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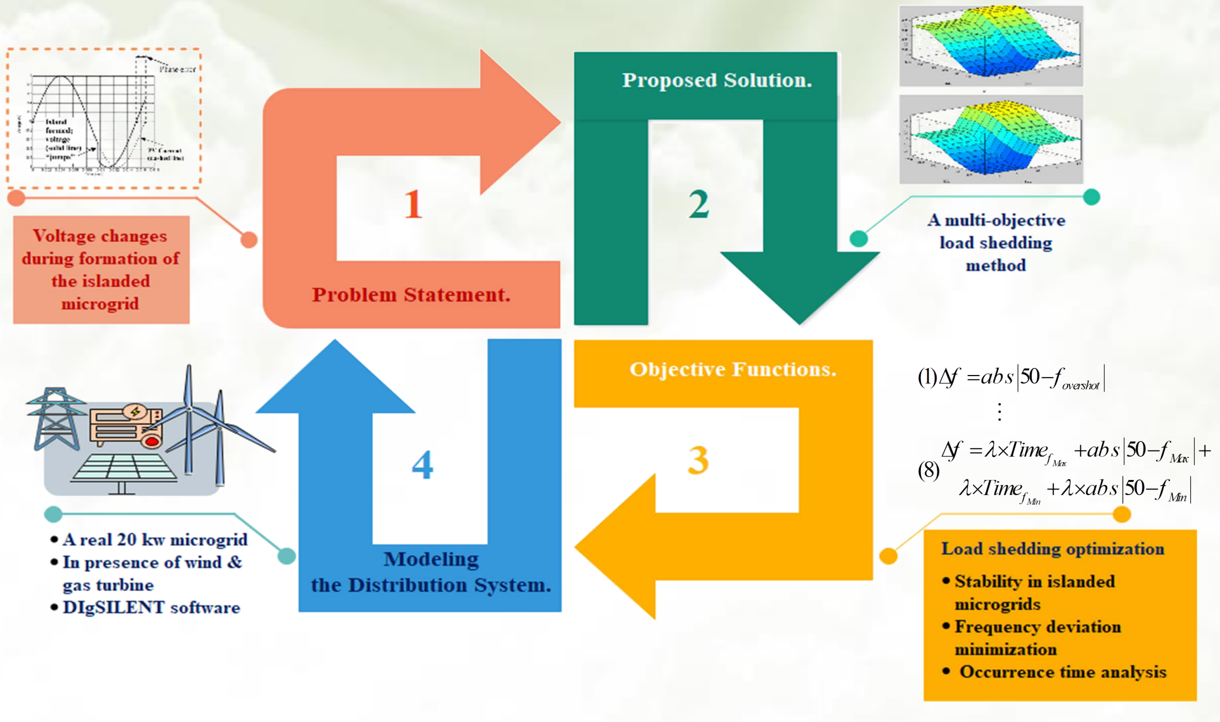
Frequency Stabilizing and Reducing Power Outages of The Islanded Power Network Using a Load Shedding Method in The Presence of Renewable Energy Resources

Reza Eslami

Highlight

- Introduction of a novel load shedding strategy for microgrids
- Aiming to stabilize frequency and minimize power outages
- Implementation of load shedding in islanded power networks with renewable energy sources
- The proposed method's benefits include flexibility, rapid response, and precision

Graphical Abstract



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Frequency Stabilizing and Reducing Power Outages of The Islanded Power Network Using a Load Shedding Method in The Presence of Renewable Energy Resources

Reza Eslami *

Electrical Engineering Faculty, Sahand University of Technology, Tabriz, Iran.

*** Corresponding Author:** *eslami@sut.ac.ir*

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ABSTRACT

Controlling the frequency and voltage of the power network with renewable energy resources is one of the most important things in the integrity of the network. Therefore, after occurring any accident or fault in the network, the frequency and voltage and in general all the basic parameters of the network must return to their acceptable range within a certain period of time. Despite all the technical, economic and environmental advantages that renewable energy resources have, the presence of these kind of sources may have negative effects on voltage profiles and protection coordination in distribution networks, it is also possible that a part of the network acts as an unwanted island, which complicates the operation and control of the network and creates a risk of electrocution for the network personnel. Therefore, islanding detection is very important and necessary in network protection and load shedding methods are usually used to eliminate this event. In this paper, a multi-objective load shedding method in microgrids is proposed for the frequency stability and reduction of power outages. Among the advantages of the proposed method can be mentioned its flexibility, speed of operation and high accuracy. The proposed method is applied and simulated on a microgrid in the DIgSILENT software environment, and the results of the simulation confirm the advantages of the proposed method.

1. Introduction

In the field of electricity industry, a massive evolution has taken place in the energy generation and transmission systems in most developed countries, which have several advantages in technical and economical cases of generation and transmission grids. This new energy generation system is called distributed generations (DGs) [1, 2].

Despite all benefits of DGs, the presence of DGs may have negative effects on voltage profiles and protection coordination in the distribution grids, so the operation and control of the grid becomes more complicated [3, 4]. Connection of DGs to the grid creates harmonics and reduces the short-circuit impedance. Additionally, it can be dangerous for grid repairmen if grid-connected DGs work as an island during outages. Islanding means wanted or unwanted disconnection of a part of the distribution system from the main power source [5]. Figure 1 shows voltage variations during islanding. The control of the grid frequency and voltage is one of the most important cases in the integrity of the grid. Therefore, the frequency and voltage and, in general, all the basic parameters of the grid should return to their acceptable state within a certain period of time (after the occurrence of an emergency condition). Load shedding is one of the common methods to control the grid emergency states. Many studies in the field of load shedding have been made in recent years. The scheme presented in [6] was not suitable for the system protection.

