Fuzzy Control of Electricity Storage Unit for Energy Management of Micro-Grids[1]

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Abstract— **A Fuzzy Logic-based framework is proposed for control of Battery Storage Unit in Micro-Grid Systems to achieve Efficient Energy Management. Typically, a Micro-Grid system operates synchronously with the main grid and also has the ability to operate independently from the main power grid in an islanded mode. Distributed renewable energy generators including solar, wind in association with batteries and main grid supply power to the consumer in the Micro-Grid network. The goal here is to control the amount of power delivered to/taken from the storage unit in order to improve a cost function, defined based on summation of payment required for purchasing power from main grid or profit obtained by selling power to the main grid and distribution power loss, through reasonable decision making using predetermined human reasoning-based fuzzy rules. Profiles of system variables such as Consumer's Load Demand, Electricity Price Rate, and Renewable Electricity Generation Rate are assumed arbitrarily for obtaining general results. Measures of payment/profit will be extracted to compute amounts of cost and balance for the network which represent benefits of using Fuzzy logic for Storage Unit control with and without considering storage unit capacity limits. Simulation results are presented and discussed.**

Keywords- Micro-Grid Network, Intelligent Control, Power Flow Analysis, Fuzzy-Logic, Load Demand, Variable Electricity Price Rate.

I. INTRODUCTION

Micro-Grid is a small-scale grid that is designed to provide power for local communities. A Micro-Grid is an aggregation of multiple distributed generators (DGs) such as renewable energy sources, conventional generators, in association with energy storage units which work together as a power supply network in order to provide both electric power and thermal energy for small communities which may vary from one common building to a smart house or even a set of complicated loads consisting of a mixture of different structures such as buildings, factories, etc [1]. Typically, a Micro-Grid operates synchronously in parallel with the main grid. However, there are cases in which a Micro-Grid operates in islanded mode, or in a disconnected state [2]. In this article we assume that when the Micro-grid is connected to the main grid and is working synchronously with it, the flow of electric power can be either from the main grid to the Micro-grid or vice-versa. If the flow of electric power is from the main grid towards Micro-grid it means that the Micro-grid is consuming the main grid's energy for each KiloWatt-Hour of which the consumer, here Micro-grid, must pay to the Grid. This borrowed power can be either sent to local load to be consumed or can be stored in battery for future use. But, in case the flow of power is from the Micro-Grid towards the main grid, this means that Micro-Grid is delivering power to the main grid. In other words, the excess power generated currently by the renewable electricity generators or stored previously in the batteries is being sold to the main grid, and the Micro-Grid, or in general the consumer, is making profit by selling energy to the main grid. Without loss of generality, we have assumed that the price rate for buying energy from the main grid is equal to the electricity price rate which is sold to the grid. The excess power can be sold to the grid whenever the storage unit or load don't need that power or whenever it is more beneficial to sell power to grid than to use it for supplying the load. However, in this article the main goal is to have the load completely supplied by the required power demand at all conditions. Authors have previously simulated the Micro-Grid assuming no maximum and minimum limit for the amount of energy stored in the battery unit [1]. In this article, storage unit's limits on maximum and minimum amount of stored energy are considered and the results are compared to the results of the previous work.

II. SYSTEM MODEL

The model used for simulation of the Micro-grid network is a three-bus system. One of the busses in the distributed generation model is assumed to serve the renewable generators which include either solar farm, wind farm, or any other renewable generation units either in association with battery storage unit or without storage. Another bus is assumed to be there as the grid (utility) bus which will provide the complement part of the power demanded by the local load that renewable electricity generation system cannot afford. The third bus will be the specific load to which the demanded power is to be provided. This load can be anything from a common building or a smart house, to even a group of plants and factories or a mixture of all of them. Figure 1 shows an

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overall Micro-Grid schematic including Renewable Electricity Generators and Storage Unit, Utility, and Local Load.

Figure 1 Micro-Grid Network Schematic

There are three scenarios defined for simulation in this article; scenario 1 deals with a Micro-Grid which includes the renewable electricity generators without any battery storage unit. Therefore there will not be any approaches required for controlling the battery storage system in this scenario. The second scenario deals with the same Micro-Grid system as mentioned in scenario one but after the battery storage unit is connected to the same bus with the renewable generators. Also, the fuzzy approach is applied in this scenario for energy management through battery unit control. The point in this scenario is that the battery storage is assumed to be an ideal battery without any maximum or minimum limits on stored energy, i.e. infinite battery capacity. In the third scenario which is the last one, the Micro-Grid is assumed to have everything mentioned in scenario two plus the fact that maximum and minimum limits of stored energy are taken into account for storage unit and are assumed to be 85% and 15% of the nominal maximum storable energy respectively. These three scenarios will be described in more detail in section III.

