MÁXIMA DURACIÓN DE CORTOCIRCUITO EN SISTEMAS ELÉCTRICOS AISLADOS CON AEROGENERADORES SÍNCRONOS MULTIPOLOS

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MAXIMUM SHORT CIRCUIT DURATION IN ISOLATED POWER SYSTEMS WITH FULL CONVERTER WIND TURBINES

ABSTRACT:
This paper analyzes the relationship between wind power integration into small isolated power systems, such as those found on islands, and the critical clearing time (CCT). This study considers full converter wind turbine technology. The CCT is an important parameter used for designing a reliable and effective protection scheme for a power system.

In order to do this analysis, CCT has been determined by dynamic analysis for different amounts of power injected by the wind turbines into the power system. A three-phase short-circuit fault has been considered for dynamic analysis. The power system studied was a PSS®E Lanzarote-Fuerteventura model, which is an example of small isolated power system. Results show a clear relationship between wind energy and CCT. A decrease in CCT values can be seen when more wind power is introduced into the power system. This decrease is due to both the outage of wind farms when a short-circuit takes place and the displacement of the conventional generators located at the power plants.

The knowledge of this relationship and its causes allow a more accurate estimation of the CCT values. Therefore, a more effective adjustment of protection scheme can be done, improving reliability and security of small isolated power systems. Moreover, actions can be derived in order to increase the contribution of this kind of wind turbines minimizing the impact on the protection scheme.

Keywords: small isolated power systems, critical clearing time, wind power, dynamic analysis, full converter wind turbine

RESUMEN:
El presente artículo analiza la relación entre la generación eólica y el tiempo crítico de eliminación (TCE) en los sistemas eléctricos pequeños y aislados, como los presentes en islas. Para este estudio se han utilizado aerogeneradores síncronos multipolos con convertidores para toda su potencia. El TCE es un parámetro importante relacionado con el sistema de protecciones de los sistemas eléctricos.

El análisis ha consistido en la determinación del TCE para diferentes cantidades de potencia eólica generada, mediante la simulación en régimen dinámico de cortocircuitos trifásicos francos. El análisis se realizó con PSS®E sobre el sistema eléctrico Lanzarote-Fuerteventura, que es un ejemplo de sistema pequeño y aislado. Los resultados demuestran que existe una clara relación entre la potencia eólica inyectada en la red y el TCE. Se ha observado una reducción del TCE a medida que la potencia eólica es mayor. Esto se debe principalmente a la desconexión de los parques eólicos al producirse los cortocircuitos y por la progresiva substitución de los generadores convencionales de las centrales eléctricas.

La determinación de esta relación y sus causas permite evaluar con mayor exactitud el TCE. De este modo pueden establecerse ajustes más eficaces en las protecciones, consiguiéndose un funcionamiento más seguro y fiable de los sistemas eléctricos. Además, permite el establecimiento de acciones para una mayor introducción de este tipo de generación eólica en los sistemas eléctricos pequeños y aislados sin causar perjuicio en el sistema eléctrico.

Palabras clave: sistemas eléctricos pequeños y aislados, tiempo crítico de eliminación, energía eólica, análisis dinámico, aerogeneradores síncronos multipolos con convertidores

1.- INTRODUCTION

Installed wind power capacity has experienced an unprecedented increase in the last decade and this trend is expected to continue, as in the case of other renewable energy sources. The global wind power capacity that is estimated to be installed in 2020 is 800600MW [1].

Thereby, wind power integration into power systems is becoming a difficult task. Large amounts of wind power could be incorporated into continental power systems, such as European power system. On the other hand, small and isolated power systems, such as those existing in islands, present some problems related to their specific characteristics which can influence stability [2]. Therefore, wind power can influence frequency of small and isolated power systems [3[4].

In addition, some issues of wind power generation can make its integration more difficult, particularly in the case of small and insolated power systems. Some of them are the unpredictable variation of generated wind power, no provision of ancillary services and wind farms outages caused by a disturbance in the power system.

Another aspect that must be considered for wind power integration is the critical clearing time (CCT). CCT can be defined as the maximum allowable duration time of a three-phase short circuit event before [5]:

- Loss of system stability
- an unacceptable value of load shedding
- an unacceptable value of voltage, frequency or load level in subsequent steady-state.

The unacceptable values of load shedding are set by transmission systems operators (TSO). A 10% of load shedding has been setup as unacceptable value for small power systems in Spain [5].

CCT can be regarded as a boundary point from which the system becomes unstable, and is used as an indicator of system stability [6-[8].

Overall protection schemes of a power system are usually designed for minimizing the consequences of disturbances. CCT is an essential parameter for TSO in order to design these general protection schemes. Therefore, it is necessary to know CCT values for the design. A subsequent significant modification of CCT values can influence protection performance. This can cause problems related to performance or stability of the power system.

Wind power integration into power systems could have an impact on previous CCT values. This impact could be more significant in small isolated power system.

