# ANALYSIS OF THE BEHAVIOUR OF ASYNCHRONOUS WIND TURBINES UNDER NETWORK FREQUENCY VARIATIONS

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ABSTRACT: In small and medium size power systems, of about 100-600 MW, network frequency variations could take place causing wind parks disconnection from the grid, in case of a non suitable setting of the frequency protection devices. In this paper, the setting of such frequency protection devices, associated to the interconnecting transmission line between the wind park and the grid, is studied for a base network representing the power systems of Canary Islands (100-600 MW), using dynamic analysis as the main tool.

## 1. INTRODUCTION

Wind parks are equipped with protection devices to assure that both external and internal faults do not cause any damage on their own apparatus nor the grid to which they are connected. Those protection devices generally are related to over- and under current, over- and under voltage and over- and under frequency. Disturbances such as conventional units outages, short-circuits and isolated operation of a wind park, can cause frequency variations, reason by which the installation and setting of a frequency protection is required.

Rules for installing an setting frequency protection devices in wind parks have been published ([1] [2] [3] [4] [5]). Nevertheless, much of those rules were developed keeping in mind large and/or interconnected power systems, paying low attention to the mentioned isolated power systems in the range 100-600 MW, which can also presents continuously growing wind penetration levels up to 20-50%. That is the case of Canary Islands, where it is planned that the present 20% wind penetration level in Gran Canaria would grow up to 50% in 2011 [5].

This paper is related to the influence of the expected network frequency variations on setting the frequency protection devices located in wind parks, in case of isolated power systems of about 100-600 MW of load an a wind penetration level of about 20-50%.

## 2. FREQUENCY PROTECTION ASSOCIATED TO WIND PARKS

Figure 1 shows a basic configuration of a wind park connected to the network through an interconnecting transmission line, also including an interconnecting circuit breaker. That circuit breaker is associated to the actuation of protection relays such as over- and under frequency and over- and under voltage.

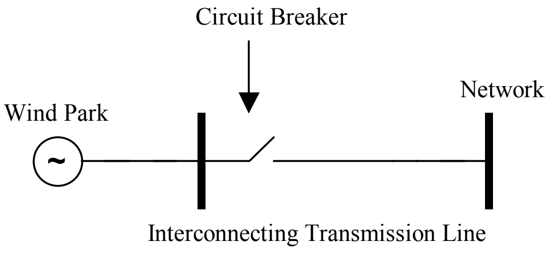

**Figure 1:** Basic configuration of a wind park connected to the network

In that scheme, an eventual isolated operation of the wind park is avoided by a voltage protection in redundancy with a frequency protection ([4] [6] [7]). If the wind park lies in isolated operation with a load lower than generation, frequency could continuously grow and autoexcitation of the induction generators could take place. The subsequent overvoltage could damage the devices and apparatus located inside the wind park, question to be considered in setting the protection relays.

Recommendations about setting those frequency relays to be applied in several European countries are summarised in Table I ([1] [2] [3] [4]).

**Table I:** Setting values for frequency relays in several European countries

| | Over frequency<br>Delay | Under frequency<br>Delay |
|---|---|---|
| Spain | 51 Hz<br>0 s | 49 Hz<br>0 s |
| Denmark | > 53.0 Hz<br>0.3 s | < 47.0 Hz<br>0.3 s |
| | 50.3-51.0 Hz<br>1 min | 47.0-47.5 Hz<br>10 s |
| | | 47.5-48.0 Hz<br>5 min. |
| | | 48.0-49.0 Hz<br>25 min |
| Germany | 51.5 Hz<br>0.2 s | 47.5 Hz<br>0.2 s |
| Sweden | 51 Hz<br>0.2 s | 47 Hz<br>0.2 s |

As can be seen in Table I, maximum values of frequency and their corresponding time of actuation are very similar in Spain, Germany and Sweden. This similarity is not observed about the minimum values, being Spain the country where that value is more restrictive. The Spanish regulations ([1]) are now being updated to include the present status of the wind energy into the overall electricity production; also, local governments of Canary Islands could contribute to fix those frequency values for every isolated power systems of those islands [5].