A. Characteristics of Buses in Scenario 1

The three buses in the model of Micro-Grid Network simulated in this article have the following characteristics in the first scenario:

- Bus 1 is of type PQ and is used as the renewable electricity generation unit's bus.
- Bus 2 is of type Slack (reference) and is used as the Utility (grid) bus.
- Bus 3 is of type PV and is used as the Local Load bus.

B. Characteristics of Buses in Scenario 2

The characteristics of the three buses in the Micro-Grid Network model simulated in this article are as follows in the second scenario:

- Bus 1 is a PQ bus and is used as the bus for renewable generation unit and infinite-capacity battery storage.
- Bus 2 will be the Slack (reference) bus and is used as the Utility (grid) bus.
- Bus 3 is of type PV and is used as the Local Load bus.

C. Characteristics of Buses in Scenario 3

Bus characteristics of the three buses in the Micro-Grid Network model simulated in this article are as follows in the third, i.e. last, scenario:

- Bus 1 is a PQ bus and is used as the bus for renewable generation unit and finite-capacity battery storage unit.
- Bus 2 will be the Slack (reference) bus and is used as the Utility (grid) bus.
- Bus 3 is of type PV and is used as the Local Load bus.

This must be noted that battery units are assumed to be ideal batteries, i.e. no dynamic transient of change in the amount of stored energy in batteries are assumed, i.e. the amount of stored energy in the batteries is assumed to be changing as a pure ramp by time in both ascending and descending direction.

III. PROBLEM STATEMENT

The important point which lies behind the idea of this article is that we have assumed the real-time pricing for electricity. The update duration of pricing is assumed to be 15 minutes, which means that the price per KiloWatt-Hour of electricity consumed by the customers of the load region is updated every 15 minutes. This means that the money consumers need to pay to the utility for the same amount of energy used during different time-intervals might be different. Therefore, a function is required to be defined which takes into account the difference between amount of power given to the utility by the Micro-Grid, and the amount of power taken from the utility by the Micro-Grid. The Equation 1 represents this cost function:

$$Cost = \sum_{t=1}^{T}\left(\Pr(t)\,.\,S_U(t)\right) \tag{1}$$

where the electricity price $\Pr(t)$ is determined by the CPS energy every 15 minutes for the next 15 minute period. $S_U(t)$ is the amount of power transferred to/from the Grid during each 15 minute period. If power is received from the Grid $S_U(t)$ will be positive, and if power is delivered to the grid in case of excess power generation by the renewable generation system $S_U(t)$ will appear in the equations with a negative sign.

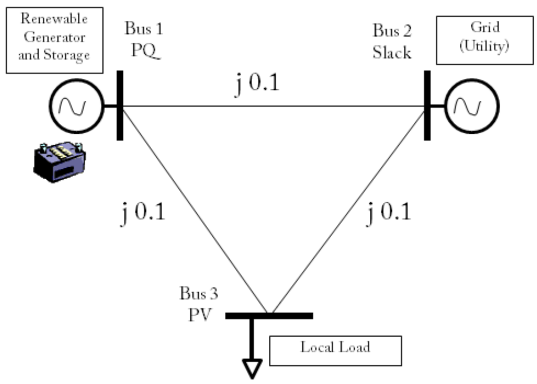


Figure 2 Three Bus Model for Micro-Grid

Figure 2 represents the three-bus model used for simulation of the Micro-Grid in different scenarios along with the branch impedances and the types of buses. Simulation is done on the Micro-Grid system considering three scenarios. In the following the summary of these scenarios is given:

A. Scenario 1

Analysis of the Micro-Grid system profits and costs under real-time electricity pricing policy; in this scenario the simulation, analysis and study will be done on a Micro-Grid model which includes the renewable generation unit without any battery storage unit. Therefore there will not be any approaches required for controlling the battery storage system.