Nowadays, the most technologically advanced wind turbine types are doubly fed induction generator (DFIG) wind turbine and full converter wind turbine. In a DFIG wind turbine, stator winding is directly connected to the grid and rotor winding is connected to the grid through an electronic converter. Full converter wind turbine has a power electronic converter, through which connection to the grid is made. In this paper, it is studied how full converter wind turbine with a wound rotor synchronous generator could influence CCT in small and isolated power systems.

A better understanding of the influence of full converter wind turbine on CCT would allow a more precise determination of its value. Therefore, a more effective and secure protection scheme can be achieve.

2.- METHODOLOGY AND MODELLING

2.1.- METHODOLOGY

In order to study how full converter wind turbines with wound rotor synchronous generator influence the CCT value in small and isolated power systems, Lanzarote-Fuerteventura was selected as an example of this kind of power system, taking into account generation capacity, system inertia and network topology.

To obtain CCT values, the study requires dynamic simulation of several three-phase short circuit events on five substations for different amounts of wind power.

Location of these five substations in the power system allows to find more significant results of the CCT and a better understanding of the power system behavior. The substations are (a) Punta Grande and Las Salinas, located at power plants, (b) Haría-Teguise and Jandía, that are the farthest substations from power plants and (c) Corralejo, which is an intermediate point between power plants mentioned before.

From a scenario without wind power, wind power is progressively introduced in the power system from 10MW to 150MW to carry out the study. Total wind power is shared between wind farms accordingly to their rated power.

Photovoltaic power generation has not been included to avoid its influence on the study about wind power and CCT. Primary and secondary reserves were taken into account to determine power generation in conventional power plants.

It is considered that CCT value is reached accordingly its definition, as seen in Introduction section. In this way, an amount equal to or higher than 10% of load is specified as an unacceptable value of load shedding.

Lanzarote-Fuerteventura power system modelling, steady-state analysis and dynamic simulation were carried out using PSS®E v32 software. Numerical method used in steady-state was Newton-Raphson with a typical tolerance of 0.1MW. PSS®E v32 make use of modified Euler method for dynamic analysis. Integration step was 0.01s.

2.2.- LANZAROTE-FUERTEVENTURA POWER SYSTEM

The Spanish islands of Lanzarote and Fuerteventura belong to the Canary Islands (Fig. 1).

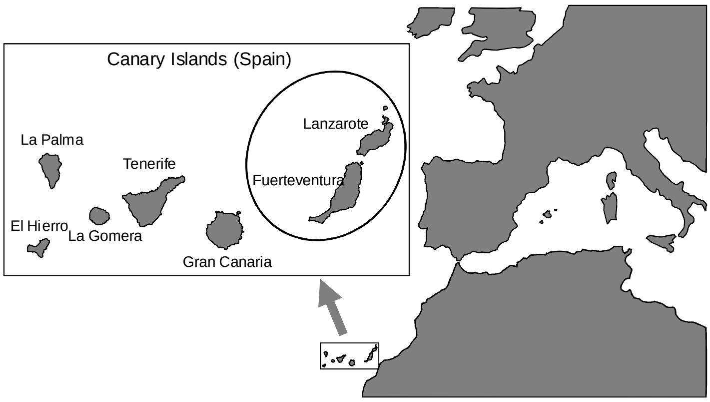

Fig. 1. Geographical location of Lanzarote and Fuerteventura islands

Lanzarote-Fuerteventura power system comprises the systems of both islands. They are interconnected by a submarine cable.

Each island has a power plant. Punta Grande power plant in Lanzarote has a capacity of 232.4MW. In Fuerteventura, the capacity of Las Salinas power plant is 187.0MW [9]. Both power plants are equipped with diesel and gas turbine generation units. New generation units are not expected for 2020 due to annual energy consumption decrease in recent years [10].

Current generation units in these power plants are shown in Table 1.

Punta Grande Generation unit	Capacity (MVA)	The Salinas Generation unit	Capacity (MVA)
Diesel 1	9.4	Diesel 1	5.4
Diesel 2	9.4	Diesel 2	5.4
Diesel 3	9.4	Diesel 3	6.3
Diesel 4	20	Diesel 4	9.4
Diesel 5	20	Diesel 5	9.4
Diesel 6	30	Diesel 6	30
Diesel 7	22.5	Diesel 7	18
Diesel 8	22.5	Diesel 8	18
Diesel 9	22.5	Diesel 9	18
Diesel 10	22.5	Gas 1	32.42
Diesel 11	22.5	Gas 2	40.93
Gas 1	27.24	Mobile Gas 1	15
Gas 2	40.93		

Table 1. Conventional generation in Lanzarote-Fuerteventura power system 2020

Peak power in 2013 was 251MW. Substations in Lanzarote and Fuerteventura are near main towns and touristic centers. It is expected 384MW of peak power for 2020 [11].

