ANALYSIS OF UFLS SCHEMES WITH INCREASED WIND GENERATION IN SMALL ISOLATED POWER SYSTEMS

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Abstract –Underfrequency load shedding (UFLS) is a last resort tool to arrest the decrease in frequency and avoid the collapse of the system in case of a disturbance. Wind power has experienced a wide development throughout the world due to technological progress in wind turbines and favorable policy incentives. There is a need to verify if the actual UFLS schemes are suited to the expected wind power increase. The feasibility of an UFLS scheme is addressed by analyzing actual and future scenarios of generation and taking into account probable contingencies within each scenario. This paper describes how future scenarios can be estimated and how the contingencies have been chosen. It also details the values and measures proposed for the assessment of the adequacy of an UFLS scheme. Finally, this paper analyzes an UFLS scheme in current and future generation scenarios of an isolated Spanish power system.

Keywords: Load shedding, frequency stability, wind power generation.

1 INTRODUCTION

In a power system, the total power generation must always match the total power demand. If at any given time generation is not equal to demand, there is a change in the frequency of the system. The system initially responds to the frequency variation with the inertia and the primary frequency control of generation units.

Isolated power systems are very sensitive to variations in generation and demand due to the small number of generation units connected and their low inertia. After a contingency the amount of lost power can be a significant percentage of the total power generated. Since isolated systems lack of adjacent systems to support them, the remaining connected generation units may not have enough reserve to restore the lost power or their response is not fast enough [1]. Underfrequency load shedding (UFLS) is used in isolated power systems as a last resort tool to arrest the decrease in frequency and avoid the collapse of the system [2]. UFLS schemes operate by disconnecting a limited set of loads to restore the balance between generation and demand using underfrequency and rate of change of frequency (ROCOF) relays.

Wind power has experienced a wide development throughout the world due to technological progress in wind turbines and favorable policy incentives. Spain is the fourth largest country in wind power installed capacity, with 19149 MW of installed capacity at the end of year 2009 [3]. The Spanish Ministry of Industry, Tourism and Commerce considers as a probable scenario 29000 MW of installed wind power capacity for the year 2016 [4]. With regard to the isolated Spanish power systems, the actually installed wind power capacity in the Canary Islands amounts to 141 MW and previsions of the Canary Energy Plan (PECAN) for the year 2015 adds to 1025 MW [5]. This could possibly lead to scenarios where wind generation could exceed the production of conventional generation units. However, since wind power generation still has many shortcomings such as inability to provide primary frequency control and lack of inertia, power system stability may be compromised with increasing wind generation. Hence, there is a need to verify if the actual UFLS schemes are suited to the expected wind power increase.

The feasibility of an UFLS scheme is addressed by building different scenarios of generation and taking into account probable contingencies within each scenario [6]. If current and future behavior wants to be analyzed, these scenarios should include current and future hourly generation scenarios of the isolated power system under study. Thus, reasonable future scenarios need to be built, taking into account the expected growth of demand, conventional generation and the expected share of wind generation.

The behavior of the UFLS scheme analyzed must ensure that no transient or final frequency values threaten the stability of the system. An UFLS scheme is acceptable when after a loss of generation, it disconnects the amount of load sufficient to restore the frequency to a reasonable final value. Shedding of load has very high associated costs due to indemnifications paid to affected customers. Thus, if more load than required is shed, there is a significant deterioration in the quality of the service and in the corporate image of the supplier company [1].

This paper proposes a method to analyze an UFLS scheme in current and future generation scenarios of an isolated power system. This paper describes how future scenarios can be estimated and how the contingencies should be chosen. Different measures of frequency values and shed load are proposed in this paper to decide if the actual UFLS scheme is able to accommodate the expected wind power without compromising system stability. As an example of the proposal analysis, a real UFLS scheme of an isolated Spanish power system within the Canary Islands is analyzed.

The paper is organized as follows: Section 2 describes the model used to represent a small isolated power system. Section 3 details the values and measures used for the assessment of the adequacy of an UFLS scheme. Section 4 focuses on the description of the case studied. Results are provided in Section 5. Section 6 concludes the paper.