B. Scenario 2

Fuzzy Control of the Micro-Grid system under real-time electricity pricing policy; the cost function assumed in this scenario is the same as the cost function used in the scenario 1. The main difference here is that the storage unit exists in the network and will appear to be on the same bus with the renewable electricity generation unit. The storage unit in this scenario is assumed to be ideal with infinite capacity.

C. Scenario 3

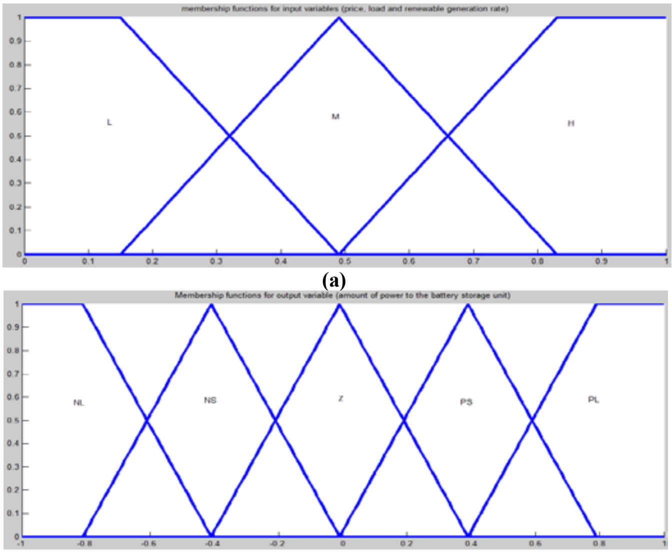
Fuzzy Control of the Micro-Grid system under real-time electricity pricing policy; the cost function assumed in this scenario is the same as the cost function described in the two scenarios 1 and 2. In this scenario also the storage unit exists in the network on the same bus with the renewable generation unit. The critical difference between this scenario and scenario 2 is that the storage unit in this scenario is assumed to be an ideal battery with finite capacity. Therefore, the maximum and minimum amounts of energy stored in the batteries are finite values and serve as boundaries which cannot be exceeded.

The power flow calculation and analysis in the Micro-Grid is the key to simulate the whole system. There are a number of well-known methods for calculation of power flow in the distributed generation network [3]. There are four different types of busses considered in a distributed generation network, the characteristics of which will be calculated in power flow algorithms. These four types include PQ, PV, Slack, and isolated [4, 5].

IV. FUZZY CONTROL APPROACH

The control strategy implemented in this paper is to use Fuzzy Logic [6] for controlling the power flow to/from the battery storage unit in order to improve the value of the cost function introduced in section III. The three input variables to the fuzzy inference engine are Electricity Price, Renewable Generation Rate, and Load Demand. The Fuzzy inference engine serves as the controller which determines a measure of the amount of power that must be sent to/taken from the battery unit during the next time interval, i.e. 15 minute period, based on the current values of its three inputs.

The fuzzy membership functions for the three inputs price, load demand, and renewable generation rate, and also for the output variable which determines the amount of power transaction with the storage unit are shown in figure 3.



(a)

(b)

Figure 3 Fuzzy Membership functions for input and output variables of the Fuzzy Controller; (a) inputs (b) output

The numerical values for these three input variables are normalized to the [0 1] interval, and then are Fuzzified using three fuzzy sets defined as Low (L), Medium (M), and High (H) as can be seen in figure 3a. The input variables after fuzzification will be fed to a fuzzy inference engine where the rule-base is applied to the input-output variables and the output will be determined by human reasoning. There is only one output variable from the fuzzy controller. This variable determines the amount of power to be stored in the battery, or to be drawn out from battery in each 15 minute interval. As represented in figure 3b, output variable fuzzy set is assumed to have five membership functions called Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Large (PL). The power drawn from the batteries can be used to complement the renewable electricity generation unit's power for providing the load's demand, can be sold to the Grid, or can be partially used for both reasons [7]. The role of fuzzy inference engine is critically important for obtaining satisfactory results. For example a rule can be as follows:

IF the *Price* is *Low*, AND the *Renewable Generation rate* is *High*, AND the *Load Demand* is *Medium*, THEN the amount of *Power to Battery* storage system should be *Positive-Large*.

