ANALYSIS OF LOAD SHEDDING APPLIED TO THE OPERATION OF THE INTENTIONAL ISLANDING OF DISTRIBUTED SYNCHRONOUS GENERATORS

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ABSTRACT

An increasing number of distributed generation has been connected to power grids, which requires new ways to control these networks. When an island region is formed due to system disturbances, many electric utilities require immediate disconnection of the Distributed Generators (DG). However, the injection of energy during the power system outage from the DG can be a strategy for continuity in the supply of electricity. Thus, with a minor imbalance of active and reactive power in the micro-grid, less complex is its operation. However, in micro-grid with significant generation deficit, Load Shedding (LS) is inevitable. Therefore, a methodology for LS to ensure the stability and the quality of electricity in this micro-grid is the focus of this work. The LS strategy uses the methodology known as Multi-objective Evolutionary Algorithm with Node-Depth Encoding (MEAN). The methodology was developed to perform automatic LS, for power imbalance analysis in micro-grids with distributed generation.

INTRODUCTION

Islanding is the condition in which a part of the distribution network becomes electrically isolated from the main power supply (substation), but remains energized by DG present in the micro-grids [1]-[3].

In this respect, the conditions for connecting DG require your immediate disconnection in the case of Islanding formation [2]. However, consolidate the formation of stable micro-grids, means maximizing the benefits of the use of DG in the power system. Given this, this subject has attracted the attention of several researchers [3]-[5]. The intentional islanding is a consolidated operation related to power quality, stability and micro-grids protection are well studied and defined procedures.

In islanding conditions, DGs are configured to control the frequency and voltage on micro-grid (f-V control) [6]. In islanded condition, the generator passes from the power factor control state or reactive power for voltage control in voltage regulation loop, and from constant power control for frequency control in the mesh of speed regulation.

Distributed Generation enjoys various technologies of electric power generation, however, the focus of this paper is limited to synchronous generators. During the move to the islanded mode, two conditions may occur: micro-grid with surplus or deficit in generation levels. In the latter case, if the capacity is lower than the load generators, the drop in frequency is inevitable. There is the possibility of increased generation in micro-grid, the frequency will violate established adjustments which will result in the output of the generators distributed by under-frequency protection scheme. In order to avoid the collapse on the micro-grid, a new balance between load and generation will be defined by any load-shedding scheme.

Thus, the actions of LS are needed to maintain the integrity of the system, in order to resolve any deficiency of generation, transmission or transformation where the load exceeds the capacity of the affected area [7].

Based on this scenario, the objective of this study is to investigate the dynamic control of intentional islanding in a micro-network with generation deficit. To do this, it proposes automatic LS using the methodology called MEAN.

DISTRIBUTED GENERATOR CONTROL MODES

The speed regulator is responsible for control of mechanical power input of the synchronous generator. Acting on the rotor speed and/or electrical power, controls the frequency of the voltage generated (isolated operation) or the electric power supplied (operation connected) [11]. In practice, three control modes are possible: fixed power control, isochronous and droop [6].

If the DG is connected to the network, a droop control is the best option, but in isolated condition and existed only generator, isochronous mode is the most indicated. For islanded operation, a fast, robust and reliable control as the digital control is required.
Given the conflicting condition between modes of control in the operation of the DG in connected and islanded condition, the conversion of control modes is essential [6]-

[11]. However, this conversion should be completed within an acceptable time without it being a false situation of islanding detection and to avoid disconnecting the generator distributed by protection devices [11].

This time is defined in this study as time restriction (t_{REST}). For a high restriction of time, there is a greater possibility of the formation of micro-network. The time restriction and variations in voltage and frequency are used in this paper to evaluate the performance of intentional Islanding.