2 SYSTEM MODELING

In this section the model used to represent a small isolated power system is described. The generation units, the system response of frequency and the operation of the load shedding relays are detailed.

Figure 1 details the power-system model used to test the robustness of an UFLS scheme of a small isolated power system with *n* generation units. The power system has been reduced to a single bus ignoring the dynamics between generation units, which is an acceptable assumption for small isolated power systems [7].

2.1 Generation unit modeling

Generation units are represented by a second-order turbine model approximation. The constants K_g, $b_{g,1}$, $b_{g,2}$, $a_{g,1}$ and $a_{g,2}$ of each generation unit *g* can be deduced from more accurate models or field tests. Since primary spinning reserve is finite, the generation units output limitations $\Delta P_{g,min}$ and $\Delta P_{g,max}$ are also modeled [6].

Each conventional generation unit is defined by its base power (M_{BASE}) in MVA, the maximum and minimum power that is able to generate (P_{max}, P_{min}) in MW and its inertia (H) in seconds.

Wind generation units have no inertia and no ability to provide primary frequency control. Therefore they are only defined by their base power and the power that they were generating at that time.

2.2 System response of frequency modeling

The system inertia block models the kinetic energy storage in all the generator rotors according to the equation (1) [1].

$$\Delta P_g + \Delta P_{reserve} - \Delta P_d = 2H\frac{d\Delta w}{dt} \qquad (1)$$

P_g, $P_{reserve}$ and P_d are the generated, the reserve applied and the demand power respectively. H is the total inertia of all the rolling masses. The overall response of loads can be taken into account by means of a load-damping factor *D* if its value is known.

2.3 Modeling of underfrequency load-shedding relays

In this model, two types of load-shedding relays are used. Underfrequency relays disconnect a portion of the load when the frequency is below a certain level during a specified time. ROCOF relays operate when in addition the slope of the frequency reaches a set value. This prevents the collapse of the system when the frequency decreases so rapidly that underfrequency relays would shed load too late [8].

The parameters that define underfrequency protections are: (a) the frequency threshold at which shedding occurs -*Freqlim*-; (b) time delay of the activation of the load shedding after reaching a *Freqlim* value -*Tdelay*-; (c) time it takes to open the breaker of the feeder of the load to be shed -*Topening*-; (d) the percentage of system load shed.

The parameters that define ROCOF protections are: (a) the frequency threshold from which the value of the slope of the frequency drop will be measured -*Freqlim*-; (b) the value of the limiting slope from which protections are activated -*ROCOFlim*-; (c) time delay of the activation of the load shedding -*Tdelay*-; (d) time it takes to open the breaker of the feeder of the load to be shed -*Topening*-; (e) the percentage of system load shed.

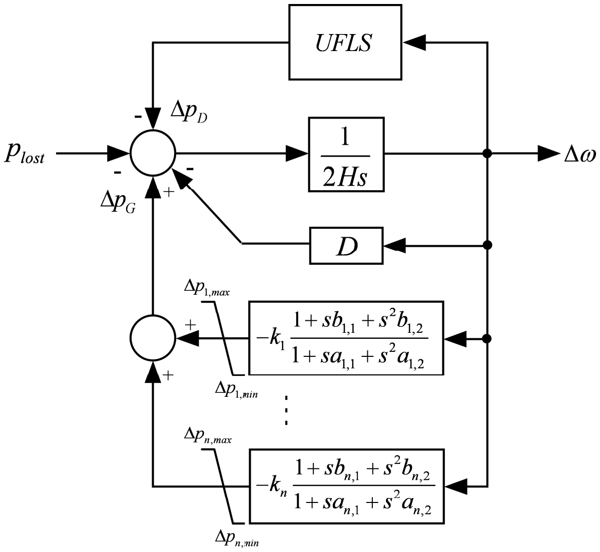

Figure 1: Model of the power system.

3 ASSESSMENT OF THE ADEQUACY OF AN UFLS SCHEME

To verify whether an UFLS scheme is robust, it should be tested in different scenarios, under several contingencies and it must satisfy different criteria. In this section, the hourly scenarios and the contingencies used to analyze the behavior of the UFLS scheme are described and the values and measures used for the assessment of the adequacy of an UFLS scheme are detailed.

