Stabilizing a DG-fed islanded system through load shedding on the basis of the rate of change of frequency and frequency decline

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Abstract — whenever a distribution network is about to become unstable, protection relays will start to work, thus creating unintentional islanding. In order to keep balance between generated and consumed power in an islanded system, it is necessary to shed loads. This paper proposes a new method for load shedding based on the rate of change of frequency (RoCoF) at the first step and on frequency decline at subsequent steps. For this purpose, three lookup tables are created in order to prioritize loads to be shed according to the willingness of subscribers to pay (WSP) and the RoCoF. The strength of the proposed method is verified by considering four cases. Consumption load is considered as voltage- and frequency-dependent in three of the cases, and as constant-power in the fourth case. The results indicate that the proposed method is flexible and, in comparison with previous research, results in a slighter frequency decline and stabilizes the islanded system in a shorter time.

Key words: DG resources, frequency decline, islanding, load shedding, rate of change of frequency, willingness of subscribers to pay.

1. Introduction

Nowadays, using Distributed Generation (DG) resources is an important issue in power systems. DG resources generate electrical power using small local generators. The advantages of such resources include small size and low installation costs. Once a DG resource is connected to the distribution network, customers will receive better quality service, less power will be lost, voltage profile will improve, pressure will be taken off the network, there will be less environmental pollution, and more economic benefit will be gained.

An instance of DG use is when an islanded system is in need of power. Islanding happens either intentionally or unintentionally. In the former case, upstream circuit breakers are opened on purpose. The latter case is when a fault occurs in the system, causing the protection relays to command islanding [1-3]. The voltage and frequency of the loads in a DG-fed islanded system should be within desired limits. The only way of achieving this would be through load shedding. Load shedding has extensively been researched over the past few years. In the approach adopted by [4], load shedding is performed according to the qv curve (the reactive power margin) outside of a limit defined for the voltage and frequency. in [5], based on operator load shedding experience and studies of three different load shedding schemes: invariable maximal load shedding with the amount of load shed per step being fixed, invariable maximal load shedding with the amount of load shed per step being variable, and variable maximal load shedding with the amount of load sheds per step being variable. When the amount of load shed per step is variable, loads are shedded in accordance with the rate of frequency decline. In [6], where load shedding is based on active power and rate of change of voltage, the Kalman filter is utilized to estimate the rate of change of voltage and frequency. In [7], estimate minimum nominal voltage and threshold voltage using pv and qv curves and defines load shedding according to under-voltage and under-frequency. This means that the under-frequency relay commands load shedding if the voltage of certain buses decreases below the threshold level. In [8], the coefficients of the Slovenian load shedding standards system is modified in accordance with power deficiency (dp). The load shedding scheme used in [9] is based on the SCADA system.

The methods and approaches reviewed above involved generators as strong as large power plants. However, to the best of our knowledge, only one study [10] has investigated load shedding in islanded systems fed by low-capacity DG resources. This reference discussed load shedding in terms of the rate of change of frequency

(RoCoF) and created a lookup table in order to prioritize loads. The main problem with this method is causing considerable frequency decline and brings about slow-pace stability.

The method proposed here aims to stabilize an islanded system in as short a time as possible. In this method, the first step is based on the RoCoF, and other steps have basis on frequency decline. Using this method, there will be less frequency decline, and stability will be reached at a faster pace.

The previous methodology is explained in detail in Section 2 and stated the problems associate with it. The proposed method is brought forward in Section 3. In Section 4 for simulation, DigSILENT Power Factory 14 is employed to tested a radial distribution system. Different scenarios have been simulated, and the numerical results are presented in Section 5. Section 6 is the conclusion of this paper and possible further works.

2. Problem Statement

Load shedding results in an economically and technically optimized islanded system. Economic optimization is accomplished if fewer loads are shed; technical optimization if the voltage and frequency of the loads are put within desired limits. Load shedding can be carried out in the following way [10]. A lookup table is created in order to determine in which order loads should be shed. Prioritization is based on the two factors of willingness of subscribers to pay (WSP), which is refered to willingness to pay (WTP) in [10,11], and the RoCoF. Table I is a lookup table. From left to right, the columns give the shedding priority of each load, the name of each load in the islanded system, the WSP for each load (as the main prioritizing factor), the RoCoF of each load, and the cumulative RoCoF (as the factor that determines the amount of load shedding at the first step).