In the mentioned study, load shedding strategy was considered based on voltage and frequency indices. In this strategy, load shedding was conducted outside the desired voltage and frequency range, according to the Q-V curve of the reactive power. Furthermore, the goal of this paper was to release the microgrid in the severe combined contingencies, where the rate of load shedding was not economically important. Reference [7] announced the operator's experience as the basis for load shedding and recommended the exact load model for better results. In this paper, the microgrid was divided into smaller islands and load shedding was performed based on the disturbance rate. In this method, the delay time of each step was assumed be of a larger value. So, this control method was inappropriate in low power microgrids, which should be stable in the shortest possible time and causes the disintegration of these microgrids. In [4, 8], speed and accuracy were introduced as the basic factors in sub-frequency load shedding to maintain the stability of the system and the use of SCADA system was presented to improve the deficiencies of adaptive protection model. As well, a static load shedding strategy was proposed in [9], in which a constant amount of load was cut off with reduction of frequency. In [10], a method was presented in the central control system to perform a fast load shedding, which was not applicable in the low power systems. In [11], difficulties of adaptive load shedding such as estimating the amplitude of the disturbance, cut-off positions and control actions by relays were introduced.

In another article, the author claimed that if there are several sources in the microgrid, it will be better to consider the result of frequency change rate graphs. In the Slovenian load shedding standard, four threshold frequency values were defined, in which the percentage of the load unplugged from the whole microgrid was defined for each threshold frequency with considering the disturbance rate. The mentioned article mostly

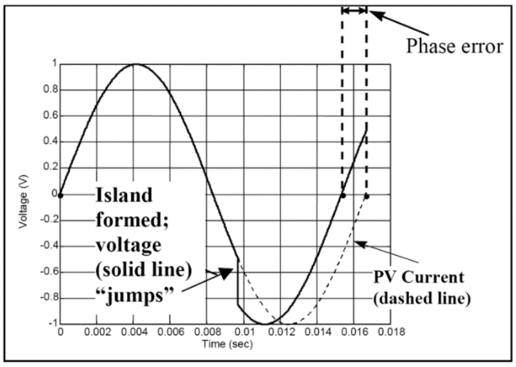


Figure 1. Voltage changes during formation of the islanded microgrid.

focused on correcting the coefficients of the cut off load percentage. This paper includes desirable results for high power systems; but it was not useful for low power systems [12]. In [13], the authors showed that, in one case out of five load shedding cases, a suitable response to power shortage could be achieved. Also, given that the slope (frequency change rate) lonely is not able to have a convincing response; the authors proposed the frequency change rate in terms of voltage. Ref. [14] fixed the grid frequency by ejecting additional loads and stabilized the grid by removing sensitive buses; however, it was analyzed only for grids containing two small hydro generators.

Moreover, [15] indicated that the concavity in the frequency of load shedding could be determined. But big disturbances led to a decline in the system frequency and the buses voltage was dependent on the shortage of active and reactive powers or it related to information of the generation inter-load unbalancing. In [16], the frequency change rate was used to estimate the amplitude of disturbance and the voltage change rate corresponding to the reactive power was used to identify the buses, which required load shedding. To calculate the change rate of frequency and voltage, using devices such as numerical stability or phase measurement units or methods such as Kalman filter to estimate the parameters was proposed. This method conferred good results; however, in modern microgrids, at least in low power systems, loads are frequently prioritized and it cannot be said that load shedding should be conducted according to the priority system conditions [16].

In [17], a new adaptive load shedding is presented, which prevents the large reduction of frequency in the emergency situations and minimizes the line overload. Size and position of disturbance in decentralized models were not known, so disturbance rate was related to the frequency change rate and inertia constant and frequency local change was related to the disturbance position. As a result, an attempt was made to optimize the threshold frequency value using these cases in this study. Then by averaging the microgrid frequency graph (total regions in the microgrid), if average of the microgrid frequency was less than threshold frequency value, then load shedding was conducted. In [18], in addition to frequency stability, the voltage stability was also considered and swing equation and telecommunication systems were used respectively to calculate the amplitude of the disturbance and transmit information. In this method, choosing small sampling time (the information sampling time to transmit) created some problems such as aberration in the frequency natural fluctuations. Also, telecommunication systems were not able to transmit the information in a short time. A relay was proposed for each station in this method. These relays implement load shedding program based on voltage level of certain buses in case of frequency change. And those buses were which reached below the threshold. The cost was not a criterion in this paper and only technical aspect was discussed.

According to [19], when the microgrid frequency reduced to a value less than the threshold frequency, load shedding was conducted according to frequency change rate. A try was made in this article to correct the threshold frequency. But it faced to the problem of normal frequency fluctuations at frequencies close to the normal frequency. So, in the mentioned article, a phase control loop was used to solve this problem and to choose the exact frequency. Moreover, six steps with six different threshold frequencies were considered for load shedding. Another load shedding strategy was based on online load measurement and frequency-load curve. But real-time load information was not always available and online load measurement was expensive for small distribution systems. Furthermore, determining frequency-load dependence of the system is often difficult. In the adaptive load shedding strategy, the relay regulation was changed with the frequency collapse curve [20], which was determined based on the frequency information of the amount of the ejected load [21]. Adaptive load shedding strategy required real time data of loads and generations and also, that was difficult to determine the microgrid inertia. The issues mentioned above were for the microgrid containing generation sources at the scale of large power plants. In [22], load shedding of the islanded microgrid, which is supplied by low-power DGs was discussed. The load shedding of the islanded distribution system should be different from high power systems due to different specifications. Most generators have small inertia in the islanded distribution system, so the frequency tends to collapse faster.

