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TRABAJO TEÓRICO EXPERIMENTAL

Influence of Wind Power on the Small Signal Stability of a Distribution Island System

Influencia de la energía eólica en la estabilidad de pequeñas señal de un sistema de distribución aislado

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RESUMEN/ ABSTRACT

Wind power generation usage is increasing nowadays, especially in the wider sense of distribution areas. Its technical impacts and restrictions are still under study, and in several aspects are kept almost untouched. One of these aspects is the small-signal stability of isolated distribution systems. This paper analyses the influence of wind power on the small signal stability of an isolated distribution system. Factors as wind power integration level, wind turbine technology, system operation, wind farm location and distributed wind farms are considered. The oscillatory modes that arise because of changes in system operating conditions are computed using modal analysis. The synchronous generators behavior is corroborated with the help of time domain analysis. The results showed that wind farm integration improves the damping ratio and reduces the oscillatory frequency of all modes. The interconnection point and dispersed wind generation has no influence on damping ratio and oscillatory frequency.

Key Works: isolated distribution system; modal analysis; small signal stability; wind power.

El uso de la energía eólica se ha incrementado en la actualidad, conectándose principalmente en redes de distribución. El impacto sobre estas redes y las restricciones a tener en cuenta son temas que actualmente se encuentran bajo estudio, y algunos aspectos están poco estudiados. Uno de estos aspectos es la estabilidad de pequeñas señales en sistemas de distribución aislados. En este trabajo se analiza la influencia de la energía eólica en la estabilidad de pequeñas señales de un sistema de distribución aislado. Factores como el nivel de integración de la energía eólica, el tipo de tecnología de aerogenerador, la operación del sistema, el punto de conexión del parque eólico con la red y la distribución de los mismos en el sistema son considerados. Los modos de oscilación que surgen como resultado de los cambios en la operación del sistema son calculados usando un análisis modal. El comportamiento de los generadores sincrónicos es complementado con el uso de simulaciones en el dominio del tiempo. Los resultados muestran que la integración de energía eólica mejora el amortiguamiento y reduce la frecuencia de oscilación de todos los modos analizados. El punto de conexión con la red y la distribución de los parques eólicos no tienen influencia en el amortiguamiento ni en la frecuencia de oscilación.

Palabras clave: análisis modal; energía eólica; estabilidad de pequeñas oscilaciones; sistema de distribución aislado.

INTRODUCTION

In the last decade, the wind power integration into power system has increased. This fact is leading to a growing concern about its influence on the operation and stability of a power system [1-2]. Much of these concerns are focused on the impact of wind power integration on voltage [3-4] and frequency stability [5-6], with less attention paid to the small signal stability. The increasing penetration of induction machines as wind generators is bringing concerns on rotor oscillations and stability of induction generators as well as distribution system has been increased.

The influence on the oscillatory frequency and damping ratio depends on the generator model used. In case of squirrel cage induction generator (SCIG), is considered that it has a positive influence on the damping of electromechanical oscillations [7]. However, for doubly fed induction generator (DFIG), applications are not generalized; in some studies the damping is reduced [8] and others report damping increasing [9]. A comparison of both technologies is presented in [10]. The results show the best behaviour for DFIG. However, the impact on small signals stability is not only dependent on the wind turbine technology, the system, its configuration, the type of generation and its control system have a strong influence on this, but also on the frequency of oscillation and damping ratio.

Different methods that have been reported for analyzing small signal stability of a power system include probabilistic methods [11], small signals stability region boundary [12], time domain simulations [7] and modal analysis by eigenvalue calculation [8]. The small signal stability analysis with wind power integration has been applied to different power systems. For instance: in IEEE 16 generators 68 buses test system [13], IEEE New England system [14], Uruguayan system [8] and a distribution system interconnected to transmission system [7], are been reported. The scope of this paper is to identify the influence of wind power on the small signal stability of the distribution island system, considering factors such as level of wind power integration, interconnecting point with the electric grid and dispersed wind generation.