3.1 Scenarios and contingencies

Apart from evaluating the suitability of an UFLS scheme for current generation and demand scenarios, this paper proposes to evaluate an UFLS scheme in future scenarios which include wind penetration. This study will help to decide if the UFLS scheme should be revised and amended.

If current generation scenarios are available, this paper proposes a method to estimate hourly scenarios for subsequent years taking into account the expected increase in demand and the expected increase in installed wind power capacity. Knowing both the expected installed MW of wind power for a particular year and the peak demand growth forecast, two different future scenarios with 40% and 80% of expected installed wind power capacity are built. The rates 40% and 80% correspond to the average power that is generated when wind is low and when the wind is high. These percentage values could be changed in function of the isolated power system analyzed. It should be noticed that focus is on the amount of installed wind power capacity. Variability of wind power over the period is taken into account by analyzing sudden losses of wind power generation and by contemplating different levels of wind power generation.

All scenarios have been provided with the same percentage of minimum reserve in order to comply with the grid code. If the way of dispatching or operation changes, scenarios should be adopted accordingly. Currently, the reserve amounts to about 22% of the maximally available power to cover the possible outage of the largest generation unit [9]. To get a percentage of minimum reserve power to apply to the new future scenarios, this paper uses the current available scenarios and studies which is the lowest reserve in all of them. Taking into account the percentage of the expected installed wind power capacity, the increase in peak demand, and the percentage of reserve power, each set of future scenarios is built as follows: First, the amount of power that should be generated by conventional and wind generation units is calculated. Second, if the amount of the conventional power is similar to the power generated in one of the current generation scenarios, the same conventional generation units remain connected. Otherwise, if the amount of conventional power is greater or lower, then additional conventional generation units should be connected or disconnected. Finally, it should be noted that the installed capacity of conventional power remains constant and that the increase in demand is covered by the increase in installed wind power capacity. In case the total conventional installed power is not enough to cover the future conventional demand, additional conventional generation units should be predicted and included. Wind power generated in each scenario has been divided into 50 MW wind farms·

For each hourly generation and demand scenario, the loss of any individual generation unit and the loss of the entire combined cycle have been tested to address the UFLS scheme adequacy. In the case of wind farms and assuming that they have similar parameters and generate approximately the same power, all possible losses, from the loss of a single wind farm to the simultaneous disconnection of all wind farms, are simulated. For example, if in a scenario, three wind farms are generating, the loss of one, two and three wind farms will be simulated.

3.2 Measures used for the assessment of the adequacy of an UFLS scheme.

This subsection describes the measures that should be obtained from the simulated contingencies in all scenarios and how they should be interpreted. This paper proposes an analysis of the results that will help to identify whether a shedding-plan is appropriate or available for future scenarios with wind power penetration.

A robust UFLS scheme must satisfy different criteria. Firstly, whenever a loss of a generation unit occurs, sufficient load must be shed to restore the frequency to a reasonable final value. Acceptable values of final frequency and minimum transient frequency depend on the power system. For example, in isolated Spanish power systems, frequency can remain below 47.5 Hz during maximum 3 s [9].

Additionally, an UFLS scheme is acceptable when after a loss of a generating unit, the remaining load can be served with the units of the system operating above their minimum technical requirements. Otherwise, the frequency would start to rise indefinitely and could only be countered by disconnecting generation units.

The measures proposed in this paper to assess the adequacy of an UFLS scheme are: (a) the minimum value that the frequency acquires during the transient (from the generation loss until the primary frequency control and the load-shedding act and the frequency reaches its final value) ($Freq_{trans}$); (b) the final value of the frequency ($Freq_{final}$); (c) the number of incidents in which load shedding occurs; (d) the amount of shed load.