2. The proposed method of load shedding in the islanded microgrid in the presence of distributed generation sources

2.1. Introducing the objective function of the paper

Load shedding with the presence of DGs is an optimization process, which is conducted for various goals. These goals enter the load shedding problem in the form of objective function parameters. Since the considered optimization problem in this paper is load shedding with the presence of DGs based on the stability and reliability factors in the sub-transmission substations. These factors will enter the objective function. so, the most important factor will enter the problem objective function. Then, by analyzing each of the objective functions and their upsides and weaknesses, the objective function could have better results was selected and the presented tables were used for each of these 8 objective functions.

2.2. Factors affecting the load shedding in the presence of distributed generation sources

The new method presented in this paper has the following steps to achieve the stability of the islanded microgrid in the shortest possible time:

- Creating a selection table based on the tendency-to-pay factor of each subscriber (formation of this table is done based on the presented method in study [22].)
- After providing the selection table and the load departure priority, by creating the 8 objective functions which are introduced in the following, a main project and 3 sub-project are written in DIgSILENT software in order to reduce the grid frequency drop, lessen the microgrid frequency overshoot and determine the times at which these frequencies will occur, and the objective functions are analyzed and the best function to attain the shortest possible time to achieve the

stability is selected. This is performed by linking two softwares, DIgSILENT and MATLAB, in which the genetic optimization algorithm is written.

In the following, the proposed load shedding strategy is analyzed, which covers the grid variables in the form of 8 objective functions.

- The first objective function:

As a first step, the following formulation is introduced to reduce the difference between the created maximum frequency and the base frequency:

$$\Delta f = abs\left|50 - f_{Overshoot}\right| \quad (1)$$

$f_{overshoot}$ in Equation (1) is the maximum frequency produced in the network due to creation of the islanded state.

- The second objective function:

The difference between the frequency and the base frequency can be minimized with the help of this objective function. In order to examine how effective this parameter is in achieving the above purposes, Equation (2) will be defined and analyzed separately.

$$\Delta f = abs\left|50 - f_{Min}\right| \quad (2)$$

- The third objective function:

One of the considered factors to achieve the suitable response is to analyze the maximum frequency created in the grid and also the minimum frequency created in the microgrid simultaneously. So, in this step, the best state is analyzed in which the minimum overshoot and the minimum frequency drop are achieved by interrupting the minimum load. Therefore, the objective function for this purpose is written in Equation (3).

$$\Delta f = abs\left|50 - f_{\min}\right| + abs\left|50 - f_{Overshoot}\right| \quad (3)$$

- The fourth objective function:

The objective function given in Equation (4) is used to survey the occurrence time of the grid maximum frequency and the maximum frequency drop.

$$\Delta f = Time_{f_{\min}} + Time_{f_{\max}} \quad (4)$$

In this Equation, $Time_{f_{\min}}$ and $Time_{f_{\max}}$ are the times that the grid minimum and maximum frequency occur respectively.

- The fifth objective function:

One of important factors considered in this paper is the time that the maximum drop occurs in the grid. For this purpose, in the objective function given in Equation (5), in which the best time that the frequency drop is at its minimum value, is introduced. This optimal time is when the frequency drop is in its minimum value.

$$\Delta f = Time_{f_{\min}} \quad (5)$$

- The sixth objective function:

Simultaneous consideration of the maximum frequency occurred in the grid along with the time at which this frequency is created, is presented in another objective function that is specified by Equation (6). In this objective function, in order to equalize the limit of numbers, the factors are multiplied by a coefficient of λ, This weight coefficient shows the importance degree of factors from a design point of view.

$$\Delta f = \lambda \times Time_{f_{min}} + \lambda \times abs\left|50 - f_{min}\right| \quad (6)$$

In Equation (6), λ equals to *0.1*.

❖ The seventh objective function:

In order to analyze separately the time that the grid maximum frequency occurs along with the relevant time, another objective function is defined by considering the points made in the previous step.

$$\Delta f = \lambda \times Time_{f_{max}} + abs\left|50 - f_{max}\right| \quad (7)$$

❖ The eighth objective function:

In order to comprehensively review and compare different important scenarios, a new load shedding method was presented in this paper that covered all the load shedding goals mentioned in Equations (1) to (7). This general objective function is introduced in Equation (8). As it is shown in the simulation results, it certainly has higher flexibility, speed and accuracy.

$$\begin{aligned} \Delta f &= \lambda \times Time_{f_{max}} + abs\left|50 - f_{max}\right| \\ &+ \lambda \times Time_{f_{min}} + \lambda \times abs\left|50 - f_{min}\right| \end{aligned} \quad (8)$$

2.3. Modeling of the under-studying Distribution system

A 20 KW real microgrid owned by Himmerland Elforsynig Factory in Denmark has been selected for this study [23]. The single-line diagram of the distribution system is illustrated in Figure 2. In this microgrid, 11 radial feeders exist named JUEL, STK1, HJOR, FLOE, REBD, MAST, STCE, SORP, STNO, STKV, STSY. A CHP (Combined Heat and Power) power plant with 3 gas turbine generators exists in the STKV feeder. Also, there are 3 constant-speed wind turbines in the SORP feeder.

SORP, STKV, STNO, STSY, JUEL, FLOE, MAST, STCE feeders were used to test the proposed method. The whole studied distribution system was modeled in the standard models of DIgSILENT v.14.1.3 software. The wind turbines were modeled as a Two-Mass system in this study, which is suitable for studying the transient mode of the power system [24]. The power factors of all turbines were 1.

In the eight objective functions which are introduced above, the coefficient of the constant power loads is 0 and the coefficient of the loads which are severely dependent on the frequency and voltage is 1. So, a value of 0.5 is considered for these coefficients in order to balance the frequency change rate.