MATERIALS AND METHODS

SYSTEM MODELING

In general, elements that should be considered in modeling of a power system for various stability studies are generators, generator controllers, transformers, transmission lines and loads. The modeling approach used in this paper is explained below.

SYNCHRONOUS GENERATOR

In transient stability analysis synchronous generators are represented by sixth order model [15]. Usually synchronous generators are connected to distribution systems as constant active power sources operating at power factor control mode. However, depending upon their capability they may support the voltage by providing the reactive power as well. For voltage control mode reactive power limit has been defined. In the system under study the diesel generators operate as base power providing voltage control.

WIND TURBINE MODEL

Wind power generators available today are classified into the following four main turbine types:

- Type A: Fixed speed wind turbine with direct-grid connected induction generator.
- Type B: Variable speed wind turbine with variable rotor resistance induction generator directly connected to the grid.
- Type C: Variable speed wind turbine with direct-grid connected doubly-fed induction generator and dc/ac rotor converter.
- Type D: Variable speed wind turbine with synchronous machine and full scale ac/dc/ac converter.

The selected technology was Type C wind turbine because it is the technology present in the power system under analysis.

Double Feed Induction Generator (DFIG) configuration corresponds to the limited variable speed wind turbine with a wound rotor induction generator and a partial scale frequency converter (rated at approximately 30% of nominal generator power) on the rotor circuit. The partial scale frequency converter performs the reactive power compensation and the smoothest grid connection. The mathematical model can be found in [16].

WIND MODEL

Wind has been modeled as a Weibull distribution, which is described as: equation (1).

$$f(v_w, c, k) = \frac{k}{c} v_w^{k-1} e^{-\left(\frac{v_w}{c}\right)^k} \quad (1)$$

Where V_w is the wind speed, k is shape factor and c is scale factor.

Time variations $V_w(t)$ of the wind speed are then obtained by means of a Weibull distribution, as follows: equation (2).

$$v_w(t) = \left(-\frac{\ln I(t)}{c} \right)^{\frac{1}{k}} \quad (2)$$

Where $r(t)$ is a generator of random numbers between 0 and 1. The output power of wind turbine depends on wind speed and the approximate relationship between them is: equation (3).

$$P = \begin{cases} 0 & v \leq v_{ci}, v \geq v_{co} \\ P_{rd} \frac{v - v_{ci}}{v_r - v_{ci}} & v_{ci} \leq v \leq v_r \\ P_{rd} & v_r \leq v \leq v_{co} \end{cases} \quad (3)$$

Where V is wind speed on fan hub, V_{ci} is cut-in wind speed, V_{co} is cut-out wind speed, V_r is rated wind speed and P_{rd} is rated power of wind turbine.

SMALL SIGNAL STABILITY

Small signal stability is the ability of the power system to maintain synchronism when it is exposed to small disturbances [15]. In this context, a disturbance is considered to be small if the equations that describe the resulting response of the system may be linearized. The system used for the small signal stability analysis is a differential algebraic equation set, in the form: equation (4).

$$\begin{aligned} \dot{x} &= f(x, u) \\ 0 &= g(x, u) \end{aligned} \quad (4)$$

Where: equation (5).

$$\begin{aligned} x &= (x_1, x_2, \dots, x_n)^T \\ u &= (u_1, u_2, \dots, u_n)^T \\ g &= (g_1, g_2, \dots, g_n)^T \end{aligned} \quad (5)$$

Where X is the vector of the state variables, U is the input vector and g is a vector of nonlinear functions relating state and input variables to output variables.