ANALYSIS OF INTENTIONAL ISLANDING IN DISTRIBUTED GENERATION

In this section, the dynamic simulation in time domain will be employed to investigate the possibility of intentional Islanding of DGs. To perform such simulations will be used the elements of Matlab/Simulink platform SimPowerSystem [14]. The implementation of AEMT methodology was held in C++ language. As the aim is to evaluate the voltage and frequency levels in the micro-grid during operation of intentional islanding, a base case was defined for this.

Base case definition

The investigations are conducted through the electric power distribution system of Fig. 1, where one has a 33 kV and 6 feeder load buses are connected to the substation (SUB) with short-circuit power of 1500 MVA.

This electrical system was based on the system presented in Fig 1. It is considered just a DG, 12.5 MVA with a steam turbine, speed Governor [14] and an excitement with automatic voltage regulator (AVR) of type IEEE DC1A [15]. The active powers of loads are indicated in the Fig. 1, and the power factor is defined in 0.94.

The base case operating conditions were defined with active power demand (PC) equal to 20 MW, loads of constant impedance type [16], generator power (P_G) of 12.5 MW and automatic voltage regulator (AVR) configured to control PQ with null reactive power.
The intentional Islanding is simulated with the opening of the breaker CB1 (Fig. *1*) *at time t = 30 seconds*. The DG is disconnected instantly if the limits of adjustments of frequency and voltage protections are violated. The adjustment ranges are: a) frequency (f): 57 Hz $\leq$ f $\leq$ 61.5 Hz; b) voltage (V): 0.70 pu $\leq$ V $\leq$ 1.10 pu.

Given these conditions, the following issues were examined: a) Case 1: P_C = 15 MW, active power imbalance. (ΔV) estimated equal a - 2.5 MW; b) Case 2: P_C = 20 MW e ΔV = - 7.5 MW; c) Case 3: P_C = 24 MW e ΔV = -11.5 MW; d) Case 4: P_C = 30 MW e ΔV = - 17.5 MW. It should be noted that in all these cases, there was no stable formation of micro-grid after the conversion of the control modes [6], due to the deficit of generation and consequently the disconnection of the DG by under-frequency protection. The t_{REST} considered is 150 ms and the shutdown of loads will be for acting under-frequency relay.

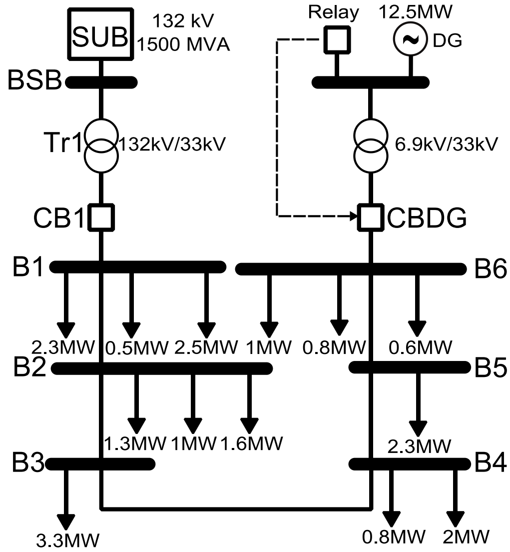


Fig. 1. Power distribution network: CA, 60 Hz.

POTENTIAL SOLUTIONS TO IMPROVE THE ISLAND PERFORMANCE

When there is generation deficit in micro-grid, the LS is a strategy indicated the control of the frequency stability [12]. There are many methods and procedures used by utility to perform the LS. However, the LS is a pre-established program to turn off loads in function of your energy balance of micro-network and of electrical system. The coordination of the LS and frequency relay is performed empirically, so that the basic assumptions are met, such as total load to be cut, minimum frequency for cutting loads, number of stages and frequency adjustment for each stage.

