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Load shedding in islanded microgrid using fuzzy linear programming

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ABSTRACT

The primary goal of any power microgrid is to provide consumers with reliable power. This becomes a challenge with the continued growth of population which necessitates a corresponding rise in power supply. However, this continued rise in power consumption with a limited power supply can result in voltage collapse and ultimately power outage. In times of severe disturbances in an islanded microgrid (IMG), load-shedding (LS) helps to avert the occurrence of a blackout. The IMG is usually supplied by distributed generations (DGs) which have low inertia or inertia less. Thus, when in islanded mode power imbalance is usually solved by performing optimal LS to prevent the system from plunging into a total blackout. This paper presents a hybrid method which is a combination of fuzzy and linear programming algorithm for optimal LS in IMG. The developed method is centered on power generation, load demand and power prioritization. The fuzzy linear programming (FLP) algorithm is tested on the IEEE 14 bus system. The simulation results show that the proposed algorithm is effective in shedding optimal loads to ensure equilibrium is restored and frequency is within set values of 50 Hz.

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1. INTRODUCTION

The nation's economic prowess is anchored in electrical power generation capacity. This is because the industrialization and livelihood of the population are dependent on this power [1], [2]. The installations of the new power plants are not able to cater for this rising power demand. The depletion of fossil-based fuels has further aggravated the problem of inadequate power [3], [4]. This has compelled engineers and researchers to find an alternative power to ensure there is system security [5], [6]. Microgrids are revolutionizing the power industry. They have made it possible for renewable energy sources (RES) to be incorporated into the distributed system [7].

The flexibility of the microgrid (MG) makes it be coupled to the grid and islanded. When connected to the grid it actively participates in power generation and when islanded from the grid it has to entirely depend on power from its generators to supply loads within the MG. Microgrid refers to a low-voltage power system network of less than 10 MW which may include the power grid [8], [9] and is usually supplied by distributed generations (DGs). The DGs are located close to load centers and this helps in reducing costs which could have been incurred in expanding transmission lines and help in the reduction of distribution losses [10], [11]. They also help in electrifying areas very far from the grid. Load shedding on another hand is a set of controls that are meant to reduce the load demand when there is a generation deficit to return the system to normal operation [12], [13].

The increasing penetration of RES has accelerated recent research to cope with emerging challenges and opened up the power industry. The main challenges of islanded microgrids (IMGs) are they are fed with inertia less sources like solar photovoltaic and fuel cells or with low inertia sources like wind power and small hydro power plants so they are prone to a lot of frequency fluctuations [14]. The stochastic nature of RES makes IMG prone to overloading or loss of generation. When faced with these scenarios a heuristic method for optimal load-shedding (LS) is required to ensure power equilibrium is restored as fast as possible.

The conventional LS schemes employed in grid system works satisfactorily well however, they cannot perform well in IMG cases. For IMG not much work regarding LS has been done [15]. Also, in conventional underfrequency load LS, a predetermined magnitude of the load is removed from the system whenever the frequency reaches a predetermined level, regardless of the electricity deficiencies. Practically, the quantity of LS is greater or lesser than the requirement to keep frequency within the allowed levels [16]. Though the conventional underfrequency load shedding (UFLS) is simple, it's unreliable in shedding the correct amount of load. Thus, to improve on its metaheuristic schemes based on artificial intelligence and machine learning have been proposed. The previous studies [17]–[19] presented a new UFLS with fuzzy inference and evolutionary algorithm for LS. The developed system was highly succinct for stabilizing large disturbances.

The previous studies [20], [21] presented a particle swarm optimization (PSO) algorithm for the improvement of voltage stability in MG. Here the proportional integral (PI) controller was used to improve system stability and PSO was used in optimizing LS for improvement of voltage stability. PSO suffers the problem of partial optimization which limits its application in determining optimal parameters when applied for LS.

An optimal LS using a genetic algorithm (GA) has been proposed in [22], [23] for optimal LS in a distribution system. The chromosomes represented a set of switches for which the algorithm was to open or close to restore the equilibrium state. A multi-objective GA has been presented in [24], [25] for service reinstatement in a distribution network. The simulations produced better results than convention GA. The drawback with the GA method, when used for LS, is that it has a slow response when applied in real-time.