Nowadays, there are eight substations in the transmission network, at a voltage level of 66kV. Rated voltage and capacity of the interconnecting submarine cable are 66kV and 60MVA respectively. New substations and power lines at 132kV are planned for 2020. Moreover, a second submarine cable with 130MVA of capacity will be installed. These new facilities are a power system reinforcement from the middle of Lanzarote to Fuerteventura south. Transmission system will have 26 substations and two voltage levels, 66kV and 132kV.

At present, there are five wind farms, with a total amount of 21.86MW of installed capacity [9]. Most of wind farms are mainly equipped by squirrel cage induction generator (SCIG) wind turbines with gear box. It is expected a significant increase of the wind power capacity in Lanzarote-Fuerteventura power system. In 2020, installed wind power capacity will reach 162MW [11]. Most of future wind farms will be full converter wind turbines with wound rotor synchronous generator.

2.3.- MODEL OF LANZAROTE-FUERTEVENTURA POWER SYSTEM 2020

The following describes the model of Lanzarote-Fuerteventura power system expected for 2020, as implemented in PSS®E version 32.

It has been modeled both conventional generation and renewable generation, as well as the transmission network. Transmission network includes power lines and substations. Distribution system and load demand are represented by aggregated loads at corresponding substations. Fig. 2 shows the single-line diagram of the implemented model.

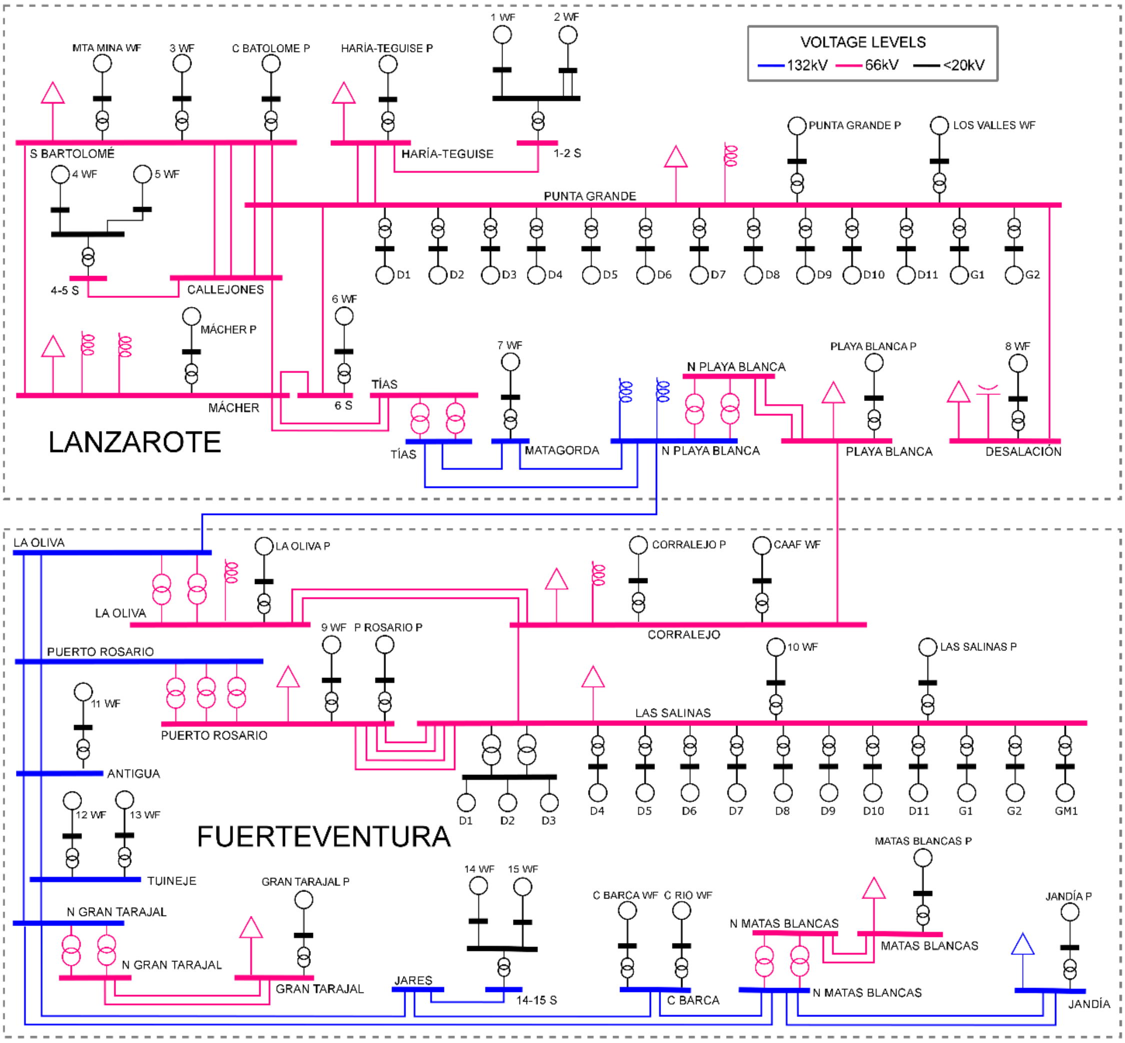

Fig. 2. Single-line diagram of the Lanzarote-Fuerteventura power system in 2020

Transmission lines have been represented using π model. Conductance is neglected. Loads were modeled with a power factor of 0.9. Transformers were implemented with models of two windings, with short circuit resistance and reactance.