The primary goal in these simulations is to provide the local load with all the power it demands at any circumstances. Meanwhile, this must be noted that whenever the price is high or low, the secondary goal will be to sell the most power to the main grid, and to purchase the most power possible from the main grid respectively. Under low-price electricity conditions, the action required by the rules might even require the Micro-Grid network to purchase power from grid and store it in the battery storage unit because the main point here is that the Price is low. This means by storing the energy in the batteries during low price times, the system will have enough stored energy in order to sell to the Grid during high-price periods. Even under cases of High local Load demand this will be a rational strategy. Therefore, having feasible rules predefined for the fuzzy system will help improve the cost function drastically. The proposed approach may even sometimes result in making the cost function value negative, which means that the system is making some profit instead of paying to the utility by the use of this control approach.

V. SIMULATION RESULTS & DISCUSSIONS

The simulation is done on the three bus system shown in figure 2. The Gauss-Seidel algorithm is implemented using Matlab for power flow calculation [8]. Some typical data are generated for electricity price rate, time-varying Load Demand and Renewable Generation Rate.

The power demand of the Load on bus 3 (Smart House) is supplied by two generators on buses 1 and 2. Bus 1 includes solar panel and/or storage unit and bus 2 is slack which is connected to utility as shown in figure 2.

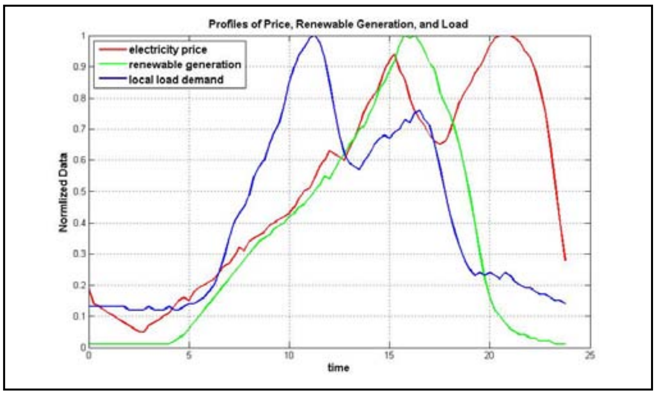


Figure 4 Profiles of Price, Renewable Generation, and the Load

The numerical values of the data profile for the three input variables which are fed to the fuzzy controller are shown in figure 4 during a typical day. These variables include electricity price which is assumed to be variable as time passes, renewable electricity generation rate, and local load demand. The data is generated arbitrarily for simulation purposes only with regard to the fact that the peak electricity consumption duration of the whole region of interest for the main grid is around 8:30 pm where the electricity price gets to its maximum value.

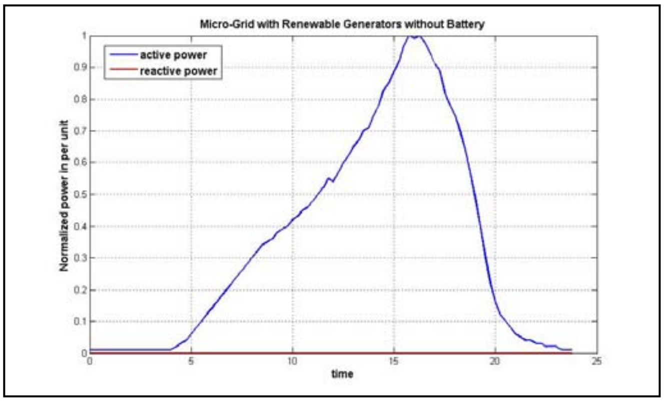


Figure 5 Power Flow of Bus 1 connected to Solar Panels; scenario 1

The simulation results for scenario 1 are represented in figures 5 to 7.