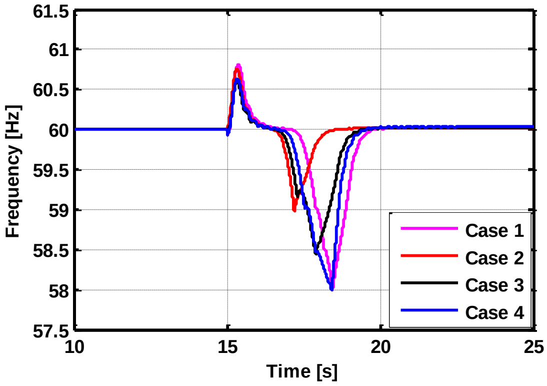
The solutions investigated in this study are: (1) load cutting with random definition of basic premises, and (2) load cutting with definition of the basic premises using the MEAN.

Through various simulations of LS for cases 1, 2, 3 and 4 and to minimize the number of stages of the cuts, the following strategy has been developed: a) Stage 1: 59 Hz – rejecting loads of Priority P3 (buses 4, 5 e 6); b) Stage 2: 58.5 Hz – rejecting loads of Priority P_2 (bus 3); c) Stage 3: 58 Hz – rejecting loads of Priority P1 (bus 2). In addition, the following parameters have been defined: a) tc (s) – time to perform the cutting load for each stage; b) PCC (MW) – amount of LS.

Load Shedding with random definition of the basic premises

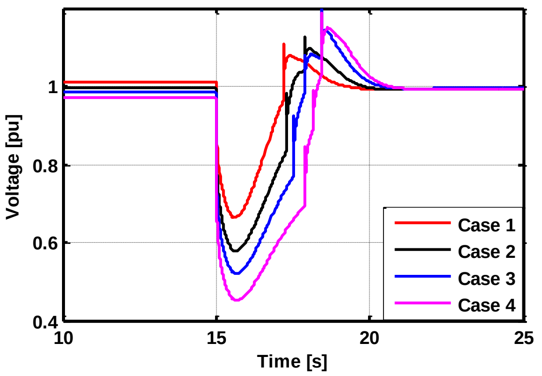
This strategy has its basic premises defined by an empirical process. In this respect, these premises were determined a priori and by means of successive simulations made the necessary adjustments to the frequency stability in the micro-grid. Fig. 2 shows the results for the cases previously defined. Fig. 2 (a) shows the behavior of the electrical frequency and Fig. 2 (b) shows the terminal voltage on DG.

It should be noted that the Islanding occurs at time t = 15 seconds. In figure (2-a), it is observed that the frequency is recovered in all cases analyzed. In case 1, only 1 stage of load cutting was sufficient, the case 2 required two stages and in cases 3 and 4 were 3 stages, as noted in Fig. 2(a) and Table 2. However, in all cases, the voltage drop at the terminals of the DG would result in disconnection of the same, Fig 2 (b), Table 1. In this aspect, the under-voltage protection will be reset to 0.5 pu, in order to favor the formation of islanding. It is observed that in cases 3 and 4 terminal voltage of the DG exceeds 1.1 pu. However, to avoid system damage, this protection will be changed. Frequency protection settings remain unchanged.



(a) Frequency of the DG during intentional Islanding after Load Shedding.

Fig. 2. Results of Load Shedding with random definition of basic premises.



(b) DG voltage during intentional Islanding after Load Shedding.

Fig. 3. Results of Load Shedding with random definition of basic premises.

Four indexes of performance are compared: (a) the magnitude of the measured voltage sags in the load bus during the transition from one DG control ($V_{SAG,}$ in rms); (b) the voltage measured at 1 bus measured after islanding and steady-state (V_{SS}, in rms); (c) restriction time (t_{REST} in seconds), (d) Transient frequency variation rate (Δf_T, in Hz). Bus-1 was selected for this appears to have lower levels of tension after islanding.

The analysis of Table 2 shows that cases 3 and 4 no resulted in stable micro-grid. Although the frequency has recovered these cases, the overvoltage protection acts after load cutting. For cases 1 and 2, the t_{REST} was defined by different factors. In the first case, the limiting factor was the protection of under-frequency, whereas in case 2, the limiting factor was the under-voltage protection. A synthesis of LS operation with random definition of the basic premises is presented in Table 2.