The analysis is based on the nonlinear set of system equations, dynamic relations as well as network equations, which are linearized in an operating point to obtain a linear system. Therefore, the nonlinear equations are linearized using Taylor series. The linear result equation is written as (6):

$$\begin{aligned} \Delta \dot{x} &= A \Delta x + B \Delta u \\ 0 &= C \Delta x + D \Delta u \end{aligned} \quad (6)$$

Where A is the system state matrix, B the input matrix, C the output matrix and D the feed forward matrix. Taking the Laplace transformation of equations (6), will result in: equation (7).

$$\begin{aligned} \Delta \dot{x}(s) &= \frac{adj(sI - A)}{\det(sI - A)} B \Delta u(s) \\ \Delta y(s) &= C \frac{adj(sI - A)}{\det(sI - A)} B \Delta u(s) + D \Delta u(s) \end{aligned} \quad (7)$$

The poles of $\Delta \dot{x}(s)$ and $\Delta y(s)$ are the roots of the equation (8):

$$\det(sI - A) = 0 \quad (8)$$

Equation (8), can be re written as equation (9):

$$\det(A - \lambda I) = 0 \quad (9)$$

Expansion of the determinant gives the characteristic equation. The n solutions of λ are the eigenvalues of matrix A . It contains information about the response of the system to a small perturbation. The eigenvalue may be real or complex. The complex values always appear in conjugate pairs if A is real.

The real component of the eigenvalues gives the damping, and the imaginary component gives the frequency of oscillation. Thus, for a complex pair of eigenvalues: equation (10).

$$\lambda_i = \sigma_i \pm j\omega_i \quad (10)$$

Where the frequency of oscillation in Hz, and the damping ratio are given by equation (11) and (12).

$$\zeta = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \quad (11)$$

Each eigenvalue represents a system mode and the relationship between this mode and the stability is given by Lyapunov [15], where the system is stable when $\sigma_i < 0$; the system is unstable when $\sigma_i > 0$; and in general, no conclusions arise when

$$\sigma_i = 0. \quad (12)$$

SYSTEM UNDER STUDY

The system under study is an isolated distribution radial system with a maximum load of 17,7 MW and 6,2Mvar. This load is only supplied by dispersed generation technology. Four 4,5 MVA MAN diesel generators connected at bus 2 and 3, and four 2,36 MVA MTU diesel generators dispersed in the system supply the loads. The main functions of MTU generators are the improvement of quality service and to support the MAN generators at maximum load condition. The distribution system has a voltage level of 34,5 kV and seven distribution substations. System without wind power integration is a base case. In [17], data related with this system is presented. The data related to diesel generators models and the automatic voltage regulator model of MAN technology is according with [17]. The base case eigenvalues are computed and 68 eigenvalues with negative real part value are obtained. Some of the most important are shown in figure 1.

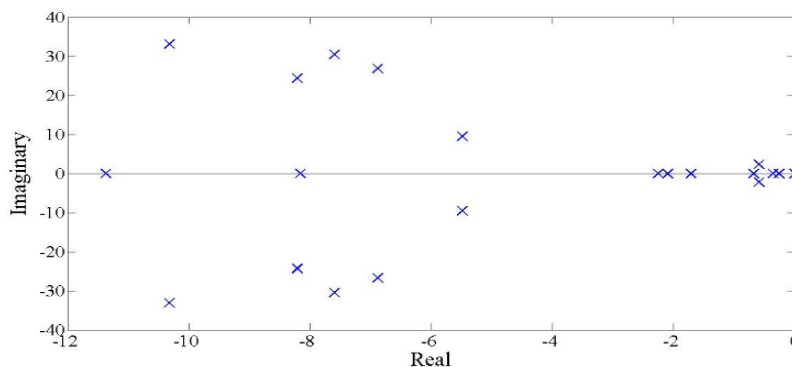


Fig. 1. Eigenvalues for the base case scenario
Source: Authors.

Since all the eigenvalues lie on the left side of the imaginary axis, the system is asymptotically stable. Nine of the eigenvalues are complex, denoting an oscillatory mode. Only the results of the oscillatory mode are shown in table 1. It is interesting to note that the oscillatory frequencies of seven of the nine modes are between 4 and 6 Hz, which is more than the frequency of electromechanical modes of large generators observed in transmission systems, which typical values are between 0,1 and 2 Hz [16].

