted. It should be noted that the values obtained for the generation tuning and load shedding are normalized between 0–1.

5. Conclusion

In the traditional distribution system, the maximum deviation of frequency and voltage is considered as an indicator for evaluating system security. However, in an islanded micro-grid that only has sources with power electronic interfaces, due to the use of the frequency and voltage droop control method to manage the micro-grid, the deviation of the frequency and voltage is regulated. Consequently, unlike traditional systems, the independent frequency and voltage deviation in the micro-grid cannot be considered as an indicator for evaluating micro-grid security. But a new indicator to assessing the safety of a micro-grid is the balance of power between generation and consumption in the micro-grid. If this balance does not exist, the micro-grid will be unsafe. Rapid detection of micro-grid insecurity is another important issue that should be addressed as well as the urgent control measures needed. In this paper, the ANFIS system is used to evaluate the security of the medium-voltage network. It is also proposed to take control of other ANFIS systems to take urgent steps to achieve a faster micro-grid safe mode. The results show the high speed and accuracy of the ANFIS system for assessing micro-grid security and suggesting the use of preventive controllers in the event of micro-grid insecurity for power and load disturbances.

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