TABLE I
A LOOKUP TABLE

Shedding priority	First Case			
	Load name	WSP	RoCoF	Cumulative RoCoF
1	Load 09			
2	Load 10			

To determine how many loads should be shedded at the first step, the RoCoF of the islanded system calculated after the first half-cycle (10ms) is compared with the cumulative RoCoF in the lookup table for that half-cycle. The shedding priority to be chosen will be the one corresponding to the cumulative RoCoF larger than the RoCoF of the islanded system.

At each subsequent step, a single load is shed. In order to determine where one step ends and the next step starts, two condition are considered: (1) the frequency of the islanded system at every step should be less than 49.5Hz (A normal system has a frequency of 50Hz), and (2) the RoCoF of the system (df/dt) for 10 continuous half-cycles should tail off as we progress from one step to the next. Load shedding stops permanently when the first condition is violated. Indeed, this violation means the system has reached stability. If the first condition still holds, but the RoCoF begins to rise, load shedding is temporarily discontinued waiting to see if this rising trend continues or reverses. Table II and Fig. 1 demonstrate the load shedding process.

TABLE II
THE METHOD PROPOSED IN [10]

	Prerequisite for load shedding in an islanded system	Load(s) to be shed in an islanded system
Step one	A comparison of the RoCoF of the islanded system after the first half-cycle (10ms) and the cumulative RoCoF in the lookup table	The shedding priority corresponding to the cumulative RoCoF larger than the RoCoF of the islanded system
Step two and the following steps	Decreasing RoCoF of the system for 10 continuous half-cycles with f<49.5Hz	a single load at each step

The method described above suffers from a major problem, which is the time required for a single load to be shedded from the second step onward. This “delay” is 100ms long (equal to 10 half-cycles). The problem becomes more serious if load shedding involves a great number of steps. This causes the frequency to decline even further and ultimately slows down the process of system stabilization. The present paper proposes a solution to this problem.

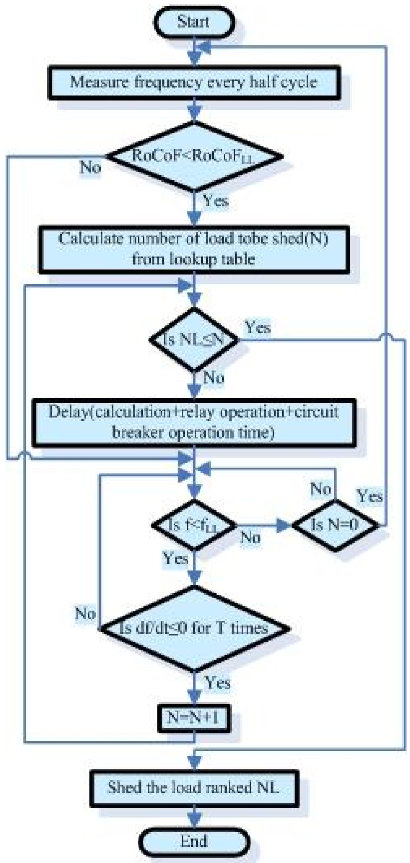

Fig. 1. The flowchart presented in[10]

3. Proposed Method

The proposed method is similar the one described above: lookup tables are created considering the two factors of WSP and RoCoF, load shedding at the first step is based on the RoCoF of the islanded system, and a single load is shed at each subsequent step.

However, a difference is that the frequency decline, rather than the RoCoF, is used for load shedding at subsequent steps. For the second step, it is decided that load shedding starts if the frequency of the islanded system declines to 49Hz. This choice is made for two reasons:

--According to [12, 13], whenever the frequency of the system declines by 1%, some corrective measure should be taken. Such reduction would be equal to 0.5Hz for each step in a system with a frequency of 50Hz. It follows that the frequency associated with load shedding at the second step should be 49Hz.