In the selection table, at which the loads interrupting priority are defined, the change rate of each parameter (i.e., frequency change rate, voltage dependent frequency change rate, power shortage) is available. This table is to see how many loads should be omitted in order to compensate for the active power shortage of the microgrid. In this regard, 3 considered scenarios are as follows:

First scenario (Table 1): it is assumed that loads with less power pay less to the distribution companies. Accordingly, arranging the loads based on cost is equal to arranging the loads in order of the minimum to maximum electrical power respectively.

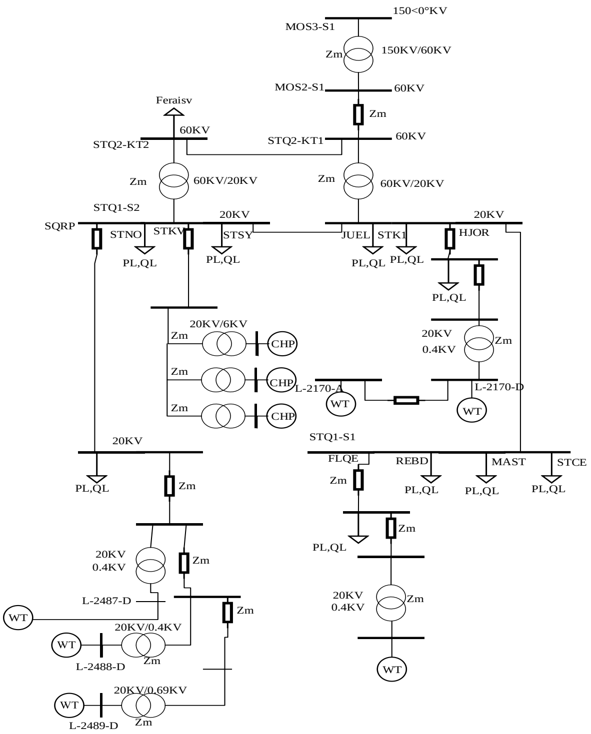


Figure 2. A local microgrid in Denmark.

Second scenario (Table 2): it is assumed that the loads cost has no relation with their power. So, arranging loads based on cost is a random function in terms of their power.

Third scenario (Table 3): like the second scenario, loads are arranged randomly, except that the maximum electrical power is in the first place.

Since the frequency changes can occur over a relatively long period of time due to various transient occurrences, the time period of the frequency changes is important. Therefore, the rate of frequency changes over time is used to detect the islanded state. Equation (9) indicates how to calculate the frequency change rate.

$$R_O C_O F = \frac{df}{dt} = \frac{f_2 - f_1}{t_2 - t_1} \tag{9}$$

In Equation (9), dt is contracted to be *10 ms* for each load in the selection table. Moreover, df is the frequency difference in the islanded microgrid, which is equal to half cycle (the microgrid frequency is *50 Hz*).

In the tables, the frequency change rate, the rate of frequency change dependent to the voltage and the microgrid power shortage are used. But in cutting off a number of loads in the first step, no significant difference was observed between this method and the method [22]. Mathematic formulations of these two functions (the rate of frequency change depends on the voltage and the microgrid power shortage) are available in [14], which are displayed in Equation (10).

$$P_{def} = \frac{2H_{COI}}{f_N}.100.\frac{df_{COI}}{dt} + \sum_{i=1}^{m} P_{L0,i} \cdot \left[\left(\frac{U_i}{U_{0,i}} \right) - 1 \right] . \frac{100}{P_{L0}} \tag{10}$$

The islanded microgrid was created in zero second. The time of 80 ms is considered for operation of the breaker and command of the relays.

Table 1. The selection table which is sorted by minimum to maximum of loads power.

First scenario

Load level	Load name	Willingness to pay of each load	Rate of change of frequency	Sum of the rate of change of frequency	Rate of change of frequency according to the voltage	Sum of the rate of change of frequency according to the voltage	Deficiency of power (dp)	Sum of the deficiency of power (dp)
1	Load 09	0.81	-21.7	-21.7	-1.7027	-1.7027	-83.5099	-83.5099
2	Load 10	0.83	-21.7	-43.4	-1.7027	-3.4054	-83.5099	-167.0199
3	Load 11	0.86	-21.7	-65.1	-1.7027	-5.1081	-83.5099	-250.5299
4	Load 07	0.87	-25.1	-90.2	-1.7908	-6.8989	-88.5935	-339.1235
5	Load 08	0.89	-28.5	-118.7	-1.8736	-8.7726	-93.4586	-432.5821
6	JUEL	0.91	-29.6	-148.3	-1.9010	-10.6737	-94.7444	-527.3266
7	STCE	0.92	-32.5	-180.8	-1.9824	-12.6561	-99.4948	-626.8214
8	FLOE	0.93	-40.9	-221.7	-2.2084	-14.8646	-111.9883	-738.8098
9	STSY	0.95	-41.1	-262.8	-2.2151	-17.0797	-112.2833	-851.0931
10	STNO	0.96	-38.7	-301.5	-2.1469	-19.2266	-108.6315	-959.7246
11	MAST	1	-48.9	-350.4	-2.4404	-21.6671	-125.1918	-1084.9164

Table 2. The selection table which is sorted by stochastic function of loads power.