Its eminent from reviewed past works that conventional algorithms provide suboptimal control and do not achieve optimal LS when applied to IMG. It can also be ascertained that little work has been done in optimal LS in IMG. To bridge this gap, this study developed a hybrid method of a fuzzy linear programming method for optimal LS.

2. STRUCTURE OF ISLANDED MICROGRID

The islanded microgrid is isolated by opening the circuit breaker at point of entry. According to the draft guide IEEE 1547 on operation, the IMG has to depend on its DGs to meet the load demands within the island. The configuration of IMG is shown in Figure 1. As seen the IMG is detached from the grid through PCC, it becomes an IMG and is composed of DGs, distributed storages (DSs), loads and a microgrid operation, and control center. The fact that DGs are located close to the customers helps in reducing transmission losses as well as network congestion.

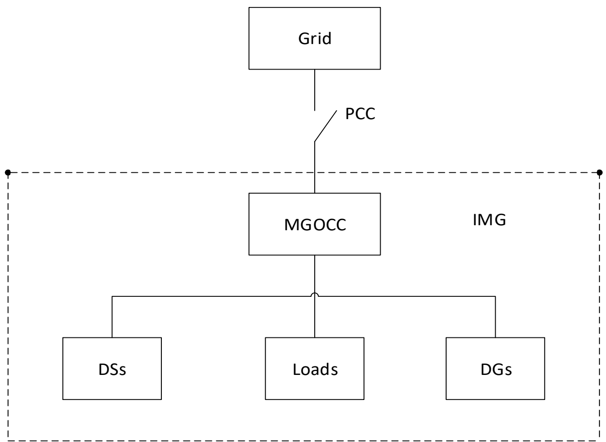

Figure 1. Islanded microgrid architecture

2.1. Fuzzy logic structure

A fuzzy logic system or controller is the non-linear mapping of input data (vector input) or linguistic variables into a scalar output. The system's general layout is shown in Figure 2 below. It consists of crisp inputs which undergo fuzzification through the membership functions. The rule base is formulated for the task to be executed. The rule base has diverse scenarios and mappings therefore one can formulate as many rules as possible. These rules are stored in the database from which inference is made to arrive at a decision at the output, the fuzzy decision is defuzzified to crisp values.

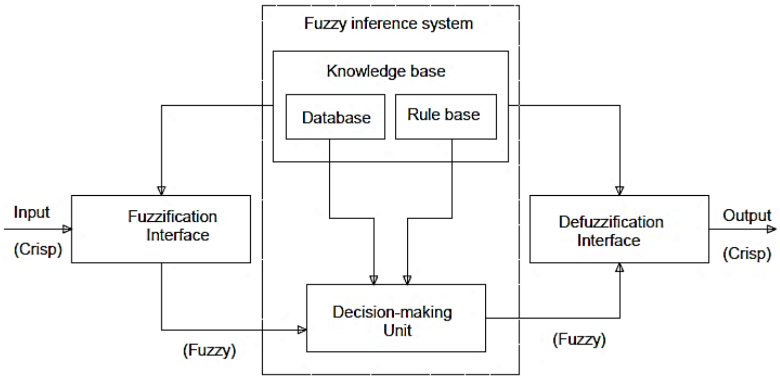

Figure 2. Fuzzy logic system architecture

2.2. Linear programming

In an optimization technique that uses a mathematical model to augment usage of scarce resources. The following are the fundamental elements of linear programming:
- Decision variables: these are the quantities to be determined.
- Objective function: this is the value that needs to be optimized in a given problem.
- Constraints: this shows how each choice variable would make use of limited resources.