--In [14], where load shedding is based on the frequency decline, a frequency of 49Hz is used at the first step. As the present method is also based on the frequency decline, a frequency of 49Hz is deployed. However, there is a difference in here since the frequency of 49Hz is used at the second step.

In the method proposed in this paper, each subsequent step of load shedding starts whenever the islanded system experiences a frequency decline of 0.5Hz. In other words, one load is shedded from the system in order of priority each time the frequency declines by 0.5Hz. Load shedding stops permanently when there is no frequency decline of 0.5Hz. Fig. 2 is a flowchart of the present method.

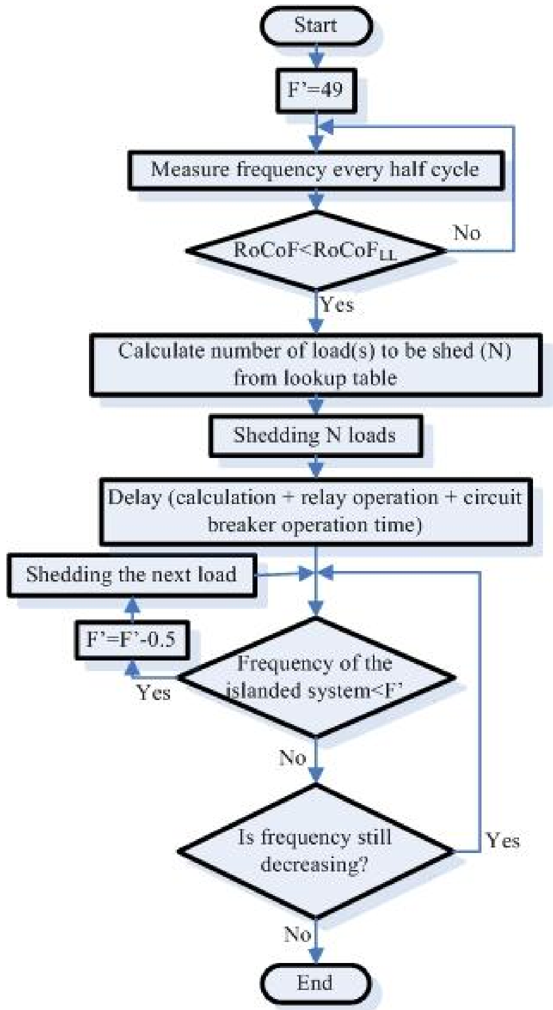

Fig. 2. The flowchart of the proposed method

It should be noted at this stage that using the frequency decline instead of the RoCoF for subsequent steps saved us the problem associated with the method described above. In the proposed method, the greatest level of frequency decline is at the last step: 47.5Hz at the fifth step for voltage- and frequency-dependent load, and 47Hz at the sixth step for constant-power loads.

4. Simulation

The proposed method is simulated using DIgSILENT Version 14.0. This software is capable of modeling power networks and simulating different kinds of faults. Fig. 3 shows the system in which the proposed method is tested.

This system is part of a distribution network in Denmark and consists of 11 loads, three 630-kW fixed-speed stall-regulated wind turbine generators (WTGs), and a combined heat and power (CHP) plant with three 3-MW gas turbine generators (GTGs). WTGs and the CHP plant operate at unity power factor. The distribution system is linked to a transmission network at Bus 05.