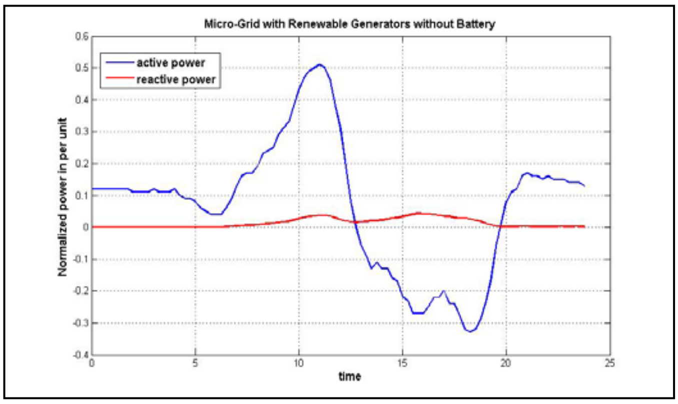


Figure 6 Power Flow of Bus 2 connected to Utility; scenario 1

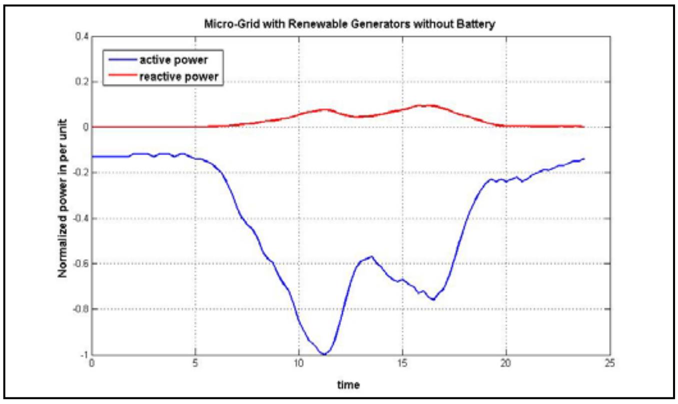


Figure 7 Power Flow of Bus 3 connected to Load; scenario 1

As it can be inferred from figure 5, the value of reactive power for bus 1 is constantly zero which corresponds to the assumption that the renewable generators do not provide reactive energy. Figure 6 shows that the active power is taken from the Utility during first half of the day time, and during most of the second half of the day the active power is being delivered to the grid. Load is evidently consuming active power regarding the blue curve represented in figure 7.

Simulation results for scenario 2 which associates ideal storage with infinite capacity to the renewable electricity generators on bus 2 are represented in figures 8 and 9.

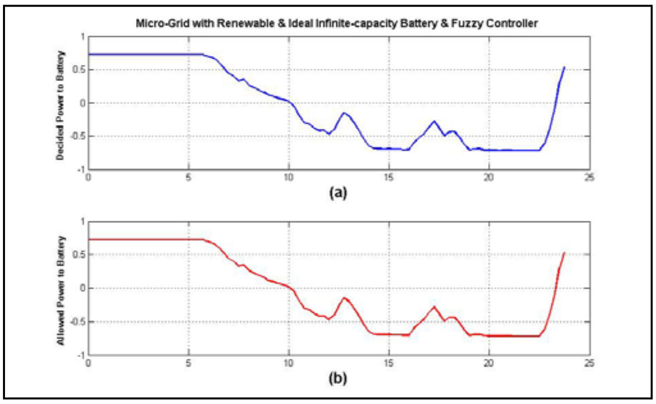


Figure 8 Output of the Fuzzy Controller, i.e. measure of the amount of power given to/taken from storage unit; scenario 2;
(a) Theoretically allocated (b) Practically feasible

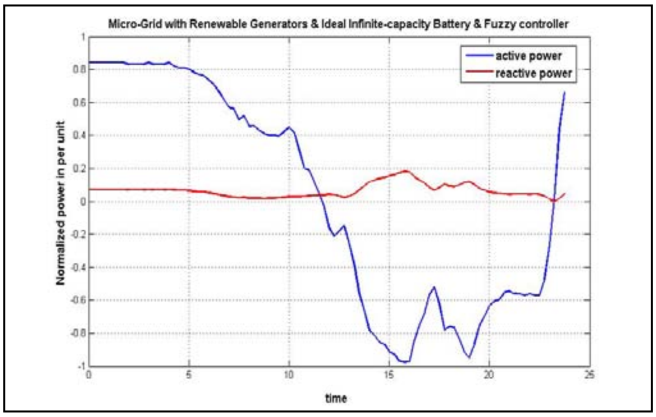


Figure 9 Power Flow of Bus 2 connected to Utility; scenario 2

Figure 8 parts a and b are matched to each other and this clearly shows that any value decided by the Fuzzy Controller for the power to be given to Battery or to be taken from it can be practical since battery unit assumed in scenario 2 is of infinite capacity. Figure 9 shows that active power is taken from the utility during first half of the day, and in the second half of day the active power is mostly being sold to the grid which can be deduced by the negative value of the blue curve in figure 9. The point is that the first part of the active power diagram is raised dramatically due to fuzzy decision making which means that the system is absorbing more active power from the grid during low-price hours and stores the power in the storage unit. Also, the second part of the active power diagram has fallen more in comparison to the same section of figure 6 which denotes on increase in the amount of power drawn from storage unit and using this power for partially charging the load and also selling the excess power to the grid during high-price hours. This strategy results in reduction of cost function value or in other words increases the profit.