Conventional Generation

Diesel and gas turbine generators have been represented with GENSAL and GENROE models respectively. GENSAL represents a salient pole synchronous generator. GENROE is a model of round rotor synchronous generator.

Turbine governor model used for diesel generators is DEGOV1 (Woodward diesel governor). In gas turbine generators, model used is GAST2A.

PSS®E models used for excitation control system for diesel generators and gas turbine generators are SEXS and ESDCA1 (IEEE type DC1A excitation system) respectively.

Wind Power Generation

As noted above, the wind power generation considered in this study consists of full converter wind turbine with wound rotor synchronous generator, also known as type 4 wind turbines [12]. In this type of wind turbines, the electrical generator rotates at variable speed, connected to the electrical network through a power electronic converter. In a first stage, the converter rectifies the variable frequency AC produced by the generator. Later, DC current is converted to AC grid frequency. Fig. 3 shows the basic scheme of this type of wind turbines. PSS®E has the EXF2 model for these wind turbines.

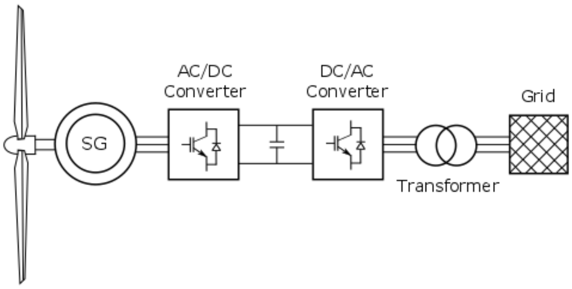

Fig. 3. Diagram of the variable speed wind turbine with power electronic converters

Main features of the model of this type of wind turbine are described in [13,[*14*].

Dynamic behavior mainly depends on the converters control systems used in this type of wind turbine and on the time duration usually selected. Therefore, it is enough to consider only these control systems in the model. Model uses command signals of control and voltage to calculate the current to be injected into the grid. Model diagram is depicted in Fig. 4.

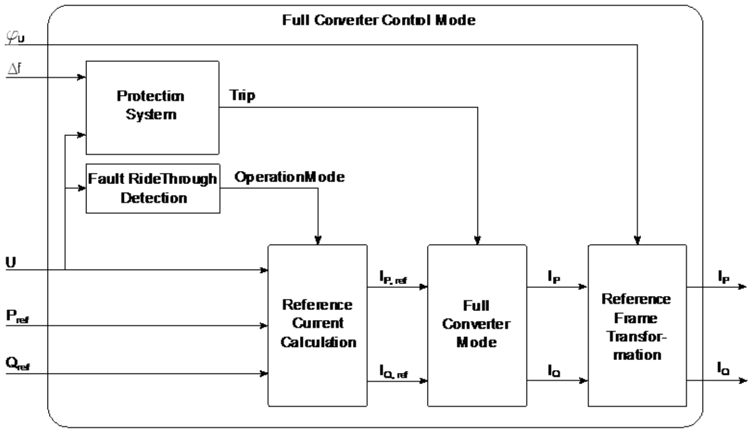

Fig. 4. Simplified diagram of the wind turbine model

This wind turbine with electronic converters is able to generate or consume reactive power. This wind turbine capability allows it to contribute to the grid voltage support. Fig. 5 shows the implemented P-Q characteristic in the wind turbine model.

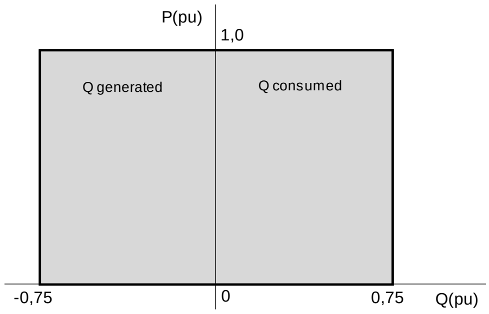

Fig. 5. P-Q characteristic of the modeled wind turbine

Under and over voltage ride through capability has been implemented in the wind turbine model. In addition, wind turbine is able to generate or consume additional reactive power in order to collaborate in voltage restoration. When a fault takes place, the reference current value $I_{Q,ref}$ associated with the total reactive power is given by the Ec. (1).

$$I_{Q,ref} = \frac{Q_{ref}}{U} + \Delta I_Q \qquad (1)$$

where Q_{ref} is the initial reactive power injected before the fault, U is the measured voltage in terminals of the wind turbine and ΔI_Q is the current corresponding to the additional reactive power that is obtained from the characteristic shown in the Fig. 6.