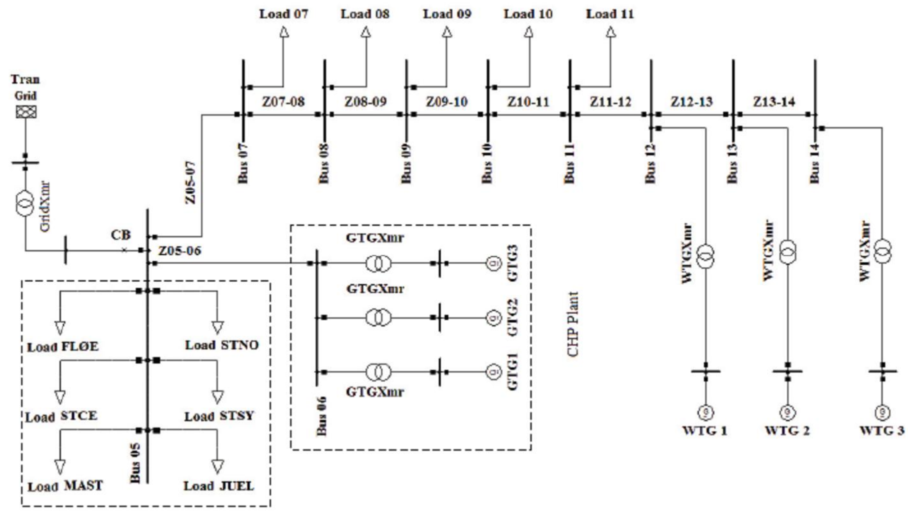

Fig. 3. The test system

For the purpose of this study, an IEEE-type ST1 excitation system [15] and GAST model [16], both available in DIgSILENT, are used to model exciter and governor systems in GTGs, respectively. In addition, WTGs are modeled as a two-mass system [17]. Islanding is simulated by opening the circuit breaker (CB). All the relevant data are given in [18].

As the loads in an actual system are always voltage and frequency dependent, the loads in DIgSILENT are set to the 100% dynamic mode so that they could truly represent the reality. Equation (1) is the mathematical representation of this simulation.

$$\begin{aligned} P &= P_0\left(1 + K_{pf}\Delta f + K_{pv}\Delta V\right) \\ Q &= Q_0\left(1 + K_{qf}\Delta f + K_{qv}\Delta V\right) \end{aligned} \quad (1)$$

where

P: active power at the new voltage and frequency

P_0: active power at the base voltage and frequency

Q: reactive power at the new voltage and frequency

Q_0: reactive power at the base voltage and frequency

K_{pf}: coefficient of the dependency of the active power of the load on frequency

K_{pv}: coefficient of the dependency of the active power of the load on voltage

K_{qf}: coefficient of the dependency of the reactive power of the load on frequency

K_{qv}: coefficient of the dependency of the reactive power of the load on voltage

Δf: frequency change in per unit

ΔV: voltage change in per unit.

The power of the load will be constant if the coefficients are 0; and highly dependent on frequency and voltage if the coefficients are 1. Thus, the value of each coefficient is considered 0.5 to have a balanced RoCoF.

Tables III, IV, and V are three lookup tables created in the present study.

TABLE III
LOOKUP TABLE FOR CASE 1

shedding priority	Case 1							
	load name	WSP	RoCoF	Cumulative RoCoF	$RoCoF_v$	Cumulative $RoCoF_v$	dp	Cumulative 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	-1.9011	-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	-17.0798	-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 IV
LOOKUP TABLE FOR CASE 2

shedding priority	Case 2							
	load name	WSP	RoCoF	Cumulative RoCoF	$RoCoF_v$	Cumulative $RoCoF_v$	dp	Cumulative 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	-669.48186
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	-1.9011	-19.2266	-94.7444	-959.7246
11	MAST	1	-48.9	-350.4	-2.4404	-21.6671	-125.1918	-1084.9164

TABLE V
LOOKUP TABLE FOR CASE 3

shedding priority	Case 3							
	load name	WSP	RoCoF	Cumulative RoCoF	$RoCoF_v$	Cumulative $RoCoF_v$	dp	Cumulative 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

The RoCoF formula is (2) below:

$$RoCoF = \frac{df}{dt} \tag{2}$$

For each of the loads in the lookup table, *dt* is conventionally decided to be 10ms, equal to a half cycle. For *df*, we needed DIgSILENT. To give us *df*, the software needed dp, the difference between generated power and consumed power in an islanded system. For different loads, we provided the software with different values of generated power and consumed power. This is because we wanted the difference between the two in the case of each load to be equal to the active power of that load.