Table 1 – Load Shedding (1)

Case	**Stage 1**		**Stage 2**		**Stage 3**	
	t_c	**P_{CC}**	**t_c**	**P_{CC}**	**t_c**	**P_{CC}**
1	17.2	5.6	---	---	---	---
2	17.3	7.5	17.9	3.3	---	---
3	17.6	9	17.9	3.96	18.5	4.68
4	18	11.3	18.2	4.95	18.5	5.85

Table 2 Results of the sensitivity analysis

Case	**V_{SAG}(pu)**	**V_{SS}(pu)**	**Δf_T(Hz)**	**t_{REST} (s)**
1	0.621	0.936	-1.29	0.32
2	0.528	0.941	-1.68	0.31
3	DG disconnected			
4				

MEAN with Load Shedding

The methodology used to perform the LS is based on MEAN, developed in [19]. The MEAN, in its version developed in [19] seeks to restore electricity in Radial Distribution Systems (RDS) upon the occurrence of one or multiple faults.

This evolutionary algorithm works in parallel with multiple subpopulations stored in tables, where the best individuals for certain features of the problem are stored in its respective subset. In addition, this algorithm makes use of so-called Node-Depth Encoding (NDE), a data structure based on graph theory.

In this type of representation, the feeders should be considered as trees, sectors such as node, switches as the edges and bus of substations as the root node of the tree. Thus, an RDS may be represented as a graph forest formed by several trees.

Thus, the NDE allows representing computationally RDSs without simplifications, as well as manipulating and generating forests store (network radial configurations) and ensure that all changes also produce a spanning forest, capable of supplying power to all the RDS. NDE is based on node concepts and depth of a node in a graph tree, and consists of a list containing the nodes of the tree and their depths, forming the type pairs (tree node, node depth). Figure 3b illustrates the NDE of forests (feeders) shown in Figure 3a. As shown in Figure 3b, all of the forest can be represented by the union of trees of NDEs.

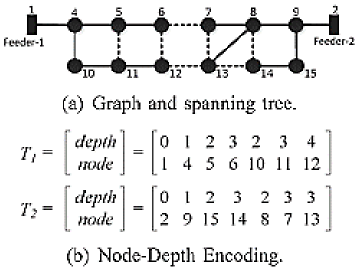


Fig. 3. Load Shedding results with automatic definition of the basic premises.

To facilitate the handling of forest stored in NDEs, with computational processing time low, were created two operators. These operators perform pruning or insertion in the trees of the forest in order to generate changes in the forest [19]. The NDE operators produce exclusively feasible configurations, that is, radial configurations able to supply energy for the whole system.

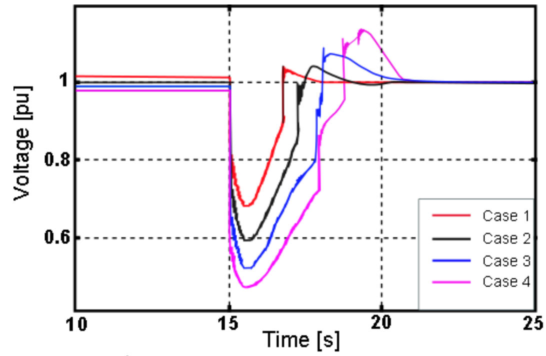
The generation of new individuals is done by applying these operators. The selection and reproduction occur according to the following steps: (i) randomly choosing a table subpopulation; (ii) randomly choosing a child individual, from an individual parent; (iii) applying one of NDE operators to generate a new individual child, from an individual parent. Then this son individual is assessed and will be inserted in a subpopulation table if it is not full, or if new individual is better than the worst individual in the table, replacing it. This procedure is performed until the maximum number of solutions generated is reached.

Load Shedding with definition of the basic premises using MEAN.