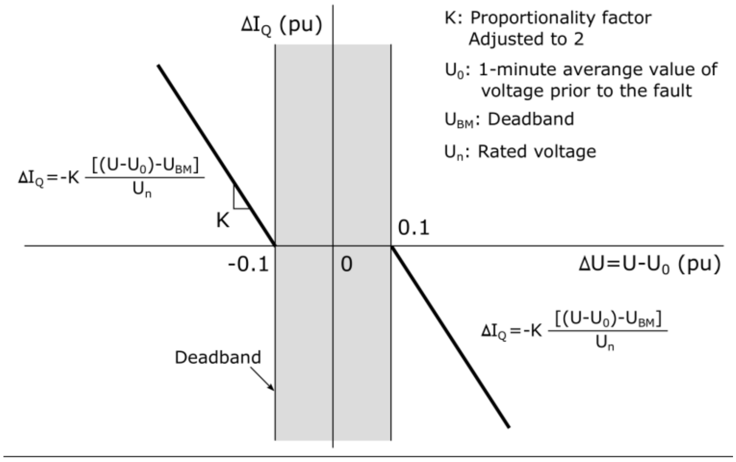

Fig. 6. $\Delta I_Q - \Delta U$ *Characteristic of the wind turbine for voltage support*

Protections

The protections of the conventional generators included in the power system model are relays of under and over voltage and relays of under and over frequency (models VTGTPA and FRQTPA), as well as over current and over speed protections. Typical setting of the relays is used, as can be seen in Table 2 [*15*].

	Under voltage	Overvoltage	Under frequency	Over frequency	Over current 1	Over current 2	Over speed
Value	0.75 pu	1.12 pu	47 Hz	52.2 Hz	1.25 pu	3 pu	1.08 pu
Time delay (s)	0.8	1	1.25	2	6.5	0.5	Instant

Table 2. Protection relays setting of conventional generation

In wind farms, relays of under and over voltage (model VTGDCA) and under and over frequency were included. As in the case of conventional generators, over current relays have been modelled. Setting values in the protections are the commonly used for this type of generation and are given in Table 3 [*15*][*17*].

	Under voltage	Overvoltage	Under frequency	Over frequency	Over current 1	Over current 2
Value	0.8 pu	1.12 pu	47 Hz	51 Hz	1.25 pu	3 pu
Time delay (s)	5	0.3	1.3	0.1	6.5	0.5

Table 3. Protection relays setting of wind turbines

Under frequency Load Shedding

A scheme of under frequency load shedding has been implemented. This scheme has three load shedding steps in every substation with power consumption. Used model is LDSHBL from PSS®E library.

Setting frequency values for the first, second and third steps are 49.0, 48.9 and 48.8Hz. Coordinated action of first and second steps causes the disconnection of an amount higher than 10% of total load. This coordinated action takes place when frequency remains below 48.9Hz during at least 0.45s, in accordance with the time delay setting.

3.- RESULTS

Dynamic analysis carried out for the determination of the CCT shows that load shedding can be expected. In all short circuit cases studied, load shedding is what determine the CCT value.

Table 4 shows the obtained CCT values for a short circuit event in the five substations studied. It can be seen a decrease in all of them when wind power is increased.

		Generated wind power (MW)															
		0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
		Critical clearing time (ms)															
Substation	Punta Grande	210	250	240	230	230	210	230	220	220	220	220	220	220	200	200	190
	Haría-Teguise	480	490	470	430	420	430	430	430	410	410	410	390	390	310	310	300
	Las Salinas	320	310	300	300	300	300	310	300	300	300	300	270	270	240	240	240
	Jandía	800	670	640	620	570	530	500	480	440	420	400	360	360	280	270	260
	Corralejo	560	560	550	510	510	530	520	510	500	510	520	420	420	340	340	320

Table 4. Obtained critical clearing times

The evolution of the obtained CCT values against total generated wind power is shown in Fig. 7. It is clear that the more wind power is generated, the more CCT decreases.