Voltage-dependent RoCoF ($RoCoF_v$) and Deficiency of Power (dp) in the tables are the functions which are used as two alternatives to the RoCoF. However, no significant difference is observed between the three functions as they determined the same number of loads to be shed. The formulae for calculating $RoCoF_v$ and dp are given in [19].

The cumulative values of RoCoF, $RoCoF_v$, and dp are calculated because we wanted to predict roughly how many loads should be shed for the islanded system to suffer from less deficiency of active power.

Following [10] and using the lookup tables, four cases are considered in order to verify the robustness and flexibility of the proposed method in shedding loads from an islanded system.

Case 1(Table III): It is assumed that customers are least willing to pay for the loads with the least active power. Thus, prioritizing loads according to WSP would mean putting the loads with the least active power before those with the greatest active power.

Case 2 (Table IV): It is assumed that there is no relationship between WSP and active power. Thus, prioritizing loads according to WSP would mean putting loads in random order according to the active power.

Case 3 (Table V): As in Case 2, loads are randomly arranged. However, the difference is that here the load to be shed first is the one with the greatest active power.

For these three cases, voltage- and frequency-dependent consumption load is taken into account and the system RoCoF is calculated to be -23.4*Hz/s*.

However, to capture all the possibilities, a fourth case is included in the simulation. This case is like Case 1, but the difference is that here the consumption load is of a constant-power type. The system RoCoF used for this case is calculated to be -24*Hz/s*.

It should be noted at this point that like in [10] the lookup tables are created using the data obtained from the test system in December 2006. These tables are then used to predict what the test system would be like in the following month (i.e., January 2007). The system is islanded at the 0^{th} second. It is also assumed that it takes each circuit breaker 80ms to open.

5. Simulation Results and Discussion

The four cases noted above will first be studied in detail. Then, a comparison will be drawn between the method proposed in this paper and the method employed in [10] along the following lines:

--The maximum amount by which the frequency of the islanded system overshoots (i.e., exceeds 1p.u.): the smaller the amount, the faster the system reaches stability.

--The maximum amount in Hz by which the frequency of the islanded system declines: the smaller the amount, the faster the system reaches stability.

--The sum of squares of frequency required for the frequency of the islanded system to reach 1p.u.: this roughly equates with variance.

--The length of time it takes the frequency of the islanded system to reach 1p.u.: the shorter the time, the faster the system reaches stability.

A. ***Case1***

The lookup table for Case 1 shows that the RoCoF calculated for the islanded system is larger than the cumulative RoCoF value of Load 09 and smaller than the value for Load 10. This means that these two loads are simultaneously shedded at 0.09s. Then, we wait for the frequency of the system to decline to 49Hz. Once this happens (at 0.11s), Load 11 is shed at 0.19s. The next step in frequency decline is 48.5Hz (at 0.16s), causing Load 07 to be shed at 0.24s. The final loads to be shedded are Load 8 and JUEL, at 0.31s and 0.42s, respectively. It is worth noting here that we simply care about protecting the islanded system from collapsing and do not wait for the response of the system. Thus, while we are waiting for a shedding command to be executed, another command may be issued for the next-priority load. Fig. 4 compare the method proposed here and the one used in [10] in terms of the status of the frequency of the islanded system after load shedding.