2.3. Fuzzy linear programming

The structure of classical linear programming and fuzzy linear programming is identical. However, the fuzzy linear programming (FLP) approach allows values to take on fuzzy features while in the classical LP approach, the values are crisps. The fuzzy controller continuously checks the power demand and power generated continuously in the IMG in real-time. The system information is necessary for the FLP controller to calculate the quantity of load to shed. The FLP objective function takes the form:

$$\begin{aligned} &min\ z\ (x) = \textstyle\sum_{i=1}^{n} \tilde{c}_i\ \tilde{x}_i \\ &subject\ to \textstyle\sum_{i=1}^{n} \tilde{a}_{ij}\tilde{x}_i \ \tilde{\leq}\ b_i \\ &\tilde{x}_i\ \tilde{\geq}\ 0 \end{aligned} \tag{1}$$

where min stands for minimize, Z is the objective function to be minimized, c_i is the fuzzy coefficient of the ith variable and x_i is the decision variable which will be mapped by fuzzy membership functions. The fuzzified version of the equation is represented by the symbols $\tilde{\leq}$ and $\tilde{\geq}$ is interpreted as roughly less than and roughly greater than respectively. The symbols signify that the upper and lower limits are not sharp but are flexible and soft [26]. This is because real-world problems involve ambiguity and uncertainty which require flexible boundaries as compared to rigid ones. The fuzzy logic here provides flexibility in modelling the LS controller, adding new rules, modifying existing ones or even removing rules from the knowledge base. The linear programming compliments the fuzzy controller by optimizing the LS rules.

3. METHODOLOGY

This proposed system uses a fuzzy linear programming load-shedding approach to stabilize the power in the IMG. The fuzzy logic uses the power generated and the power demanded. The fuzzy controller sends this value to the linear programming controller for optimization and LS according to the priorities of the loads. Figure 3 is a summary of the LS process.

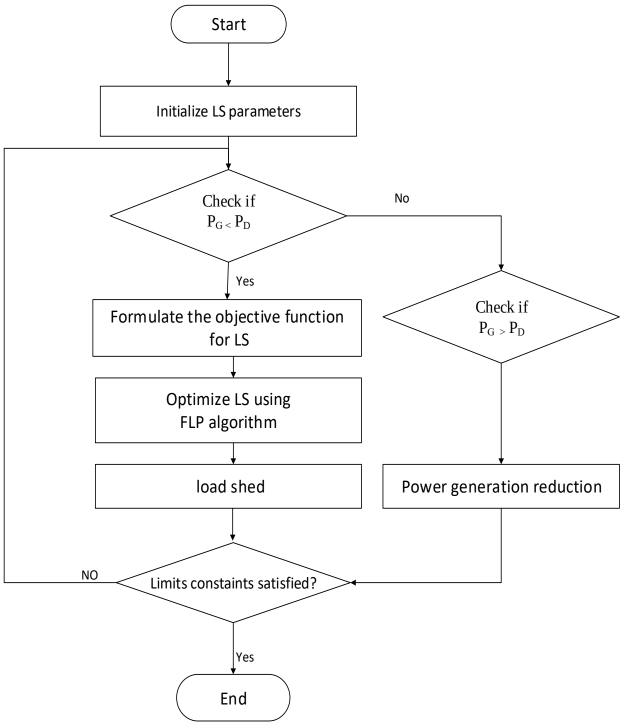

Figure 3. FLP algorithm

The structure of FLP and traditional LP are identical. The discrepancy is that in the traditional linear programming technique, in FLP all of the parameters take on fuzzy qualities while the values and operators utilized are crisp. The following fundamental procedure is followed to formulate LPP:

a) Identification of decision variables.
b) Creation of the objective function.
c) Defining non-negativity constraints and formulating restrictions.
d) Adding slack variables to equations to transform an inequality.

The optimal LS in the IMG using the FLP algorithm was performed on the modified IEEE 14 bus test system. The loads were assigned priorities. This was to ensure in case of power mismatch the less important loads are shed first, then if the system does not attain equilibrium, semi-vital loads will be shed in that order. The vital loads are not shed as they are composed of important installations like a hospital and military installation. The following contingencies were studied; generation loss and overload scenario.