Some studies in distribution systems also show a frequency of oscillations around 3 Hz [7]. However, these systems are connected to a transmission system through a strong connection link. Other example is the Uruguayan power system [8] with a frequency oscillation of some modes around 3 Hz. Comparing these with the system under study and having into account that the diesel generators are near between them the results of the oscillatory frequencies are logical.

Table 1. Electromechanical mode of the study system

Modes	$\sigma \pm j\omega$	Frequency (Hz)	Damping Ratio
Mode 5, 6	-10,319±33,0976	5,518	0,298
Mode 7, 8	-11,8387±34,1594	5,754	0,327
Mode 9, 10	-7,5949±30,5123	5,004	0,242
Mode 11, 12	-6,8791±26,7876	4,402	0,249
Mode 14, 15	-8,2088±24,3146	4,084	0,320
Mode 16, 17	-8,2077±24,3217	4,086	0,320
Mode 19, 20	-8,2067±24,3288	4,086	0,320
Mode 25,26	-5,4895±9,5765	1,757	0,497
Mode 39,40	-0,5952±2,2881	0,376	0,252

Source: Authors

The damping ratio is considered poor for values lower than 0,05 according to [8, 18]. All damping reflected in Table 1 are above of these values. So, it is possible to say that the distribution system under study has a good damping.

Due to the number of generators and their distribution in the system, it is possible to analyze two local modes and the inter-area mode between area one and area two. A local mode of area one is represented by the MAN generators, according to the participation factors analysis, the major contribution of these generators is in the modes 9 and 10. The area two is represented by MTU generators and the most important mode with less damping ratio is the modes 5 and 6. Finally, the inter-area mode is represented in the modes 14 and 15. The time domain analysis was performed to visualize the rotor oscillations of synchronous generators for base case scenario. For this, a three phase short-circuit fault was applied at bus 8 in the second 10 of the simulation and cleared after 70 ms. The rotor speeds of MAN and MTU synchronous generators were observed at figure2.

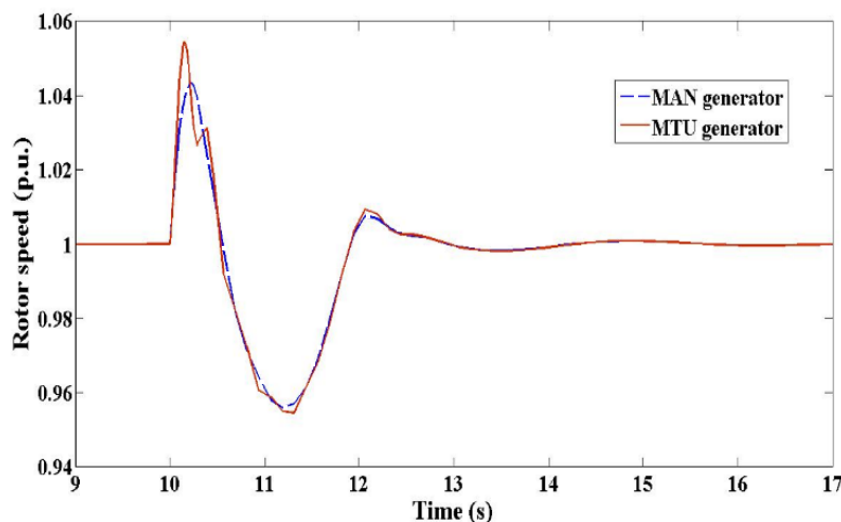


Fig. 2. Response of MAN and MTU synchronous generator

Source: Authors.

The behaviour for both synchronous generator technologies is very similar. The frequency of oscillation is around 0,35 Hz, corresponding with modes 39 and 40 shown in table 1. In this case, these modes are the dominants and correspond with the excitation system of MAN generators. In order to check this behavior a comparison is made with a real life event occur in the system under study. Figure 3, shows the frequency response of the system against a disturbance. The real frequency of oscillation in the system is around 0,34 Hz, which is also the range shown by eigenvalues analysis. The difference with the simulation is less than a 3%, therefore, the system behaviour and models are validated and the system is ready for the small signals analysis with wind turbines.