Once these values have been obtained by simulating all the contingencies in all the future scenarios, they can be graphically analyzed. First, a bar plot is drawn that represents the number (%) of incidents as a function of the minimum and the final frequency value in future and current scenarios. These graphs will help to analyze if the UFLS scheme, actually and in the future, aloud inappropriate frequency values or if the number of incidents with more dangerous frequency values increase with the wind penetration. A second bar plot represents the number (%) of incidents in which load-shedding occurs in each set with respect to the total simulated incidents. A third bar plot shows the average values (%) of shed load in current and future scenarios. The average value of shed load in each case is calculated by adding the load shed in each incident with load shedding, divided by the sum of total incidents with load-shedding in this case.

If the results show that current UFLS schemes should be revised, possible amendments could be found in [10] and [11].

4 DESCRIPTION OF THE CASE STUDIED

This section describes the power system that has been analyzed. This system corresponds to an isolated Spanish power system within the Canary Islands.

Firstly, the hourly scenarios and the contingencies used to analyze the behavior of the UFLS scheme are described. Secondly, the generation units are described. Finally, the current setting of the load-shedding relays is detailed.

4.1 Scenarios and contingencies

To analyze the behavior of the UFLS scheme, the starting points are 24 current hourly generation and demand scenarios of the isolated power system. These 24 scenarios belong to a representative day covering all typical values including peak load and valley load scenarios.

These initial hourly scenarios contained no wind generation. In addition to the current hourly scenarios, other hourly scenarios have been estimated for the years 2009 and 2015 taking into account the expected increase in demand and the expected increase in installed wind power capacity according to PECAN [5]. For the years 2009 and 2015, hourly scenarios of 40% and 80% of the installed wind power capacity have been built. All scenarios have been provided with a reserve of 22%. This results in five sets according to the time horizon (2009 or 2015) and the installed wind power capacity (0%, 40% and 80%). If the way of dispatching or operation changes, scenarios should be adopted accordingly.

Table 1 summarizes the following data for each set of 24 hourly scenarios: (a) percentage of the installed wind power that is covering the demand; (b) name of the set of the 24 hourly scenarios; (c) Peak demand in MW; (d) conventional generation units installed power in MW; (e) current and expected installed wind power capacity in MW.

	SETS OF 24 HOURLY SCENARIOS				
	2009			**2015**	
Percentage of intalled wind power capacity	0%	40%	80%	40%	80%
Name of the set of 24 hourly scenarios	2009-0	2009-40	2009-80	2015-40	2015-80
Peak demand (MW)	528.10	528.10	528.10	739.34	739.34
Conventional installed power (MW)	928.34	928.34	928.34	928.34	928.34
Wind installed power (MW)	0	101	101	225	225

Table 1: Table summarizing the 5 sets of 24 hourly scenarios data.

For each hourly scenario, the contingencies described subsection 3.1 are simulated.

4.2 Generation units

The isolated power system consists of 22 conventional generation units comprising 1 combined cycle power plant, 7 steam, 5 diesel and 7 gas turbines. Table 2 shows the parameters that define each kind of generation unit.

Table 3 shows the number of conventional generation units connected during peak and valley hours in all sets. Figure 2 shows a box plot that represents the power generated with conventional generation units during all the scenarios in all the sets.

	GENERATION UNITS					
	Steam	**Gas**	**Diesel**	**Combined cycle**		
				Gas$_{cc}$	**Gas$_{cc}$**	**Steam$_{cc}$**
M_{BASE} (MVA)	100	92.78	15	92.78	92.78	92.78
P_{max}	74.24	68.7	11.34	67.6	67.7	67.8
P_{min}	27.84	9.7	4.58	3.23	3.24	3.25
H (s)	5.6	5.084	1.5	5.084	5.084	5.084
K_g (M_{BASE})	16.67	20.21	25	20.21	20.21	16.67
$b_{g,1}$	0	0	4.3	0	0	0
$b_{g,2}$	0	0	0	0	0	0
$a_{g,1}$	5.35	0.44	5.96	0.44	0.44	5.35
$a_{g,2}$	1.75	0.09	1.65	0.09	0.09	1.75

Table 2: Parameters of the generation units.

	NUMBER OF CONVENTIONAL GENERATION UNITS				
	2009-0	**2009-40**	**2009-80**	**2015-40**	**2015-80**
Peak	12	12	12	17	14
Valley	12	12	12	12	12

Table 3: Number of conventional generation units connected during the peak and the valley hours in all the sets.