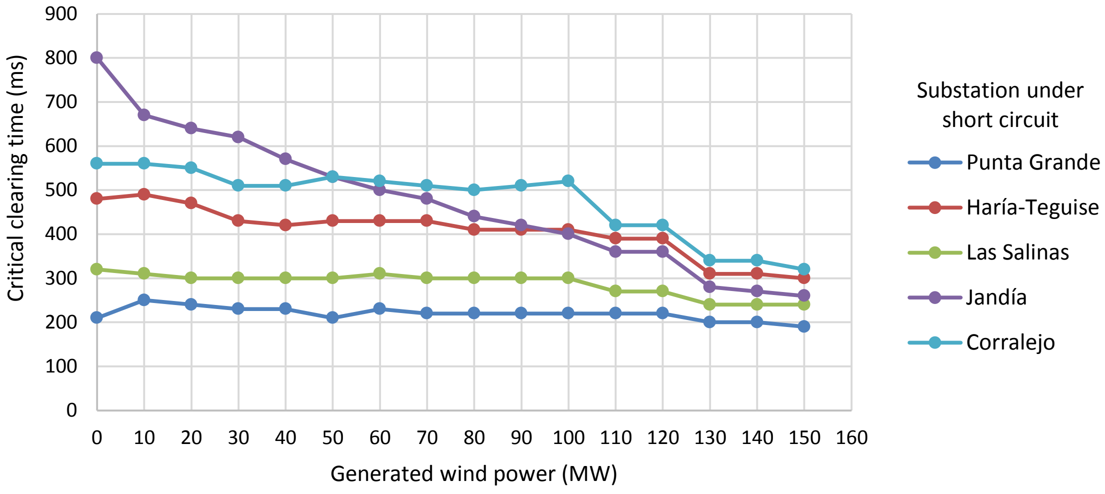

Fig. 7.Critical clearing time against generated wind power

Fig. 8 shows total inertia constant of the power system against power generated by wind farms. This figure indicates that there is also a relationship between these magnitudes.

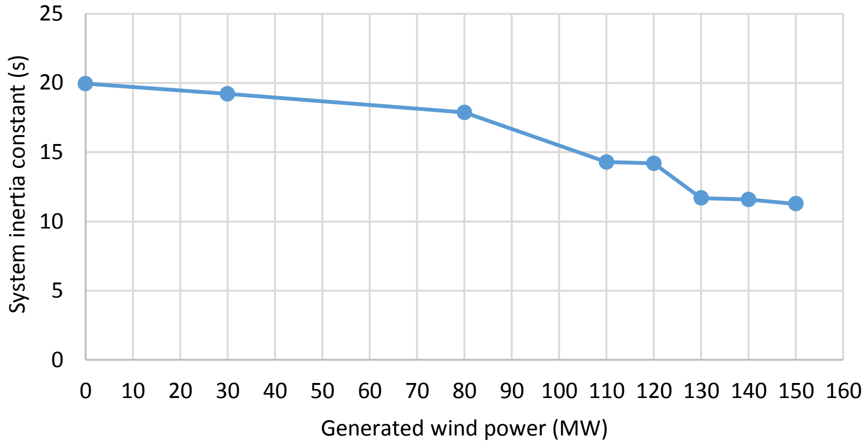

Fig. 8. Total inertia constant of the power system depending on the generated wind power

Fig. 9 shows time evolution of frequency when a three-phase short circuit of 230ms of duration takes place at Punta Grande substation, for different values of injected wind power. It can be seen that frequency deviation is higher for the higher values of wind power. In addition, wind farms outages take place and the moment in which they occur is shown in the figure. Frequency setting of load shedding second step has also been indicated in Fig. 9.