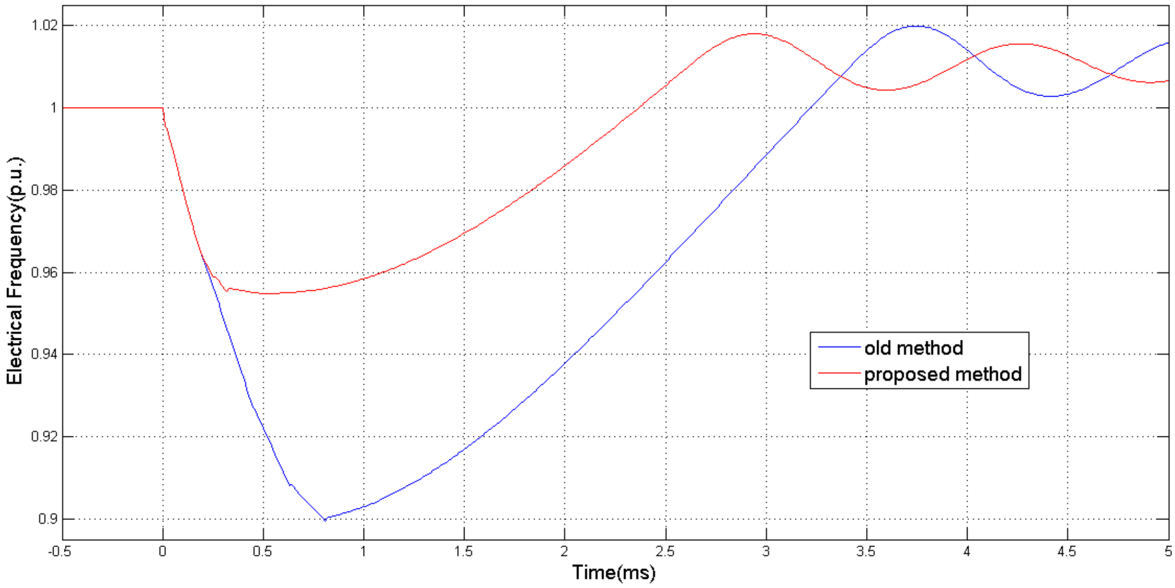

Fig. 4. Frequency of the islanded system after load shedding in the proposed method and method used in [10]

As can be seen, the proposed method has two major advantages over the method used in [10]:

--The maximum amount by which the frequency of the islanded system declines is 2.7688Hz in the proposed

method and 5.0336Hz in the method used in [10].

--The frequency reaches 1p.u. at 2550ms in the proposed method and at 3230ms in the method used in [10].

*B. **Case2***

The lookup table for Case 2 shows that the RoCoF calculated for the islanded system is smaller than the cumulative RoCoF value for the first-priority load (i.e., STSY). This load will be shed at 0.09s. Then, once the frequency of the system goes down to 49Hz (at 0.13s), Load 10 is shed at 0.21s. Finally, the system frequency drops to 48Hz (at 0.34s), causing STNO to be shedded at 0.42s. Fig. 5 depict the post-shedding status of the frequency of the islanded system in the proposed method and the method employed by [10], respectively.