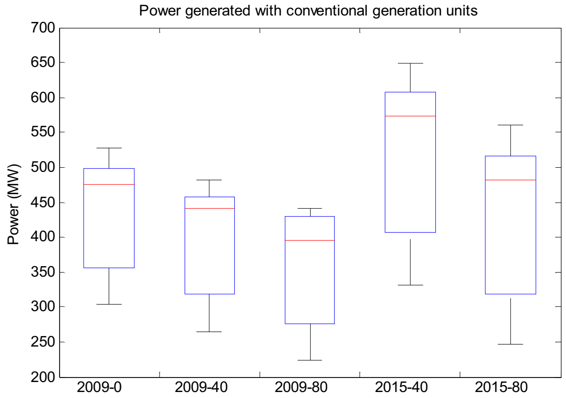

Figure 2: Power generated with conventional generation units during all the scenarios in all the sets.

4.3 Load shedding relays

The shedding-plan analyzed includes underfrequency and ROCOF protections. It has 103 relays, 90 of them are underfrequency and 13 are ROCOF relays.

Table 4 and Table 5 show the ROCOF and underfrequency relays parameters, respectively.

ROCOF					
Step	**Freqlim (Hz)**	**ROCOFlim (Hz / s)**	**Tdelay (s)**	**Topening (s)**	**Load (%)**
1	49.3	-0.8	0.15	0.2	9.98

Table 4: Parameters of the ROCOF relays.

UNDERFREQUENCY				
Step	Freqlim (Hz)	Tdelay (s)	Topening (s)	Load (%)
1	49	0.1	0.2	3.43
2	48.92	0.15	0.2	5.28
3	48.85	0.2	0.2	5.02
4	48.79	0.3	0.2	5.69
5	48.72	0.4	0.2	4.17
6	48.66	0.5	0.2	9.95
7	48.6	0.6	0.2	5.46
8	48.55	0.7	0.2	3.05
9	48.5	0.8	0.2	4.07
10	48.35	0.9	0.2	5.9
11	48	1	0.2	10.34

Table 5: Parameters of the underfrequency relays.

5 RESULTS

In this section, the measures obtained from the simulations of contingencies in all the hourly scenarios are shown. In addition, an analysis of the results is carried out to identify whether the UFLS scheme is appropriate for future scenarios with wind power penetration.

5.1 Frequency of the system

This section presents several graphs of the frequency obtained in the different hourly scenarios.

Figure 3 shows the frequency obtained during all the contingencies occurring in year 2009 with no wind penetration (Set 2009-0).

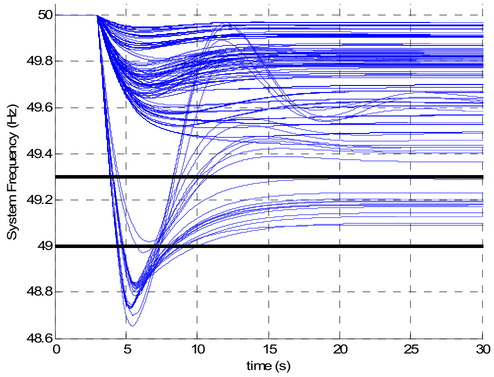

Figure 3: System frequency (Hz) in all incidents (including loss of the combined cycle power plant) for all scenarios (24) (Set 2009-0).

This figure shows that transient frequency values ($Frec_{tran}$) and final frequency values ($Freq_{final}$) for all the simulated contingencies are over 48.6 Hz.

Incidents can be classified into two groups:

- Those where the transient frequency does not decrease below 49.3 Hz and no load shedding occurs. These incidents correspond to cases where less percentage of generation is lost or connected generation units react fast.
- Those where the transient frequency decreases below 49 Hz, corresponding to incidents where the combined cycle is lost. These contingencies produce high frequency declines that involve substantial load shedding, because the lost generation is very high in relation to the served demand.