Present wind penetration level in Denmark is about 20%, value which is planned to grow up to 40% in a few years

([8]). High wind penetration levels like those mentioned (Denmark, Canary Islands) suggest the need for a new way in which the entire power system must be operated. An example could be, in Denmark, the requirements for assure stability in case of a fault in the network by means of a reduction in power generation from wind parks, being frequency and voltage the control input signals ([2]). Danish recommendations for frequency protection relays, shown in Table I, are more detailed than others. This fact could be related to the need for wind parks to contribute to the system stability and, consequently, its disconnection from the grid must take place only when a severe risk of security loss exist.

## 3. FREQUENCY VARIATIONS IN A POWER SYSTEM

Frequency variations in a power system are closely related to the imbalance between real power generation and load (plus losses) in the overall network, all the time ([9]), as showed by the swing equation of the synchronous machine:

$$\frac{d\omega}{dt} = \frac{P_m - P_e}{2H} \qquad (1)$$

$$\frac{d\delta}{dt} = 2\pi f(\omega - 1) \qquad (2)$$

where

ω: speed (p.u.)

δ: internal angle (rad)

$P_m$: mechanical power applied to the shaft (p.u.)

$P_e$: real power (p.u.)

H: inertia constant (MW-s/MVA)

f: rated frequency (Hz)

That power imbalance causes a variation in the kinetic energy stored in the synchronous generating system, and is obtained through a speed variation from the synchronous machine.

On the other hand, the rotor slip of an induction machine depends on the synchronous speed and on the balance between mechanical and electrical torques, being (3) the corresponding electromechanical equation:

$$\frac{ds}{dt} = -\frac{1}{2H}\left(\frac{P_m}{1-s} - P_e\right) \qquad (3)$$

where

$$s = \frac{\omega - \omega_{IM}}{\omega}$$

$\omega_{IM}$ = speed of induction machine (p.u.)

A simplified model of the power system ([10]) can be useful to estimate frequency variations. That model assumes no coupling between frequency f and voltage V, so real power variations influences frequency but not voltage. Such no coupling is not strictly observed in small and medium size power systems, by the model gives orientates values of frequency variations.

Using that model, the frequency variations after a load change, or a wind power change, will be estimated as following:

$$\Delta f_0 = -\frac{M}{\beta} \quad (Hz) \qquad (4)$$

where

M: load or wind power change (MW)

β: frequency response characteristic

Wind generators with power control by stall method seem to be the most influenced by network frequency variations. When the frequency and consequently the rotor speed are high, the stationary power curve of the generator changes and the point of maximum power presents a higher value. Therefore, overheating could case the actuation of protection devices ([11]).

To evaluate the influence of the network frequency variations on the frequency protection setting of the wind parks, dynamic analysis has been performed ([12]).

A base network representing the power systems of Canary Islands is selected (fig. 2). Wind penetration level of that base network is 20%, although in particular operational cases 50% is selected.

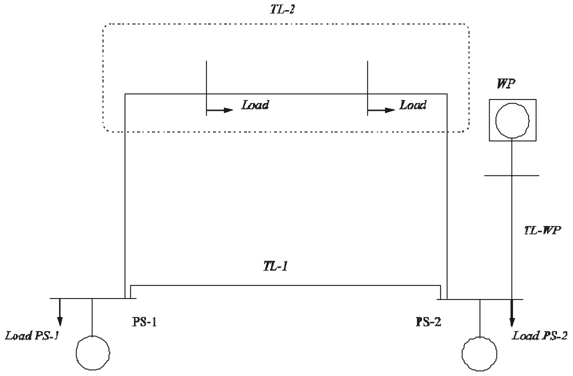

**Figure 2:** Base network

Dynamic analysis is performed through commercial software SIMPOW ([13]). Synchronous machines are represented by a dq model, adding suitable models for steam turbines and diesel motors an their corresponding speed governing systems and excitation control systems [14].