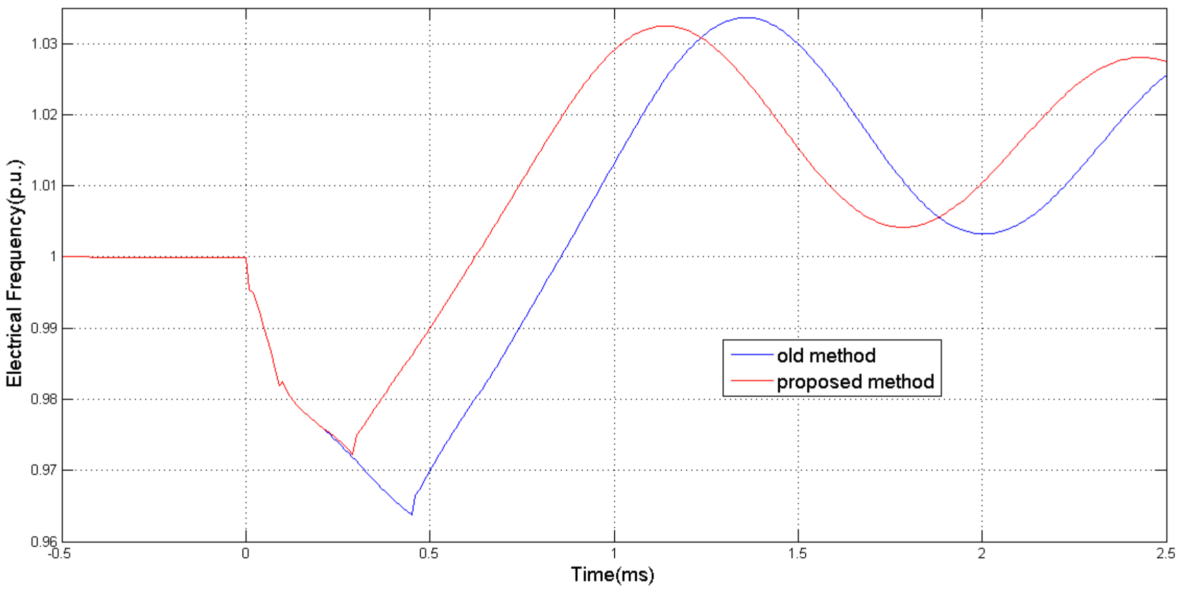

Fig. 5. Frequency of the islanded system after load shedding in the proposed method and method used in [10]

According to the figure, the proposed method is better than the method used in [10] in two main ways:

--The maximum amount by which the frequency of the islanded system declines is 1.7276Hz in the proposed method and 1.8146Hz in the method used in [10].

--The frequency reaches 1p.u. at 810ms in the proposed method and at 860ms in the method used in [10].

C. *Case3*

The lookup table for Case 3 shows the RoCoF is calculated for the islanded system to be smaller than the cumulative RoCoF value for the first-priority load (i.e., MAST). This load will be shedded at 0.09s. However, load shedding does not go beyond the first step since the frequency of the system does not drop to 49Hz. No difference is observed in this case between the method proposed here and the one used by [10]. Fig. 6 illustrates the post-shedding status of the frequency of the islanded system which turned out to be the same in the proposed method and the method employed in [10].

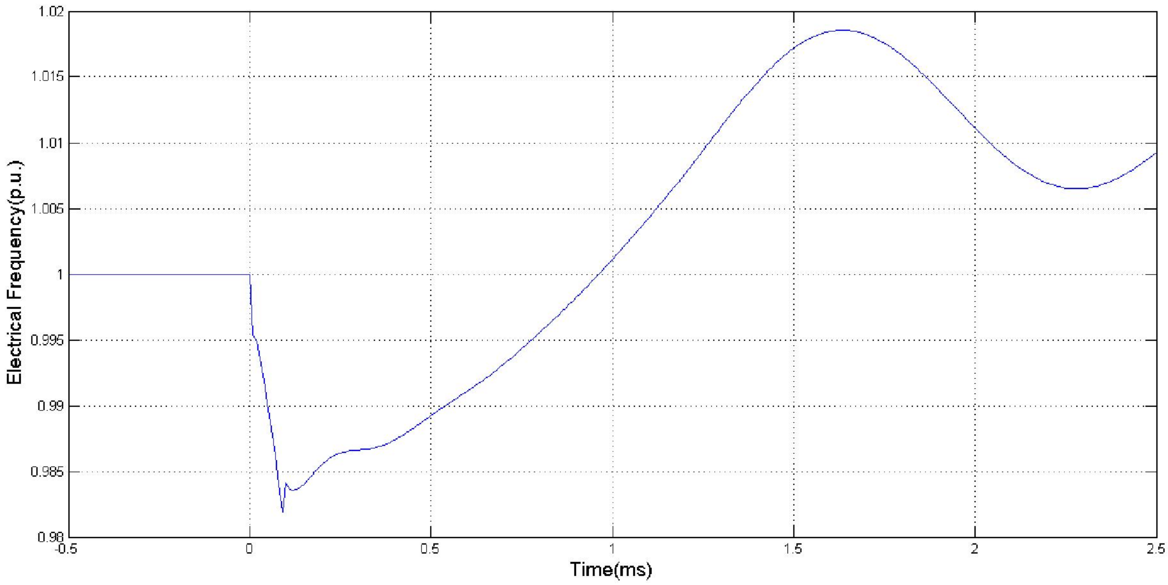

Fig. 6. Frequency of the islanded system after load shedding in the proposed method and the method used in [10]

Before we deal with Case 4, it is well worth considering that in terms of the length of time it takes the frequency of the islanded system to reach 1p.u., the amount by which
the system frequency declines, the number of steps involved in load shedding, and a few other factors, Cases 1 and 3 are the worst and the best, respectively. Case 2 falls somewhere in between.