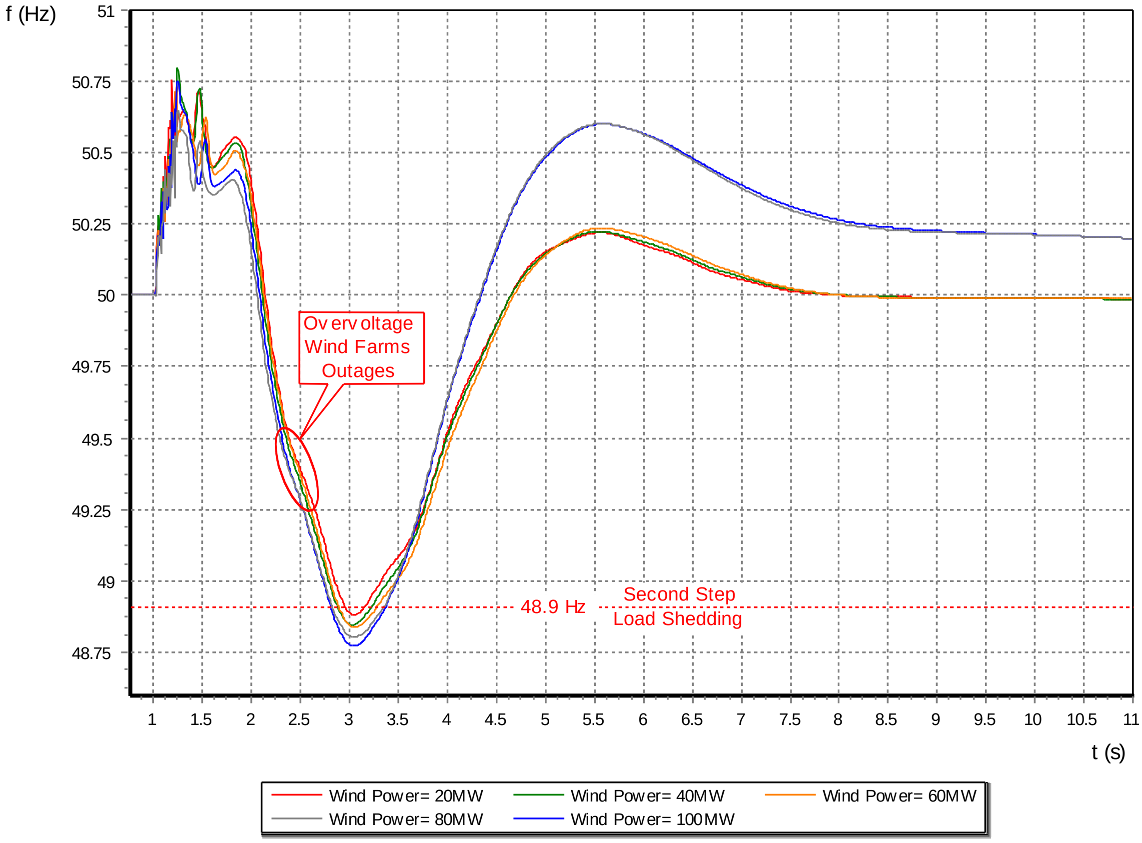

Fig. 9. Time evolution of system frequency for a 230ms short circuit at Punta Grande substation for different amounts of wind power generation

Time evolution of voltage at wind farms for a three-phase short circuit of 250ms duration at Las Salinas substation and with 50MW of total wind power is shown in Fig. 10 and Fig. *11*. Different values in voltage dips and the subsequent voltage restoration are shown.

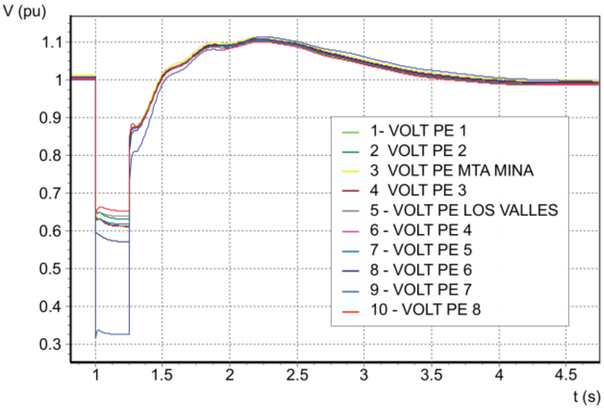

Fig. 10. Time evolution of voltage at wind farms of Lanzarote during a three-phase 250ms short circuit at Las Salinas substation with 50MW of generated wind power

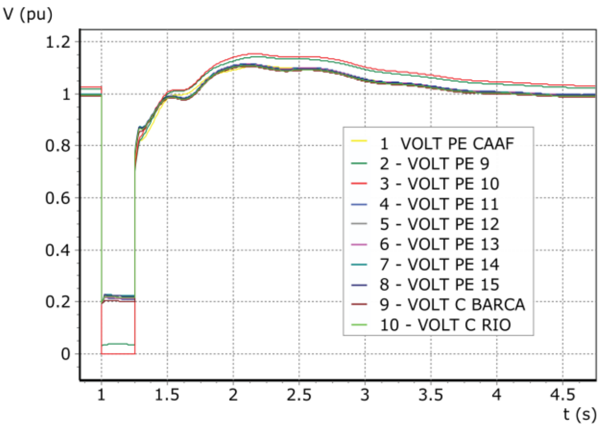

Fig. 11. Time evolution of voltage at wind farms of Fuerteventura during a three-phase 250ms short circuit at Las Salinas substation with 50MW of generated wind power

4.- DISCUSSION

As shown in Fig. 7, CCT decreases when more wind power is introduced into the power system. This is due to wind farms outages that take place when a short circuit occurs.

Because of the small size of the type of power system analyzed in this paper, voltage dip affects to all wind farms. See Fig. 10 and 11.

Fig. 10 and 11 also show an overvoltage after the short circuit clearance. This overvoltage has also been observed in other studies of small and isolated power systems [18]. Due to the value and duration of that overvoltage, the protections of the wind farms cause their outages.

It is also noted that in the case of a short circuit event at Punta Grande or at Las Salinas power plants, with a duration greater than or equal to 230ms and 310ms respectively, wind farms outage by over frequency can be expected. These outages are only about 9% of the analyzed short circuit cases. The rest of wind farms are disconnected by the overvoltage mentioned in the previous paragraph.

Swing equation of synchronous machine (Ec. (2)) is related to power system stability. Swing equation shows how wind farm outage can have an impact on system frequency and consequently on CCT.

$$\frac{2H}{\omega_{syn}}\omega_{pu}(t)\frac{d^2\delta(t)}{dt^2} = P_m(t) - P_e(t) - \frac{D}{\omega_{syn}}\frac{d\delta(dt)}{dt} \qquad (2)$$

where:

H: Inertia constant (s)

ω_{syn}: Synchronous speed (rad/s)

$\omega_{pu}(t)$: Angular speed of rotor (pu)

$\frac{d^2\delta(t)}{dt^2}$: Angular acceleration (rad/s^2)

P_m: Mechanical Power (pu)

P_e: Electrical Power (pu)

D: Damping Coefficient (power pu / speed deviation pu) [19]

During a short circuit, speed $\omega_{pu}(t)$ and system frequency usually increase due to the suddenly decrease of the electrical power P_e.