Second scenario

Load level	Load name	Willingness to pay of each load	Rate of change of frequency	Sum of the rate of change of frequency	Rate of change of frequency according to the voltage	Sum of the rate of change of frequency according to the voltage	Deficiency of power (dp)	Sum of the deficiency of power (dp)
1	STSY	0.79	-41.1	-41.1	-2.2151	-2.2151	-112.2833	-112.2833
2	Load 10	0.84	-21.7	-62.8	-1.7027	-3.9178	-83.5099	-195.7933
3	STNO	0.85	-38.7	-101.5	-2.1469	-6.0647	-108.6315	-304.4248
4	Load 09	0.86	-21.7	-123.2	-1.7027	-7.7674	-83.5099	-387.9348
5	STCE	0.89	-32.5	-155.7	-1.9824	-9.7498	-99.4948	-487.4296
6	Load 07	0.9	-25.1	-180.8	-1.7908	-11.5407	-88.5935	-576.0232
7	Load 08	0.91	-28.5	-209.3	-1.8736	-13.4144	-93.4586	-669.4818
8	FLOE	0.95	-40.9	-250.2	-2.2084	-15.6229	-111.9883	-781.4702
9	Load 11	0.98	-21.7	-271.9	-1.7027	-17.3256	-83.5099	-864.9802
10	JUEL	0.99	-29.6	-301.5	-1.9010	-19.2266	-94.7444	-959.7246
11	MAST	1	-48.9	-350.4	-2.4404	-21.6671	-125.1918	-1084.9164

Table 3. The selection table which is sorted by stochastic function of loads power and the maximum load is in the first level.

Third scenario

Load level	Load name	Willingness to pay of each load	Rate of change of frequency	Sum of the rate of change of frequency	Rate of change of frequency according to the voltage	Sum of the rate of change of frequency according to the voltage	Deficiency of power (dp)	Sum of the deficiency of power (dp)
1	MAST	0.89	-48.9	-48.9	-2.4404	-2.4404	-125.1918	-125.1918
2	Load 07	0.9	-25.1	-74	-1.7908	-4.2313	-88.5935	-213.7853
3	Load 09	0.91	-21.7	-95.7	-1.7027	-5.9340	-83.5099	-297.2953
4	Load 10	0.92	-21.7	-117.4	-1.7027	-7.6367	-83.5099	-380.8053
5	STCE	0.93	-32.5	-149.9	-1.9824	-9.6191	-99.4948	-480.3001
6	STNO	0.94	-38.7	-188.6	-2.1469	-11.7660	-108.6315	-588.9316
7	Load 11	0.95	-21.7	-210.3	-1.7027	-13.4687	-83.5099	-672.4416
8	JUEL	0.96	-29.6	-239.9	-1.9010	-15.3698	-94.7444	-767.1860
9	FLOE	0.97	-40.9	-280.8	-2.2084	-17.5783	-111.9883	-879.1744
10	Load 08	0.99	-28.5	-309.3	-1.8736	-19.4520	-93.4586	-972.6331
11	STSY	1	-41.1	-350.4	-2.2151	-21.6671	-112.2833	-1084.9164

3. Simulation results

The sample grid introduced for simulation using the proposed method is analyzed in two states:

- The overshoot state, in which the maximum frequency value of the islanded microgrid became more than 1 P.U during frequency stability. Optimal situation for this state occurs when this factor has the minimum value, because the islanded microgrid will be stabilized more quickly.
- Second simulation is performed based on the maximum value of frequency drop in the islanded migrogrid. It is obvious that the less value is the better when the simulation is performed.

To identify the capabilities of the present paper in creating stability in the islanded microgrids, comparisons with [22] have been made; because both articles have the same purpose. These comparisons have been done in 6 states that cover all the states involved in the islanded mode. These 6 states are:

- Minimum microgrid frequency
- Maximum time, at which the overshoot occurs along with the maximum time, at which this frequency occurs.
- Maximum time, at which the frequency of the islanded microgrid decreases.
- Maximum frequency drop in the sample islanded microgrid along with the maximum time, at which this frequency occurs.
- Maximum overshoot frequency along with the maximum time, at which the maximum frequency drop occurs.
- Maximum microgrid frequency, maximum overshoot time, maximum frequency drop and its maximum time.

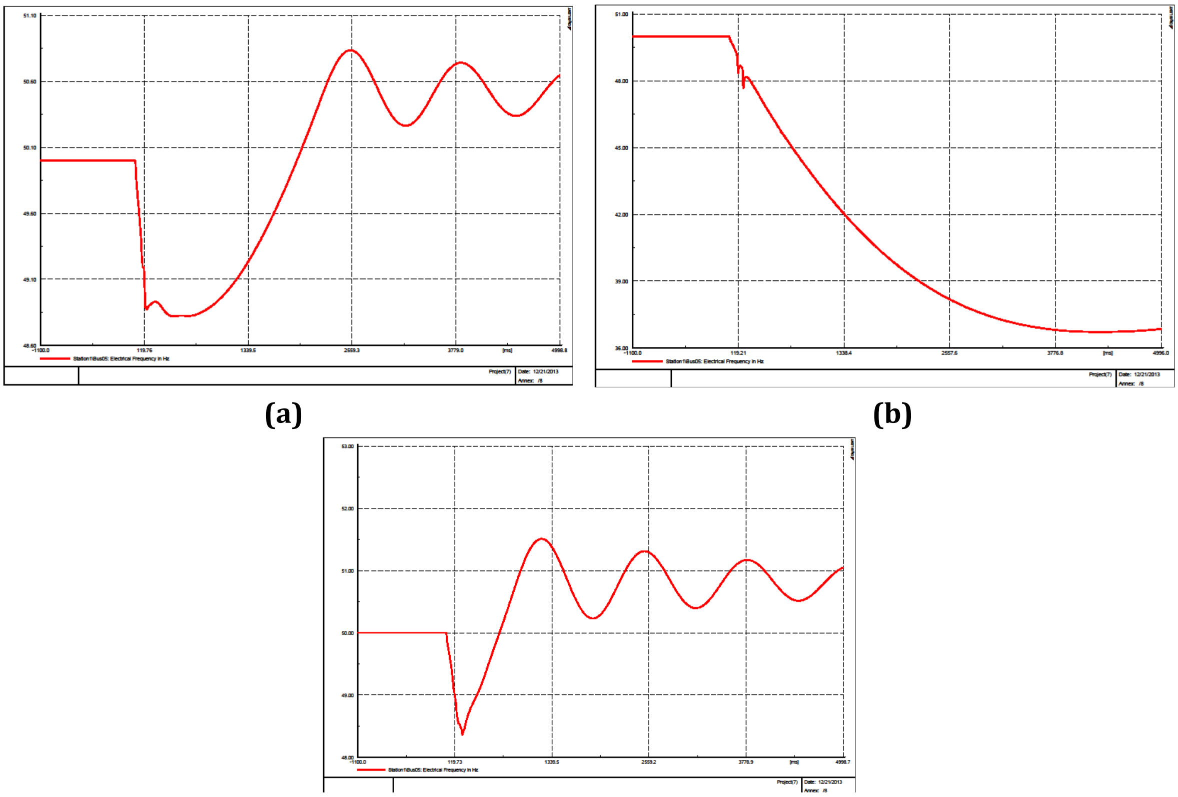
In the following, each of the proposed tables has been analyzed with the defined objective functions.