Remembering that the pricing periods are assumed to be 15 minute periods and one day is 24 hours overally there will be 96 periods of pricing during one day period. The summation of payment/profit and the loss during each of the periods will give us the overall value of cost function for one day. The process can be extended to one week, one month, one year etc.

Simulation results for scenario 3 in which ideal finite-capacity storage is added on bus 2 in Micro-Grid network are represented in figures 10 to 12.

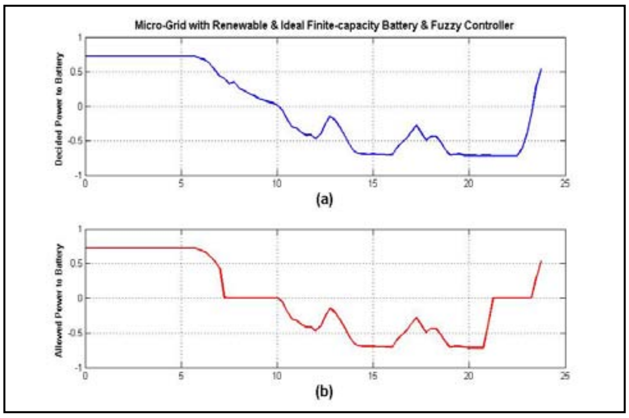


Figure 10 Output of the Fuzzy Controller; scenario 3;
(a) Theoretically allocated (b) Practically feasible

Figure 10 parts a and b are not matched to each other and this shows the fact that the values decided by the Fuzzy Controller for the power to be given to Battery or be taken from it might not be practical since battery unit assumed in scenario 3 is of finite capacity and the maximum and minimum limits of stored energy should be taken into account.

Output of the fuzzy inference engine which represents the power rate given to battery is shown in figure 11. Whenever the value of this variable is positive it means that power is delivered to the storage unit and if the power is drawn from the storage unit, the value will be negative.

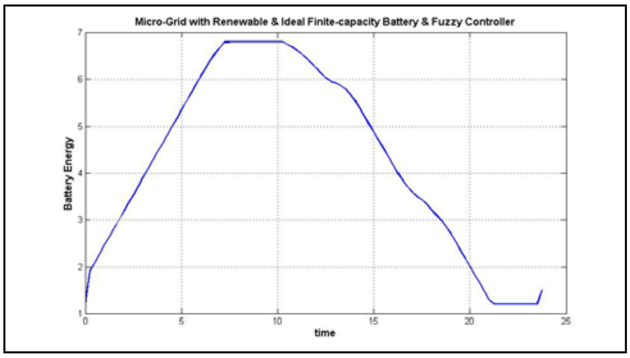


Figure 11 Measure of Energy stored in Battery; scenario 3

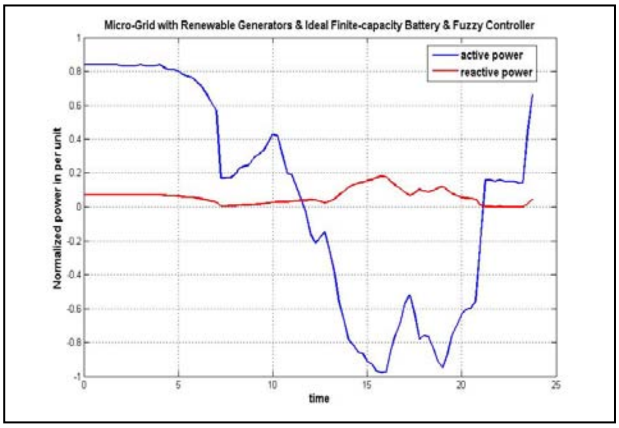


Figure 12 Power Flow of Bus 2 connected to Utility; scenario 3

The Center of Gravity, i.e. Centroid, defuzzification method is used for computing the crisp values of the output variable from the union of the Fuzzy rules. The formula used for defuzzification is shown in Eq. 2

$$y_{crisp} = \frac{\sum_{i=1}^{n}(max_{\mathrm{j}}\,(\mu_i) \times y_i)}{\sum_{i=1}^{n} max_{\mathrm{j}}\,(\mu_i)} \qquad (2)$$