D. *Case4*

The lookup table used here is similar to the one used for Case 1. This worst-case lookup table is used because we believed that if the proposed method could prove robust and flexible in this case, it would certainly prove the same in other cases. Fig. 7 display the post-shedding status of the frequency of the islanded system in the proposed method and the method employed by [10], respectively.

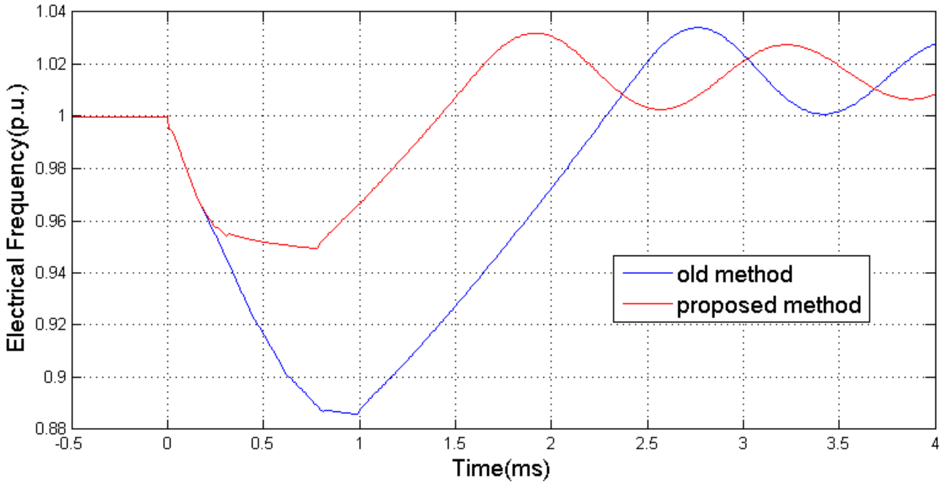

Fig. 7. Frequency of the islanded system after load shedding in the proposed method and method used in [10]

From the figure it can be seen that the proposed method has two important advantages over the method deployed in [10]:

--The maximum amount by which the frequency of the islanded system declines is 3.0301Hz in the proposed method and 5.7184Hz in the method used in [10].

--The frequency reaches 1p.u. at 1580ms in the proposed method and at 2300ms in the method used in [10].

On the whole, the proposed method proved to be more desirable than the method used in [10] as Table VI summarizes. Both methods result in the same number of loads being shed in each case; however, in addition to improving the factors in the table, the proposed method causes the frequency of the islanded system to dampen in a shorter time.

TABLE VI
THE FACTORS INVOLVED IN THE COMPARISON OF THE METHOD PROPOSED AND THE METHOD EMPLOYED IN [10]

		Frequency overshooting (p.u.)	Frequency decline (Hz)	Variance	Time at which frequency reaches 1p.u. (sec.)	Simulation time (sec.)
old method	case1	0.0198	5.0336	1.402	3.23	5
	case2	0.0336	1.8146	0.044	0.86	2.5
	case3	0.0185	0.9058	0.011	0.97	2.5
	case4	0.0339	5.7184	1.281	2.3	4
new method	case1	0.0184	2.7688	0.392	2.55	5
	case2	0.0334	1.7271	0.038	0.81	2.5
	case3	0.0185	0.9058	0.011	0.97	2.5
	case4	0.0323	3.0301	0.298	1.58	4

6. CONCLUSION

The conventional load shedding strategy that is used in large power systems cannot be implemented as successfully in islanded systems because the two systems are characteristically different. The load shedding strategy introduced in this paper takes account of economic and technical considerations as it results in few loads to be shedded and puts the voltage and frequency of the loads within desired limits, respectively. Two main advantages of the proposed method is that it causes less frequency decline and stabilizes the islanded system faster than does the old method.

As a further works after stabilization of the islanded system, one could think of finding a procedure to add load consumption back to the system in shortest time and with highest load.

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