3.1. The selection table which is sorted by the first scenario

The goal of the comparison made in this state is to evaluate the capability of the proposed method at the time of the maximum overshoot in the islanded microgrid. Table 4 shows the loads cut-off time according to their priority with the first, fifth and eighth objective functions. In fact, this table indicates the time after which of the loads should be disconnected from the grid when the islanded mode occurs. Accordingly, load 9, which has the shortest operating time, is the least important one among the grid loads and should be unplugged faster than the other grid-connected loads. On the other hand, the result of Table 4 points out that the MAST load has the longest operating time, so this load is the most important load. The objective function of this state presented in Section 2 is ptimized by the genetic optimization algorithm, the results of which are presented in Table 5. Additionally, Figure 3(a-c) shows the diagram of the grid frequency variations in the islanded microgrid and the load shedding for the first, fifth and eighth objective functions respectively.

Table 4. Interruption times of loads for the first, fifth and eighth objective functions in the first scenario.

Load breaker	First objective function	Fifth objective function	Eighth objective function
Load 09	0.0809	0.1025	0.0869
Load 10	0.095859	0.604287	0.133594
Load 11	0.096759	0.924487	0.143394
Load 07	0.100484	1.303721	0.16479
Load 08	0.116384	2.343321	0.16559
Load JUEL	0.137028	2.758584	0.200397
Load STCE	3.288928	3.193084	0.226897
Load FLOE	3.794485	3.537994	0.454497
Load STSY	4.384085	3.974594	0.535197
Load STNO	6.350155	4.484685	1.189543
Load MAST	7.233555	4.663485	2.034243



(a) (b)

(c)

Figure 3. The load shedding implementation in the first scenario
a. With the first objective function, b. With the fifth objective function, c. With the eighth objective function.

Table 5 exhibits the optimal state obtained from the proposed method using the first, fifth and eighth objective functions. As shown by the first objective function column, the optimal state and stability of the microgrid are achieved by leaving out 6 loads. The convexity and concavity times in this state are specified in the table. It is obvious from the minimum and maximum times of frequency presented in this table, the stability state of the microgrid has been achieved by the presented method.

According to the values indicated in Table 5, the mentioned objective function has three main advantages compared to the method [22]:

- The frequency drop in the proposed method is much less than the method presented in Ref. [22]. This advantage results in fewer loads outages in the method presented in this paper.
- The maximum frequency of the islanded microgrid in the proposed method is closer to the standard frequency compared to [22], which shows the frequency stability.
- The time to achieve stability in this method is much shorter than the method presented in [22].

Leaving out only 2 loads seemed to be suitable at first. However, the results obtained from fifth objective function indicated that this function could not meet our goals. According to the fact that the microgrid maximum output load was less than the previous step, but this amount of output load was not able to restore the grid stability state and continuation of this process would certainly lead to leaving out all available loads in the islanded microgrid. Therefore, just leaving out the fewer loads cannot be a reason for the excellence of this objective function compared to the previous objective functions.

The eighth objective function is intended to decrease the microgrid maximum frequency, the maximum overshoot time and the maximum frequency drop. So, it is clear that the maximum and minimum frequencies in the proposed method have been significantly improved in this section, which can improve the stability of the microgrid and bring significant technical and economic advantages. According to the comparisons made in the expressed objective functions and considering all the goals of this paper, which are the minimum frequency drop at an optimal time and also reducing the microgrid overshoot at the best time in order to have the minimum output load and the faster stability of the microgrid, the eighth objective function can be an appropriate option in this case.

3.2. The selection table which is sorted by the second scenario

The genetic algorithm of loads cut-off time of the second, sixth and eighth objective functions loads are presented in Table 6 based on the random function of the loads power.

The objective function of this scenario is optimized by the genetic optimization algorithm, the results of which are presented in Table 7. The simulation results of the microgrid after load shedding in the second objective function are given in the second column of Table 7, the purpose of which is to reduce the maximum frequency drop of the islanded microgrid. The results obtained from this objective function show that this function cannot meet our goals in load shedding. According to the fact that the maximum output load of the microgrid is less than the previous steps, but this amount of load leaving could not restore the grid to the stable state and the continuation of this process absolutely will interrupt the all-available loads in the island.

Table 5. Results of the genetic optimization algorithm to investigate the ability of the proposed method at the time that the maximum overshoot occurred in the islanded microgrid for the first, fifth and eighth objective functions in the first scenario.