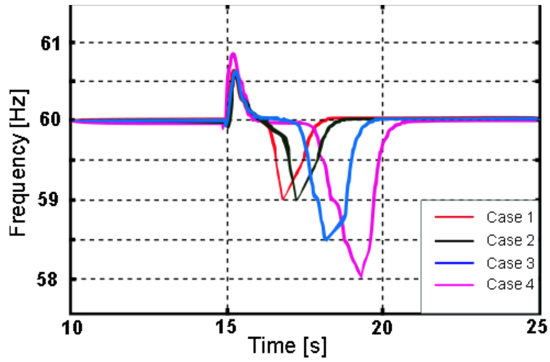
In this option, the basic premises are set by the MEAN. Is defined subpopulations stored in tables formed by solutions such as P1 - lower total load to be turned off; P2 - the best minimum cutoff frequencies for the loads; P3 - smaller numbers of stages and frequency adjustment for each stage.

For comparison with the previous example the islanding also occurs at time t = 15 seconds. The under-voltage protection was adjusted to 0.5 pu. As the empirical process, this method also retrieves the frequency in all cases analyzed (Fig. 4). In case 1 and 2, only one step of load shedding was sufficient, the case 3 requires two steps and in case 4, three steps were required as shown in Figure 3 (a), thus reducing the number of LS required.

An analysis of Table 3 summarizes the action of load shedding with definition of the basic premises through MEAN and shows that the case 4did not result in a stable micro-grid, although the frequency has recovered, the protection actuated after LS. In all other cases, the voltage drop across the terminals DG does not result in a disconnection.



(a) DG frequency during intentional Islanding after Load Shedding.



(b) DG voltage during intentional Islanding after cutting load.

Fig. 4. Load Shedding results with automatic definition of the basic premises.

Table 3 Results of the sensitivity analysis

Case	V_{SAG}(pu)	V_{SS}(pu)	Δf_T(Hz)	t_{REST} (s)
1	0.711	0.306	-1.19	0.32
2	0.583	0.437	-1.21	0.31
3	0.498	0,592	-1.30	0.28
4	DG disconnected			

Table 4 - Load Shedding – Best solutions found by (MEAN)

Case	Stage 1		Stage 2		Stage 3	
	t_c	P_{CC}	t_c	P_{CC}	t_c	P_{CC}
1	16.87	5.6	---	---	---	---
2	17.6	10.8	---	---	---	---
3	18.2	9	18.6	3.96	---	---
4	18.3	11.3	18.8	4.95	19	5.85

Figure 5 shows the percentage that the final solution found the best possible way the defined conditions and stored in tables for each case study. It is observed that the difficulty in finding feasible solutions increases with the load amount in the system, as in this case study, the disconnection of loads is linked to the bus and it is not possible to disconnect them individually.

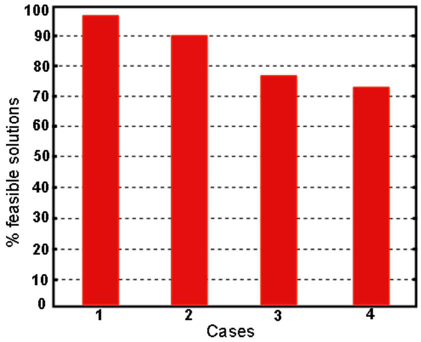


Fig. 5. Percentage of feasible solutions for each case.

CONCLUSION

This paper presented two methods to solve the LS problem applied to operating intentional islands in distributed synchronous generators. The first one uses empirical analysis, while the second one uses the MEAN, that is, a methodology for power restoration adapted for LS analysis problems with distributed generation in islanded system. In order to improve the selection of the best loads for cutting tests were performed when the system is in islanded condition to evaluate the methodology. According to the results, the method is able to deal with the problem of islanding in distributed generation studies, and potentially providing effective solutions to be applied in larger systems.

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