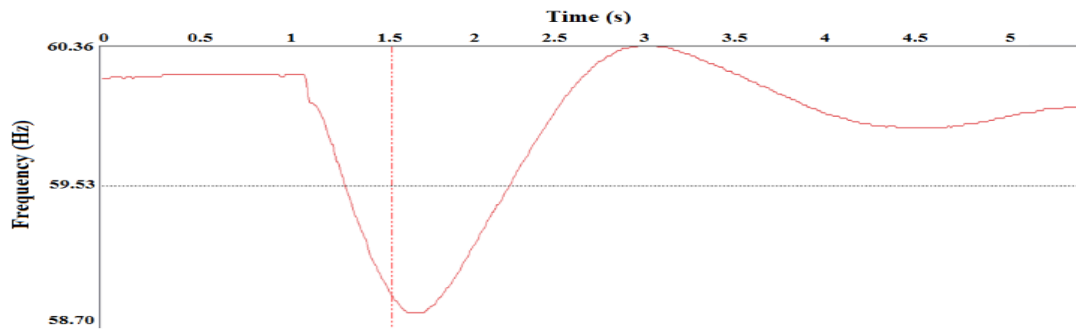


Fig. 3. Real frequency response
Source: Authors.

SIMULATIONS RESULTS AND DISCUSSION

The worldwide concern on environmental issues and legislative changes is supporting the use of more renewable energy resources which are likely to be integrated to the distribution system in the future. For analyzing the influences of wind farm integration into the system under study, the following topics are analyzed:

- 1 - Influence of wind power increase on the oscillatory modes without disconnecting diesel generators.
- 2 - Influence of wind power increase on the oscillatory modes disconnecting diesel generators.
- 3 - Influence of interconnection point of wind turbines.
- 4 - Influence of dispersed wind farm on the oscillatory modes.
- 5 - Time domain simulation.

It is assumed that the wind farm (WF) is connected to the system through a line with a resistance of 0.292 pu and a reactance of 0.267 pu, with the same bases of Appendix A. The wind farm consisting of type DFIG wind turbines with a total capacity of 2 MW is connected to the grid. The power is injected into the grid at unity power factor. This is achieved through the pulse-width modulation frequency converter between the rotor of the generator and the grid. The used model of this technology is presented in [17].

INFLUENCE OF WIND POWER INCREASE ON THE OSCILLATORY MODES WITHOUT DIESEL GENERATORS DISCONNECTED

A wind farm made up of DFIG is connected to bus 19. The starting power of wind farms was 2 MW, and the same is increased to 2 MW while the output power of the MTU generators is reduced to its limits, and then was reducing the power output of MAN generators, by the same amount so that the total power remains the same. The damping of oscillatory modes chosen for the study is presented in figure 4, and the oscillatory frequency in table 2. The maximum wind power which was possible to integrate under these conditions was 6 MW.

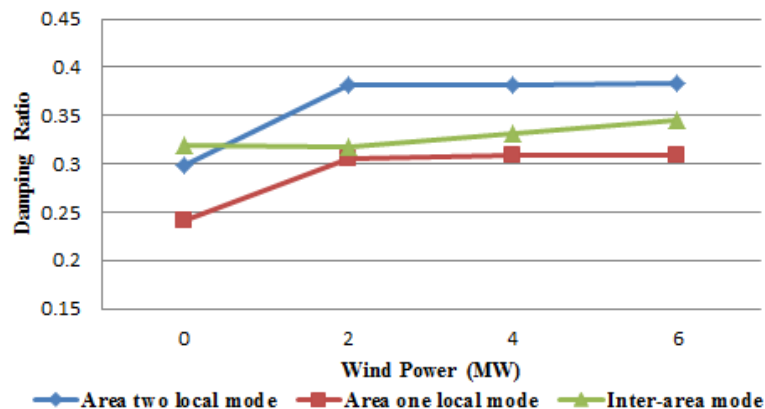


Fig. 4. Influence of wind power increase using DFIG on the damping of electromechanical mode
Source: Authors.