	Load shedding with first scenario	Load shedding with fifth scenario	Load shedding with eighth scenario
The difference between the maximum frequency and the base frequency	0.8353	1.09	0.51
The maximum frequency	50.8353	51.09	50.51
The concavity time	2530	4.96	1200
The difference between the minimum frequency and the base frequency	1.18	12.25	1.64
The minimum frequency	48.8196	37.75	48.35
The convection time	458	616	212
The number of loads which have experienced power outages	6	2	7

Table 6. Interruption times of loads for the second, sixth and eighth objective functions in the second scenario.

Load breaker	Second objective function	Sixth objective function	Eighth objective function
Load STSY	0.0997	0.098	0.0935
Load 10	0.7315	0.101209	0.102941
Load STNO	0.8259	0.132609	0.119241
Load 09	1.94401	0.973655	0.559156
Load STCE	3.96241	1.137755	0.736256
Load 07	4.753467	2.850715	0.83812
Load 08	4.767467	3.343215	1.52432
Load FLOE	5.900207	4.186286	1.689759
Load 11	6.090407	5.348086	2.272759
Load JUEL	7.420477	6.002209	2.52469
Load MAST	9.340277	6.588609	3.43919

So, ejection of only two loads in the first step cannot be a guarantee for the success of this method. The proposed formulation in the sixth objective function is presented with the goal of reducing the maximum frequency drop in the sample islanded microgrid along with the time, at which this frequency occurred. The frequency of the proposed method is closer to the main frequency in comparison with [22]. Also, in the proposed method, the time to reach 50 Hz after the frequency drop is shorter than [22]. Therefore, this objective function is suitable for load shedding and can reduce the times obtained from the study [22] to an acceptable level. The eighth objective function is considered with the aim of reducing the maximum frequency of the microgrid, the maximum overshoot time, the maximum frequency drop and the maximum time. The number of the proposed outputs of this objective function is three.

Table 7. Results of the genetic optimization algorithm to investigate the ability of the proposed for the second, sixth and eighth objective functions in the second scenario**.**

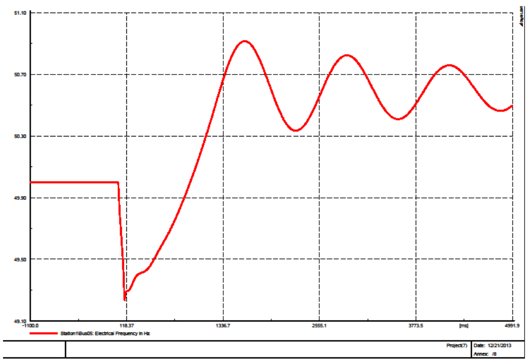
	Load shedding with second scenario	Load shedding with sixth scenario	Load shedding with eighth scenario
The difference between the maximum frequency and the base frequency	-	1.47	1.55
The maximum frequency	-	51.47	51.471
The concavity time	-	954	941
The difference between the minimum frequency and the base frequency	5.47	1.11	1.14
The minimum frequency	44.52	48.89	48.86
The convection time	743	144	105
The number of loads which have experienced power outages	2	3	4

The time of the microgrid maximum frequency drop and the time of the grid maximum frequency in the proposed method are improved in comparison with [22]. Moreover, in the proposed method, the time to reach *50 Hz* after the frequency drop is at *402 ms* and in the method [22], it is *860 ms*. Minimum frequency drop and reducing the microgrid overshoot, both at an optimal time, are the objectives of this paper in order to have the minimum output load and faster stability of the microgrid. According to the comparisons, first and eighth objective functions can be suitable to achieve these purposes.

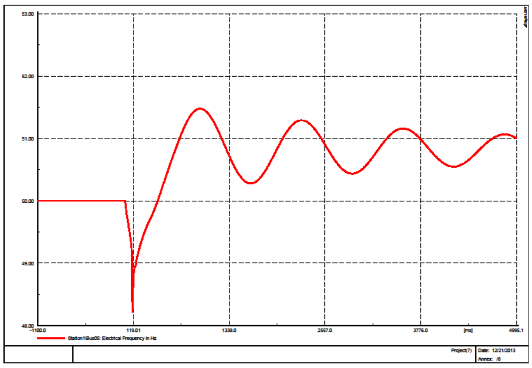
3.3. The selection table which is sorted by the third scenario

The genetic algorithm of the loads cut-off time for the third, seventh and eighth objective functions is proposed in Table 8 according to their priorities based on the random function of the loads power with the difference that the maximum electric power is in the first place. The figures of the final frequency for the third, seventh and eighth objective functions are given in the Figure 4(a-c). The simulation results after load shedding are given in Table 9 using the third objective function. The number of recommended outputs of the third objective function is 1. The loads cut-off time according to its priorities is presented in Table 8 in the seventh objective function so as to reach the goals of reducing the maximum overshoot time and the maximum frequency drop time. The figure of the final frequency and the simulation results after load shedding are given in the third column of Table 9.

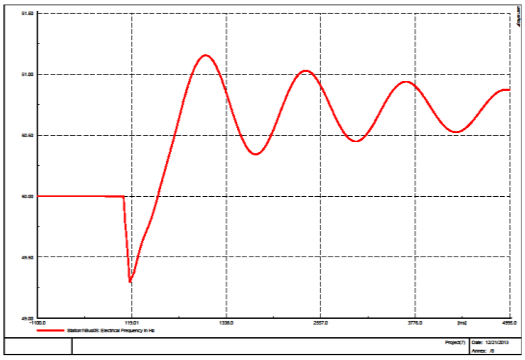
The maximum frequency drop of the microgrid in the eighth objective function is *0.708* in *103 ms*; which is *0.90* in the method [22]. The maximum frequency of the grid is *51.1154 Hz* in *1083 ms*; which is *50.926 Hz* in the method [22]. The time to reach *50 Hz* after the frequency drop in the proposed method is *463 ms* and in the method [22] is *970 ms*.