Conventional induction wind generators at wind parks are represented by the transient model ([16]), including the inertia of the blades. Wind parks are connected at a unique node to the network.

## 4. DETERMINING MAXIMUM AND MINIMUM VALUES OF FREQUENCY

Dynamic analysis enables estimation of the maximum and minimum values of frequency to be used for setting frequency protection devices. Simulations are carried out after selecting several perturbations which generates network frequency variations. From the equations (1) and (2) it is observed that both a load change and an power generation change cause frequency variations. Therefore, a short-circuit is selected as perturbation for analysing over frequency and a loss of power generation is selected for under frequency (Table II).

Spinning reserve is selected to be enough to cover the greater conventional unit outage, in the general case. As a particular case, one operational scenario without any appreciable spinning reserve is also studied.

**Table II:** Selected perturbations, properties and location.

| Perturbation | Properties | Location |
|---|---|---|
| 3 phase short-circuit without reclosure | 50, 100, 250, 500 ms | Main bus at Power Station |
| 3 phase short-circuit with reclosure | 100, 250, 500 ms. | Network node |
| Conventional unit outage | Unit at higher load level | With spinning reserve |
| Conventional unit outage | Unit at higher load level | Without spinning reserve |

Analysing the simulations results, some considerations about system behaviour can de made. Expected maximum and minimum values of network frequency, for short-circuits of several durations in the main power station bus, are indicated in figure 3.

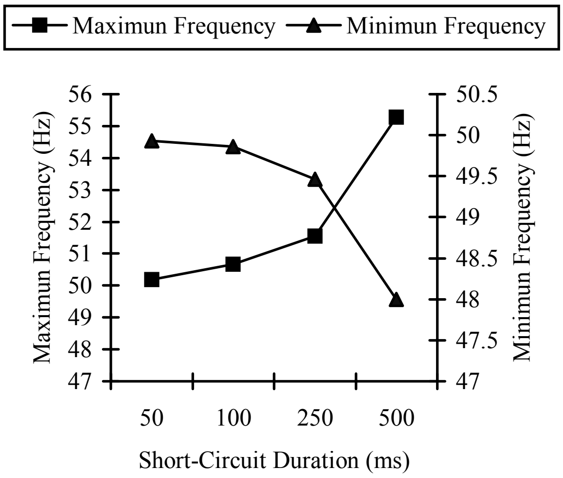

**Figure 3**: Obtained maximum and minimum network frequencies versus short-circuit duration (Power Station)

**3 phase short-circuit without reclosure (500 ms)**

- Short-circuit take place at the main bus of the power station and is cleared without lost of any appreciable load. Maximum time required for detecting and clearing the fault is estimated as 500 ms for this network.
- Expected maximum and minimum frequency values are 55.27 Hz and 48.0 Hz, respectively (Fig. 4). Those values could be selected as the first reference for frequency protection adjust in this network.

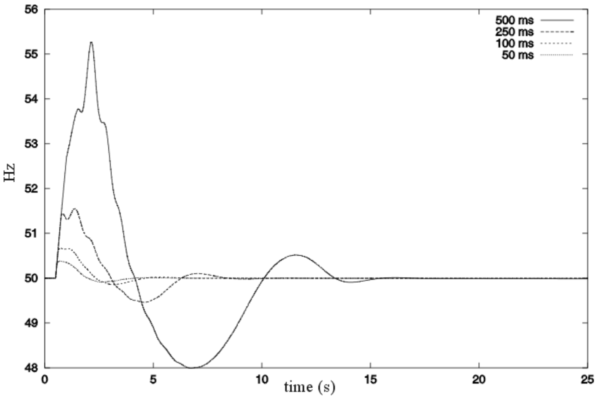

**Figure 4**: Shortcircuits without reclosure: frequency

- Real power from wind generators could reverse for about 0.5 s, as can be seen in figure 5.