Table 2. Oscillatory frequency for increase wind power

Wind farm	Area One	Area Two	Inter-area
Base Case	5,004	5,518	4,084
2MW	4,826	5,354	4,095
4MW	4,846	5,359	4,072
6MW	4,853	5,356	4,062

Source: Authors.

The results show that damping of the inter-area frequency mode slightly increases when the wind farm capacity is up to 6 MW while the local modes are positively influenced. The increase of damping ratio of area one was a 29% and for area two was 28%. The oscillatory frequency in area one and two for DFIG wind farm up to 6 MW decreased, while in inter-area mode it slightly decreased.

INFLUENCE OF WIND POWER INCREASE ON THE OSCILLATORY MODES WITH DIESEL GENERATORS DISCONNECTED

Normally, conventional units can be replaced by wind power capacity. In this section an increase of wind power means a shutdown of a diesel generator, starting for MTU technology, except the MTU generator at bus 12, this way keeping the voltage nearby between limits. When three of the four MTU are disconnected and the wind power is continuously increased, it is necessary to disconnect a MAN generator. When DFIG wind turbine is connected the damping ratio of area one local mode is practically constant around 0,25 until a wind farm of 6 MW; for 8 MW the damping ratio rise to 0,34. At this point the system is working with all MAN generators and the MTU generator at bus 12. When the installed capacity of wind farm is up to 10 MW, one MAN generator at bus 3 is disconnected. At this condition, the wind farm substitutes a synchronous machine with excitation system. Therefore, the damping in area one is affected and has a reduction down to 0.3.

The integration of DFIG wind turbine up to 10 MW improves damping ratio and reduces the oscillatory frequency of the system under study. Under this condition, the system is stable for small signal, as is shown in figure 5, with a real negative part for all eigenvalues.

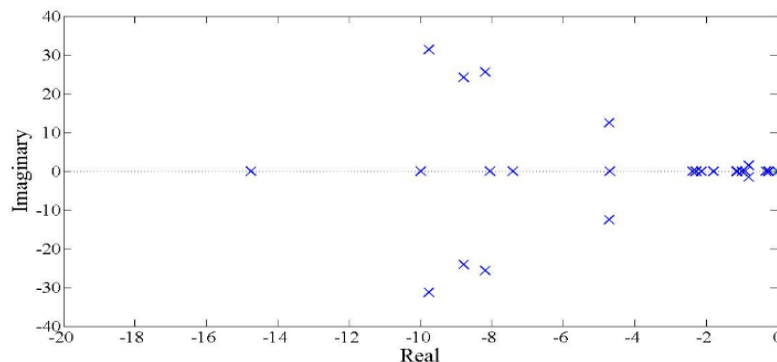


Fig. 5. Eigenvalues for 10 MW with a DFIG wind farm.

Source: Authors.

The damping of area two is the same when the wind farm is up to 10 MW, notes that the wind farm is interconnecting to the system in area two; in some way the wind farm integration in this area substitute the damping lose for the disconnection of diesel generators. The inter-area damping is slightly increased up to 0,34.

A decrease in the frequency of the oscillation in area one from 5 to 4,28Hz (15% of reduction) is observed. In area two, the reduction of the oscillatory frequency was 5%, while the inter-area mode frequency is mostly the same for all values of wind farm integration.

INFLUENCE OF THE INTERCONNECTION POINT OF WIND TURBINES

To study the influence of change in wind generator locations on the small signal stability of a power system, the 4 MW wind farm was connected in different buses. In these cases, no diesel generators are disconnected in the power system. The results are presented in table 3.