(a)



(b)



(c)

Figure 4. The load shedding implementation in the third scenario
a. With the third objective function, b. With the seventh objective function, c. With the eighth objective function.

Table 8. Interruption times of loads for the third, seventh and eighth objective functions in the third scenario.

Load breaker	Third objective function	Seventh objective function	Eighth objective function
Load MAST	0.0801	0.0923	0.0814
Load 07	0.88581	0.100993	0.083267
Load 09	1.00441	0.133293	1.307267
Load 10	1.408599	1.212483	2.043744
Load STCE	1.786699	1.803783	3.144644
Load STNO	1.970225	1.852836	3.295747
Load 11	2.409325	1.855336	3.314747
Load JUEL	2.82646	2.899916	3.334513
Load FLOE	3.10646	3.335916	3.588913
Load 08	3.509112	4.2736	3.716606
Load STSY	4.199612	4.6577	3.959106

According to the comparisons made in the expressed objective functions and the purposes of this paper, the eighth objective function can be a suitable option for this case. A comparison of these three scenarios with the selected objective function of each is observed in Figure 5. By comparing the selected functions for each of these three scenarios, the third objective function has the best response for the proposed objective function. For this scenario, maximum 2 cut-off loads for load shedding, the maximum frequency drop of *0.71 Hz* at the best time of *103 ms* and the maximum frequency rise of *0.59 Hz* at the time of *1083 ms* are recorded. After that, the second scenario gives the proposed suitable response with maximum 3 loads for load shedding, the maximum frequency drop of *1.034 Hz* in *102 ms* and the maximum frequency rise of *1.55 Hz in 901 ms*. Finally, the first scenario gives the proposed objective function with maximum 7 loads for load shedding, the maximum frequency drop of *1.64 Hz* in the best time of *212 ms* and the maximum frequency rise of *1.51* in *1200 ms*. The obtained results show the superiority of the method presented in this paper over similar study made in [22], because as shown, the time to achieve stability in this paper is much better than the mentioned study in the all states. In addition to improve the stability of the grid and creating many technical benefits in the grid, this issue helps significantly in reducing the costs of the distribution companies. Because the numbers and duration of outages are decreased by the method proposed in this paper.

Table 9. Results of the genetic optimization algorithm to investigate the ability of the proposed for the third, seventh and eighth objective functions in the third scenario**.**

	Load shedding with third scenario	**Load shedding with seventh scenario**	**Load shedding with eighth scenario**
The difference between the maximum frequency and the base frequency	0.914	1.157	1.154
The maximum frequency	50.914	51.157	51.154
The concavity time	1611	1093	1083
The difference between the minimum frequency and the base frequency	0.764	0.919	0.708
The minimum frequency	49.236	49.08	49.29
The convection time	91	113	103
The number of loads which have experienced power outages	1	2	3

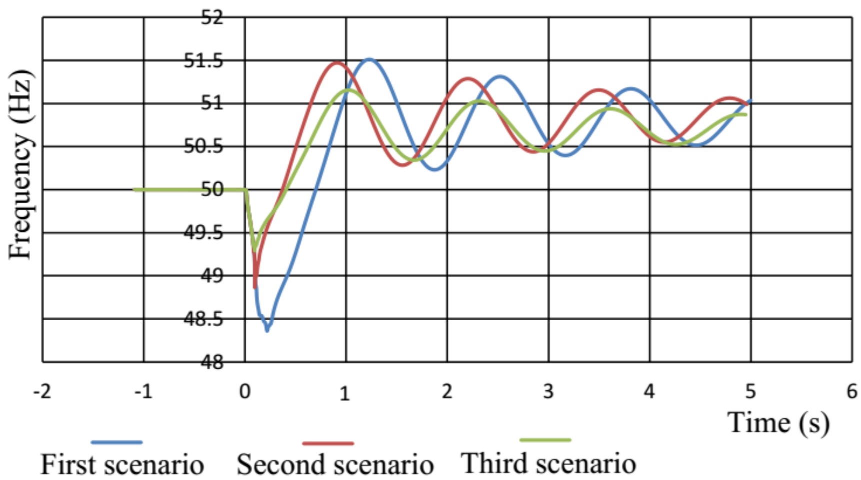


Figure 5. The comparison of the first, second and third scenarios**.**

4. Conclusions

Despite its advantages, operation of DGs in the islanded state may cause some concerns, the most important of which is the frequency stability.

Regarding the concerns, in this paper, solutions for load shedding of the small grids with the aim of stabilizing the frequency of these grids are analyzed and presented. In the method used in this paper, the technical and economic purposes related to load shedding strategy are considered simultaneously. The proposed method does not require the telecommunication infrastructures in order to communicate between the component and the real microgrid data.

The automatic load cut-off is done according to the frequency drop, frequency drop time, overshoot and its time. Other advantages of the proposed method in this paper compared to the previous studies are low drop of the frequency and achieving the stability in a shorter time. So, the importance of the results obtained from the implementation of this project can be summarized in the following cases:

- Successful exploitation of DGs in the islanded mode along with ensuring the frequency stability of the grid
- Increase in public satisfaction rate of consumers by creating frequency stability and a subsequent reduction in the outages of their sensitive loads

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Credit Authorship Contribution Statement

Reza Eslami: Conceptualization, Data curation, Formal analysis, Funding acquisition, Project administration, Software, Supervision, Validation, Roles/Writing - original draft, Investigation, Methodology, Resources, Visualization, Writing - review & editing.

Bibliography

Reza Eslami received the B.Sc., M.Sc. and Ph.D. degrees in Electrical and Electronics Engineering from the Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran, in 2010, 2012 and 2017 respectively. He has also worked as an Associate Professor with the Department of Electrical Engineering, Sahand University of Technology, Tabriz, Iran, since 2017. His research interests are smart grids and power system protection.