As the worst incident in an hourly scenario is the loss of the combined cycle power plant, Figure 4 represents all incidents involving the loss of the combined cycle power plant in all the 24 hourly scenarios of the five sets defined in Table 1. The lowest transient frequency value is achieved at the incident of the loss of a combined cycle power plant in hour 1 within the set 2009-0 (48.65 Hz). The lowest frequency final value is, however, in hour 11 within the set 2015-40 (48.98 Hz). Although the incidents within set 2015-80 have a greater initial drop in frequency, final frequency values may be substantially higher due to load shedding than in other incidents with less lost of generation and without load shedding.

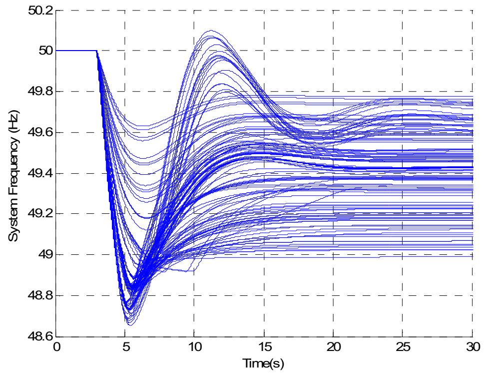

Figure 4: System frequency (Hz) in the incidents of the loss of the combined cycle power plant in all the scenarios in all the sets.

5.2 Results and interpretation

This section compares all cases analyzed in this paper using the measures proposed in subsection 3.2 to evaluate the response of the UFLS schemes of the system. Firstly, the minimum frequency values that occur in all incidents in all scenarios of each set will be compared. Secondly, the final frequency values will be compared. Finally, the number of load-shedding actions and percentage of shed load in each case will be studied.

5.2.1 Minimum frequency value.

In all incidents the minimum frequency value during the transient ($Freq_{trans}$) is above 48.6 Hz.

Figure 5 shows the number of incidents (%) within each set of 24 scenarios as a function of $Freq_{trans}$.

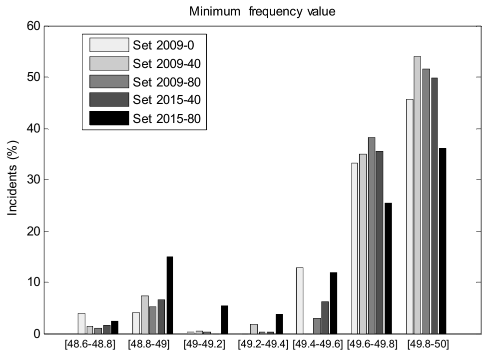

Figure 5: Number of incidents (%) as a function of the minimum frequency value ($Freq_{trans}$) in all the sets.

From Figure 5 it can be inferred that all sets have approximately the same number of incidents in each minimum frequency interval except the set 2015-80, which is the set with more incidents with lower frequency values and less incidents with higher frequency values. A series of clarifications must be made:

Figure 2 of subsection 4.2 shows that the power generated by conventional generation units in set 2015-40 is higher than that provided by conventional generation units in set 2015-80, since in the second case the incorporation of wind energy accounts for 80% of installed capacity (instead of 40%). Therefore, if a generation unit is disconnected in one of the 24 scenarios of the set 2015-40, there are more conventional generation units (providing primary frequency control) online. Having less inertia in set 2015-80 causes the frequency to drop more steeply and thus frequency attains its lowest values. Another relevant fact is that a different number of generation units, as shown in Table 3 of subsection 4.2, or a different type of generation units is connected. In set 2015-80, since there is less generation provided by conventional generation units, the response may be slower. This is due to the fact that several generation units provide reserve faster than for example a single generation unit with the same characteristics. The type of generation unit (diesel, steam or gas) influences the speed of the primary frequency control, depending on the technical characteristic.

5.2.2 *Final frequency value.*

In all incidents the final frequency value (*Freq*$_{final}$) lies between 48.8 Hz and 50 Hz.

Figure 6 shows the number of incidents (%) within each set of 24 scenarios as a function of *Freq*$_{final}$.