Table 3. Damping and oscillatory frequency for a 4 MW DFIG wind farm

farm location	Area One		Area Two		Inter-area	
	Damping	Freq.(Hz)	Damping	Freq.(Hz)	Damping	Freq.(Hz)
Bus 10	0,307	4,828	0,381	5,360	0,333	4,067
Bus 14	0,307	4,827	0,382	5,355	0,332	4,070
Bus 19	0,309	4,846	0,382	5,359	0,332	4,072
Bus 26	0,308	4,824	0,383	5,352	0,331	4,075
Bus 28	0,307	4,825	0,383	5,352	0,332	4,074
Bus 33	0,315	4,912	0,383	5,345	0,330	4,090
Bus 36	0,307	4,830	0,381	5,357	0,333	4,064

Source: Authors

For a 4 MW wind farm with DFIG technology the interconnection point does not influence in the damping ratio and the oscillatory frequency. Both parameters are nearly the same for all area modes at any wind location.

INFLUENCE ON THE OSCILLATORY MODES OF DISPERSED WIND FARM

Normally, in distribution system the interconnection of renewable energy resources is dispersed into several points of the grid. The influence of dispersed wind farm in damping ratio and the oscillatory frequency of every mode is analyzed. The comparison was made between a 6MW wind farm concentrated at bus 19 and six wind farms of 1MW at buses 10, 14, 19, 26, 28 and 33. The results are shown in table 4.

Table 4. Frequency and damping ratio for a DFIG wind farm

Wind farm	Damping ratio		
	Area One	Area Two	Inter-area
Concentrated	0,309	0,383	0,346
Dispersed	0,308	0,379	0,349
	Oscillatory frequency		
	Area One	Area Two	Inter-area
Concentrated	4,853	5,356	4,062
Dispersed	4,845	5,359	4,038

Source: Authors

In all cases, damping ratio and the oscillatory frequency are very similar for local and inter-area modes.

TIME DOMAIN SIMULATION

In order to check the behavior of synchronous generators with the integration of wind energy a time domain simulation is carried out. The analysis was making for the most critical condition; correspond with the second scenario, in other words, the scenario when the diesel generators was disconnected in behalf of wind turbine integration. In this case, the wind farm is 10 MW and represents the bigger wind penetration in all studied cases. For the analysis a three phase short-circuit fault was applied at bus 8 and cleared after 70 ms. The rotor speeds of MAN generators were observed at figure 6.

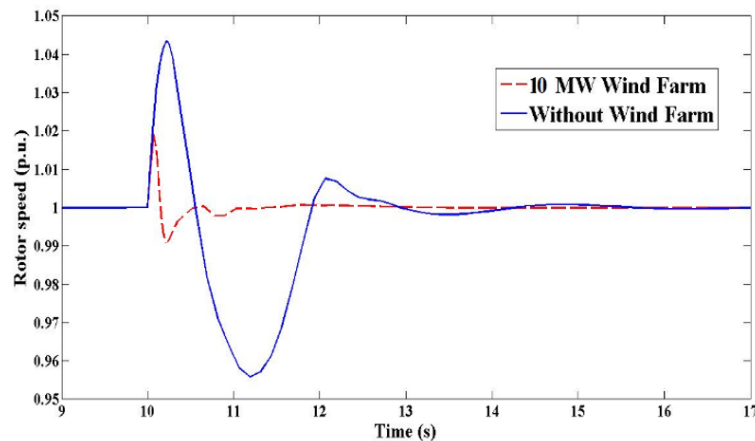


Fig. 6. Response of MAN generator with a without wind energy integration
Source: Authors.

The connection of a 10 MW wind farm improve the MAN generator response, the rotor speed have a better behavior with less peak, less oscillation and better frequency of oscillation.

CONCLUSIONS

The small signal stability of a distribution system with integration of DFIG wind farm was investigated. For base case were observed frequency oscillation modes with roughly 5 Hz. The system has a good damping ratio for both local and inter-area modes and is stable for small signals. The wind farm integration improves the damping ratio and reduces the oscillatory frequency of area one, area two and inter-area mode. A difference is found when diesel generators are disconnected, due to the integration of wind power. For a DFIG wind farm is possible to integrate 10 MW. An improvement in damping ratio and a reduction in oscillatory frequency is observed when is compared to the base case. The interconnection point of wind farm with the system and the dispersed wind farm integration has no significant influence in damping ratio and the oscillatory frequency of local and inter-area modes.

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