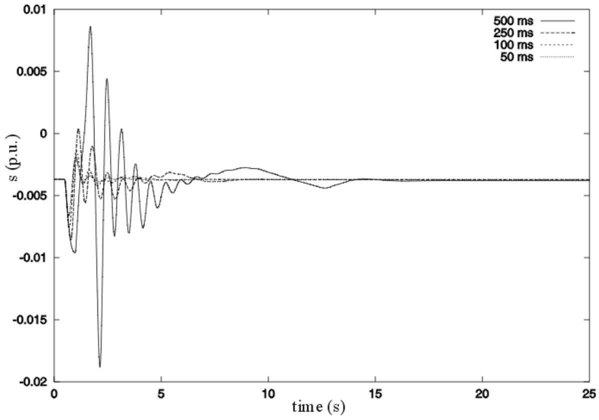

**Figure 5**: Short-circuits without reclosure: wind generators slip.

**3 phase short-circuit with reclosure (500 ms)**

- This short-circuit in a network bus, not located in the power station, is cleared loosing the bus load. That load is reconnected by reclosure 0.2 s later (Fig. 6).
- Maximum value of frequency is observed at 51.57 Hz and the minimum at 49.38 Hz.
- As an example of a bad protection setting, it must be notes that in case of a setting value of 51.5 Hz in the overfrequency relay associated to the interconnection transmission line, the wind park is disconnected from the network. The subsequent imbalance of real power in the overall system causes a network frequency drop. Although, in this case, there is enough spinning reserve to match the amount of generation loss, load shedding could take place and consumers could be seriously influenced (Fig. 7).

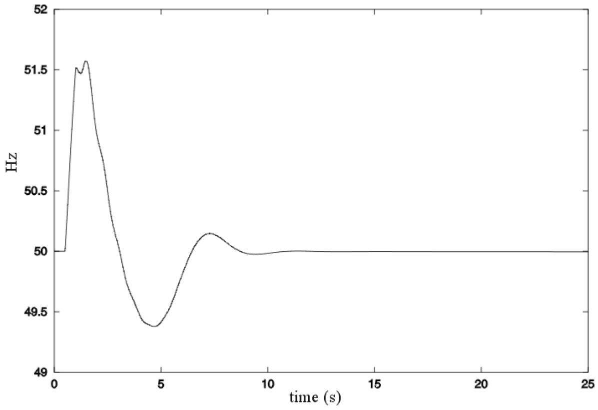

**Figure 6:** Shortcircuit 500 ms with reclosure (Power Station): frequency

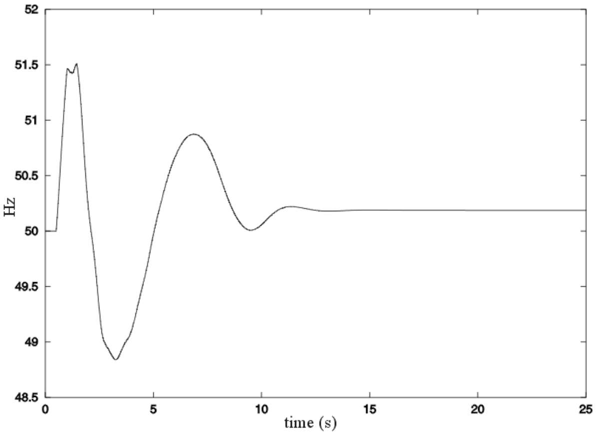

**Figure 7:** Short-circuit 500 ms with reclosure (network node) plus disconnection of the wind park: frequency

**Conventional unit outage (no spinning reserve)**

- Loss of the larger conventional synchronous generating unit causes a frequency drop which forces a load shedding, as usual in power system operation (Fig. 8). It is observed that, after the unit outage, the power system could be able to reach a new stable state through load shedding.
- This case could also be selected to setting the frequency protection relay actuating on the main circuit breaker of the wind park. As an example, if the underfrequency value of that protection is setting to 49 Hz at 0.1 s ([2]), the unit outage would cause an initial load shedding and the wind park disconnection. The subsequent high real power imbalance would causes a higher frequency drop and the system could be unstable (Fig. 9).