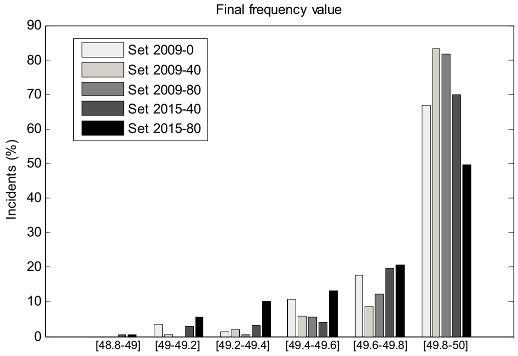

Figure 6: Number of incidents (%) as a function of the final frequency value (*Freq*$_{final}$) in all the sets.

From Figure 6 it can be outlined that all sets have approximately the same number of incidents in each final frequency interval except the set 2015-80, which is the set with more incidents with lower final frequency values and less incidents with higher final frequency values. This is due to the fact that in this set there are many wind generation units connected to system (about 25% of the total demand is covered by wind power generation) and therefore, losing the whole wind power generation is much more severe in this set than in other sets. Note that there are cases where 190 MW of wind power generation can be lost, which is a relatively high amount of lost power compared to 70 MW of a single conventional generation unit or 180 MW of a combined cycle power plant.

5.2.3 *Load-Shedding.*

It is interesting to compare the number of incidents in which load shedding occurs in relation to the total number of events simulated within each set of 24 hourly scenarios. Table 6 shows these values:

	SET OF 24 HOURLY SCENARIOS				
	2009-0	**2009-40**	**2009-80**	**2015-40**	**2015-80**
Incidents with Load-Shedding	23	19	17	24	51
Total Incidents	289	220	264	293	294

Table 6: Incidents with load shedding and total number of incidents in each of the analyzed sets.

The percentage of incidents in which load shedding occurs in each set is shown in Figure 7. Set 2015-80 clearly presents more load-shedding incidents. By contrast, set 2009-80 has less load-shedding incidents. The remaining sets present a similar percentage of incidents (around 8% of simulated incidents).

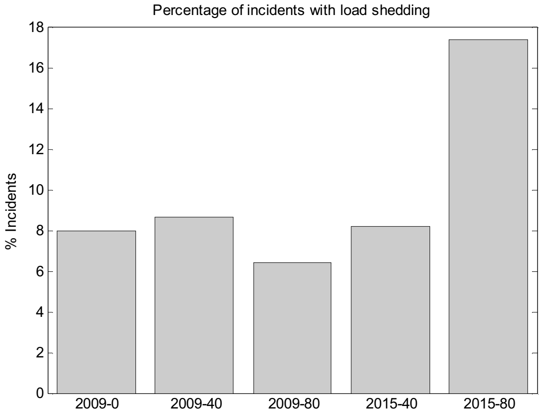

Figure 7: Incidents (%) in which load shedding occurs in each set with respect to the total simulated incidents.

The average value of shed load of all incidents for each set is shown in Figure 8. Despite being the set 2015-80 the one with more load-shedding incidents, the average load shed is higher for set 2009-0 reaching a value of 7.78% in each load-shedding incident. In sets 2015-40 and 2015-80 similar average values of load shed are obtained. That means that despite being set 2015-80 the one with more load-shedding incidents, the average amount of shed load in each set is quite similar. This is due to the fact that in set 2015-80 more incidents are simulated because more wind farms are connected, but the loss of a wind farm is less severe as they generate less power. In view of the results, the System Operator would decide if the reliability level of the future system should be the same as the one found in the current system or if it should be revised and amended.

Figure 8: Average value (%) of shed load in each set.

6 CONCLUSIONS

In this paper, a method has been proposed to analyze an UFLS scheme in current and future generation scenarios of an isolated power system. The paper describes how future scenarios can be estimated and how the contingencies should be chosen. Different measures of frequency values and shed load have been proposed to decide if the actual UFLS scheme is able to accommodate the expected wind power without compromising system stability. As an example, a real UFLS scheme of an isolated Spanish power system within the Canary Islands has been analyzed. Results show that as the installed wind power capacity increases, the number of incidents with load-shedding increases, but not the average amount of shed load of all incidents. Moreover, the behavior of the UFLS scheme analyzed is considered acceptable in current and future scenarios since transient and final frequency values are within acceptable limits.

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