Where y_{crisp} stands for crisp value of output variable. i changes between 1 and n, and refers to the number of discrete point at which the calculation is being done. j changes between 1 and the number of membership functions of output variable which in this case is 5, and represents the number of membership function curve for which we are getting the membership value of i^{th} point in the universe of discourse of the output variable. Therefore, $max_j(\mu_i)$ represents the final membership value of the i^{th} point in the universe of discourse of output, i.e. y_i. Equation 3 shows the relation between Balance, Distribution Loss and the overall Cost of Electricity.

$$Balance = Cost - Loss \quad (3)$$

$$Loss = \sum_{t=1}^{T}\big(\Pr(t)\,.\,S_L(t)\big) \quad (4)$$

Where Cost is calculated using Equation 1 and represents the amount that the microgrid owner has to pay to the main grid, if Cost > 0, or will get from the main grid, if Cost < 0. Loss stands for the overall sum of multiplication of the electricity price and wasted power on distribution branches for all 15 minute periods, i.e. $S_L(t)$. Loss will always be greater than or equal to zero. Balance will then be the measure of the amount than microgrid owner had to pay to the main grid or the amount of revenue that the microgrid owner will get from the main grid in case the power network were lossless.

Table 1. Simulation results for Loss, Cost and Balance

	Loss	Cost	Balance
Scenario 1	0.1339	1.2294	1.0955
Scenario 2	6.6039	-14.8711	-21.4750
Scenario 3	6.6039	-13.3021	-19.9059

In table 1 and Figure 13, total values of distribution loss, cost, and balance on one typical day for the three scenarios mentioned in section III are summarized. It must be noted that the values in the table are unit-less, and they can be regarded as measures for payment that the end-user should make to the utility because of regular operation of Micro-Grid, or profits earned due to improved operation and control of the Micro-Grid. The shaded cell represents the final cost or final revenue of the practical case using Fuzzy controller.

With no loss of generality, it is assumed that the reactive power has one tenth the value of active power.

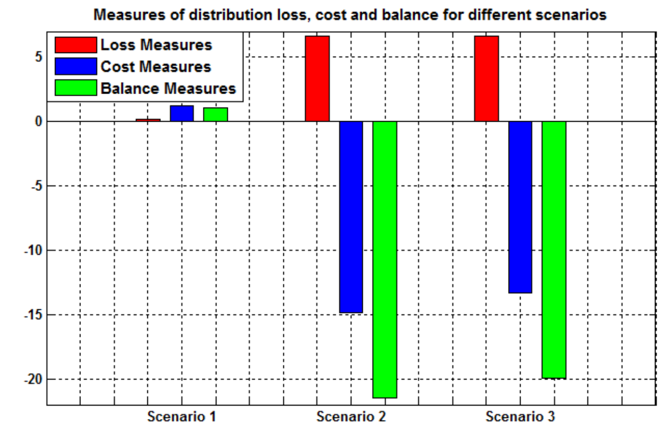


Figure 13 Measures of Loss, Cost and Balance for different scenarios

We can see that scenario 2 will provide the consumer with the most possible profit on balance and this is because of the fact that the battery unit used in scenario 2 is assumed to be of infinite capacity. Therefore there will be chance for utmost storage of power in the battery whenever required and the battery can provide that stored power completely to the Micro-Grid for appropriate usage any time. This is not a practical case though. In scenario 3 which is the practical case compared to the second scenario, battery storage unit is assumed to be of limited capacity and therefore, maximum and minimum limits of the stored energy in the battery might prevent the control system to apply the decided action on the storage unit thoroughly. This might cause a drop in the benefits that consumer will obtain using this approach as it can be seen by comparing the values of Balance for the two scenarios 2 and 3. However, by improvements in the battery production technologies this issue can be solved to good extents.

VI. Conclusion

The proposed Fuzzy-Logic based control method is applied for Battery Management in Micro-Grid Systems. In the micro-grid system three buses are considered as renewable generator and storage, utility, and load (smart house). The goal was to reduce the balance which is based on distribution loss and cost. The Micro-Grid was simulated under three scenarios. Simulation results obtained for Micro-Grid under scenario 2 where the ideal infinite-capacity storage is involved with the Fuzzy controller outperform the other two scenarios. However this is not practical. In third scenario, ideal limited-capacity storage was involved and the results were satisfactory. Therefore, using fuzzy controller it is possible to reduce the cost of the Micro-Grid system, and even let the customers make profit from selling the excess power to the utility.

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