## 5. CONCLUSIONS

Values of frequency deviations over 55 Hz and below 47 Hz would not be reached in a power system like the one studied in this paper. Such values would probably causes actuation of several protection devices in the external grid side.

It was also observed that appreciable frequency variations could be related to a transient behaviour of the wind generators as motors (Fig. 5). Conventional synchronous units usually include an delayed reverse power protection to avoid turbines damages ([15]). In some European countries, like Sweden ([4]), regulations about wind energy suggest such protection in wind parks. In power systems like the one studied in this paper, those protection device could not be needed if suitable operational procedures were adopted, avoiding an added cause of real power imbalance.

In general terms, sudden loss of wind power can seriously influences isolated power systems with high penetration level. Therefore, a suitable and particular setting of the frequency protection devices is needed for each individual isolated system, to avoid unnecessary disconnecting actions. Taking into account the revised regulations and other recommendations from bibliographic references ([1] [2] [3] [4] [5]) and after carried out a lot of simulations, suggested values for setting frequency protection in Canary Islands could be as indicated in Table III.

**Table III:** Suggested maximum and minimum values for setting frequency protections in Canary Islands

| | Over frequency<br>Delay | Under frequency<br>Delay |
|---|---|---|
| Canary Islands | > 53.0 Hz<br>1s | < 46.0 Hz<br>1 s |
| | 50.5-53.0 Hz<br>3 s | 46.0-49.5Hz<br>3 s |

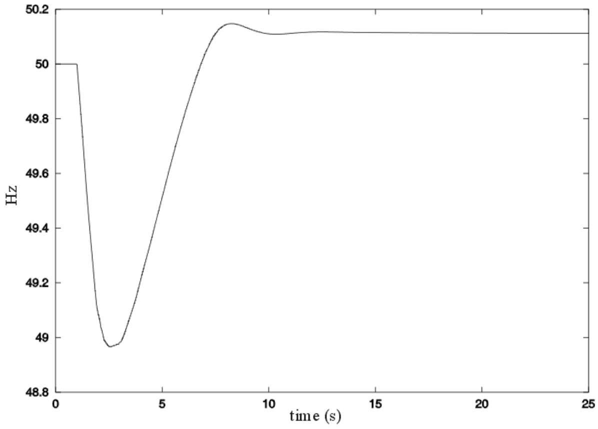

**Figure 8**: Loss of unit at higher load level and load shedding: frequency

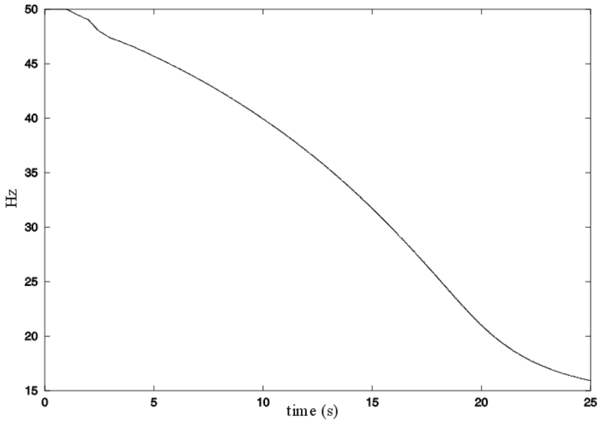

**Figure 9**: Loss of unit at higher load level and disconnection of the wind park: frequency

## 6. REFERENCES

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