The objective function for LS is formulated as (2).

$$\min z = \sum_{i}^{n}(P_{ri} x P_{LSi}) \tag{2}$$

Where Z is the representation of the objective function, n represents number of buses, P_{ri} is the priority of the loads, P_{LSi} is the amount of load to be shed from bus i. Subject to the following inequality constraints. The frequency is constrained as (3).

$$f_{i\,min} \leq f_i \leq f_{i\,max} \tag{3}$$

The voltage magnitude must satisfy, as in (4).

$$|V_i|_{min} \leq |V_i| \leq |V_i|_{max} \tag{4}$$

The power angle between bus i and bus k must satisfy, as in (5).

$$|\delta_i - \delta_k|_{min} \leq |\delta_i - \delta_k|_{max} \tag{5}$$

The active power P_{Gi} and reactive power Q_{Gi} are constrained as (6).

$$P_{Gi\,min} \le P_{Gi} \le P_{Gi\,max}$$
$$Q_{Gi\,min} \le Q_{Gi} \le Q_{Gi\,max} \quad (6)$$

The total active power and reactive power generated should meet the load demand and losses:

$$\sum_i P_{Gi} = \sum_i P_{Di} + P_L$$
$$\sum_i Q_{Gi} = \sum_i Q_{Di} + Q_L \quad (7)$$

where P_{Di} and Q_{Di} are the active and reactive power demanded while P_L and Q_L are the active and reactive power losses. The active power load flow equation, as in (8).

$$P_i = |V_i| \sum_{\substack{k=1 \\ k\neq i}}^{n} V_k\, |Y_{ik}|\, sin(\delta_i - \delta_k) \quad (8)$$

In an actual power system, the loads are dependent on the frequency and voltage, this is modelled as (9).

$$P = P_0 \left(\frac{V}{V_0}\right)^a x\left(1 + K_{pf}\Delta f\right)$$
$$Q = Q_0 \left(\frac{V}{V_0}\right)^b x\left(1 + K_{qf}\Delta f\right) \quad (9)$$

The power loss minimization is achieved using (10).

$$min\, P_{Loss} = \sum_{n=1}^{N} G_n \left(V_i^2 + V_j^2 - 2V_iV_j \cos \delta_{ij}\right) \quad (10)$$

Where G_n is the conductance of the n^{th} branch connected within the i^{th} and j^{th} buses. The model of FLP was created in the MATLAB/Simulink environment. The fuzzy logic toolbox was used to code the load-shedding rules. The power generated and demand were the two inputs to the FLP controller as shown in Figure 4. The output were the loads to shed to keep the frequency within the predetermined range.

Extremely very low (EVL), extremely low (EL), very low (VL), and low are the power generated linguistic variables input to the controller (L). The high negative (HN), low negative (LN), low positive (LP), and high positive (HP) linguistic variables used in the power demanded are the ones that are input to the controller. Very tiny shed (VSS), small shed (SS), big shed (BS), and very big shed (VBS) are the linguistic variables for the LS controller's output [27]. The rules are summarized in Table 1.

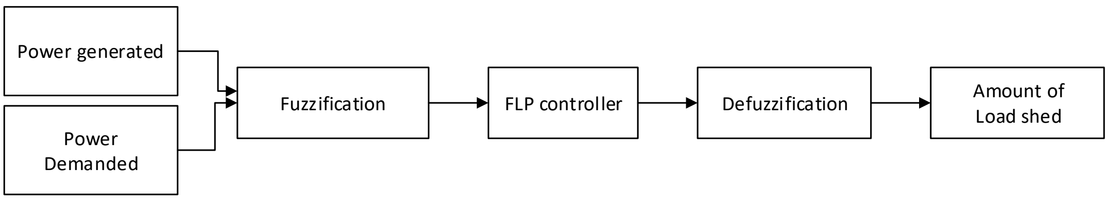

Figure 4. Fuzzy linear programming design

Table 1. FLP rules design

		Power generated			
Power demanded		EVL	EL	VL	L
	HN	VBS	BS	BS	SS
	LN	VBS	BS	SS	SS
	LP	SS	SS	VSS	VSS
	HP	VSS	VSS	VSS	VSS

4. RESULT AND ANALYSIS

The proposed FLP algorithm was tested in modified IEE14 bus system and results tabulated. The results obtained depicts that the FLP algorithm is effective in shedding optimal loads to ensure equilibrium is restored in IMG and frequency is within range of 50 Hz. This is elaborated in following subsections.