After a short circuit is cleared, system frequency begins to drop due to the restoration of electrical power and the decrease in mechanical power P_m performed by the power-frequency primary control. This causes frequency to fall below the frequency reference value. In that moment, wind turbine outage occurs due to an overvoltage. This wind turbine outage leads to a higher power imbalance between electrical and mechanical power $P_m(t) - P_e(t)$, causing a further decrease in network frequency.

The more wind power is disconnected, the higher frequency deviations occurs. This can be seen in Fig. 9, in which the largest frequency deviations and smallest frequency nadir take place for the higher values in wind power generation. Highest frequency deviations often reach 48.9Hz and cause the tripping of the first and the second step of load shedding relays. This tripping implies a load shedding higher than 10%, constituting the fact that determines the CCT.

Low CCT values are also caused by the decrease in the number of operating conventional generators. Progressive introduction of wind power into the power system causes a decrease in the power generated by conventional units. This can imply a smaller number of the running conventional generators, because power balance between generation and consumption should be maintained (Boucherot theorem).

A lower number of running conventional units in a power plant means a lower total inertia value of the power system. Full converter wind turbine can not provide inertia due to the fact that its generator is decoupled from the power system. By this reason, full converter wind turbine is not able to replace the inertia of a conventional generator. The decrease in the power system inertia can be seen through the value of the inertia constant H shown in Fig. 8. This figure indicates that, for example, when 80MW of wind power is introduced in power system H decreases from 19.94s to 17.87s, because wind power replaced Gas 1 (Punta Grande) and Mobile Gas 1 (Las Salinas) units. As a consequence, power system has no longer the inertial response of these conventional generators.

Considering again Ec. (2), when H is low the absolute value of angular accelerations is high, causing high system frequency deviations for a given value of $P_m(t) - P_e(t)$. In this way, system frequency can reach a value that causes the tripping of load shedding relays when H is low. Therefore, a short circuit with a short duration can reach 48.9Hz more easily, causing load shedding and determining CCT. It is clear the relationship between these magnitudes when the variation of H (Fig. 8) and the evolution of the CCT are compared (Fig. 7).

In addition, a decrease in the number of conventional generators running at a power plant causes a decrease in the power-frequency control capability (primary reserve) and in the voltage control capability of the overall power system.

Regardless of generation unit inertia, power-frequency control is the response of conventional generators when a power imbalance occurs. Likewise, voltage control in power system is mainly performed by the ability of conventional generators to adjust the voltage in their terminals, generating or consuming reactive power.

Although power-frequency control and voltage control can be provided by full converter wind turbines with wound rotor synchronous generator, these control capabilities can not be fully applied. This is due to the settings typically applied to its own protection relays. Therefore, wind turbines can not replace conventional units in this aspect, affecting CCT in this way. In comparison with large power systems, small and isolated power systems are more sensitive to a decrease in these control capabilities due to their low inertia.

5.- CONCLUSIONS

This paper discusses the relationship between wind power generation and the critical clearing time (CCT) in small isolated systems. Full converter wind turbine with wound rotor synchronous generator is considered. Lanzarote-Fuerteventura power system expected by 2020 is used as a case of small and isolated power system.

CCT is an important magnitude when implementing general protection schemes in power systems. Therefore, CCT is related to the performance and safety of the power systems.

Results obtained in this paper show the existence of the above mentioned relationship for the analyzed power system. CCT values decrease when the generated power by wind turbines increases gradually. It has been seen that the decrease is mainly due to the disconnection of wind farms as a consequence of a short circuit event and the reduction in the number of conventional generators in the power plants.

When a short circuit event takes place, these aspects cause higher frequency deviations and load shedding. This leads to lower CCT values. The decrease of TCE values can be unacceptable, and it could be a limiting factor for the wind power integration.

Knowledge about the previously mentioned aspects helps to a better understanding of how full converter wind turbines with wound rotor synchronous generator influence CCT in small and isolated power systems. Thereby, a more precise determination of CCT can be done, allowing a more suitable setting of the protection system. Therefore, a more secure and reliable operation of the power system can be achieved. In addition, it also enables the study of strategies to prevent or minimize this influence, enabling the increase of wind power penetration. A strategy could be the revision of overvoltage relays setting in wind turbines. If wind turbines could remain in operation when an overvoltage takes place, the system frequency will not be affected. Therefore, CCT values will not decrease by wind turbine outages.

Usually, when wind power is introduced in a power system, this wind power should be included in studies for determination of CCT values. When wind power is introduced in small and isolated power system, an individual study is needed for every particular case, since specific characteristics of each system can influence CCT in a different way.

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