4.1. Generation contingency

Scenarios for loss of generation contingencies was investigated and tabulated in Table 2. The load was fixed at 315 MW and power generation was varied at interval of 5 MW from 265 MW to 305 MW. From the observation, the load to shed from buses decrease proportionally from 5.0246 MW to 3.0609 MW. The power losses also increased from 0.2349 MW to 0.2371 MW when the generation was 305 MW. It can be observed that the load to shed decrease with the reduction of the difference between power generated and connected load.

Table 2. Load shedding for a fixed load at 315 MW

Power generated (MW)	Power losses (MW)	Amount of load shed (MW)
265	0.2349	5.0246
270	0.2348	4.7993
275	0.2349	4.5497
280	0.2350	4.3004
285	0.2353	4.0516
290	0.2360	3.8032
295	0.2365	3.5553
300	0.2368	3.3079
305	0.2371	3.0609
310	0.2378	2.8143

4.2. Generator output before and after load shedding

Table 3 displays the outcomes of the bus 9 simulation with a fixed quantity of 50 MW load shedding. The LS has slightly lowered the bus voltages and line flows, consequently causing a decrease in the output power of generators 4 and 5. After LS, there was a reduction in demand and the available generation was able to meet the load demand which consequently led to a decrease in line power flows as a consequence of low impedance in the line.

Table 3. Generator output before and after LS

Parameter	Before LS	After LS
Bus voltage (pu)	1.0605	1.0597
Line flow (MW)	145.0	132.7
Generator 1	232.4	232.4
Generator 2	40.0	40.0
Generator 3	0.0	0.0
Generator 4	125.0	75.0
Generator 5	50.0	0.0

4.3. Bus voltages before and after load shedding

Table 4 shows the observation of the bus voltages at each of the buses with and without load shedding in per unit values. It can be observed that after LS is performed the voltage profile improve remarkable in most buses. The more the values approach closer to 1.0 pu it shows that the system is approaching equilibrium state.

Table 4. Bus voltages before and after LS

Bus	Voltage without LS (pu)	Voltage with LS (pu)
1	1.05	1.05
2	0.981	1.02
3	0.97	1.01
4	0.961	1.00
5	0.953	0.996
6	0.946	0.991
7	0.943	0.988
8	0.94	0.986
9	0.936	0.983
10	0.933	0.981
11	0.925	0.976
12	0.922	0.974
13	0.919	0.972
14	0.917	0.970

4.4. Line flows before and after load shedding

In Table 5 most of the lines, including lines 4-7 and 7-8 where the restrictions were exceeded before LS was applied, have seen a reduction in line flows as a result of LS. The reduction in line flow is because after LS is performed load demand is reduced implying that that the power flow will reduce signifying that the line is not overloaded. This greatly helps in reducing the possibilities of the system collapsing during overload.

Table 5. Line flows before and after LS

Line	Flow without LS (pu)	Flow with LS (pu)	Line	Flow without LS (pu)	Flow with LS (pu)
1-2	0.657	0.650	4-9	0.251	0.249
1-5	0.304	0.302	5-6	0.262	0.260
2-3	0.476	0.472	6-11	0.381	0.377
2-4	0.402	0.4	6-12	0.523	0.518
2-5	0.251	0.25	6-13	0.393	0.389
3-4	0.237	0.236	7-8	0.238	0.244
4-5	0.413	0.410	9-10	0.288	0.285
4-7	0.245	0.255	9-14	0.284	0.282

5. CONCLUSION

In this paper, the minimization and optimization of the LS objective function were met using the FLP approach to achieve the best LS in IMG. The results were validated using modified IEEE 14 bus system. The findings show that the FLP algorithm was successful for LS in IMG. The LS was tested for generating contingencies and overload contingencies. To make sure the operating limits were not violated in the IMG, optimal LS was carried out for each scenario. The simulated outcomes showed that the FLP LS method was successful in stabilizing the frequency through optimal load shedding.

The inputs to the controller were imprecise, the fuzzy logic controller handled the ambiguity to process and execute the proper LS rules. Load shedding and optimization were accomplished via linear programming. The feasible solution of the LS objective function was defined by the inequality constraints. The results obtained show that in case there is an overload in IMG due to contingencies, the minimum quantity of load is shed to ensure an overloaded IMG is restored to equilibrium state.

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