Assessment of Transient Stability Indicators in Wind-Integrated Power Systems: An Open-Source Simultaneous Approach

Evaluación de Indicadores de Estabilidad Transitoria en Sistemas de Potencia con Integración de Energía Eólica: un Enfoque Simultáneo de Código Abierto

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DOI: 10.22517/23447214.25259
Artículo de investigación científica y tecnológica

***Abstract*—The energy transition relies on the integration of non-conventional renewable energy sources. These disruptive technological developments alter the functioning and operation of the electric power system. This paper examines the impacts of wind power on transient stability indicators of the power system, using an implicit formulation and the nine-bus test system. The research findings indicate that transient stability indicators are sensitive to the location and duration of faults. Furthermore, there is an observed trend of increasing maximum rotor speed deviation and oscillation duration, indicating reduced stability margins.**

***Index Terms*—Differential-algebraic equations, power system dynamics, power system stability, renewable energy sources, wind power grid integration.**

***Resumen*— La transición energética se basa en la integración de fuentes no convencionales de energía renovable. Estos avances tecnológicos disruptivos modifican el funcionamiento y operación del sistema de potencia. Este documento describe los impactos de la energía eólica en los indicadores de estabilidad transitoria del sistema eléctrico, utilizando una formulación implícita y el sistema de prueba de nueve barras. Los hallazgos de esta investigación muestran que los indicadores de estabilidad transitoria son susceptibles a la ubicación y duración de la falla. Además, hay una tendencia creciente en los resultados para el rotor máximo. desviación de velocidad y la duración de la oscilación, lo que significa que los márgenes de estabilidad se reducen.**

***Palabras claves*—Dinámica de sistemas de potencia, ecuaciones algebraicas diferenciales, estabilidad del sistema de potencia, fuentes de energía renovables, integración de la red de energía eólica.**

This manuscript was sent on month day, year and accepted on month day, year. This work was supported by the Institución Universitaria Pascual Bravo.

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I. Introduction

WIND power arises as an alternative to the growing demand for electrical energy in a safe, reliable, and economical way, that also provides benefits such as a balanced, sustainable, environmentally friendly, and diversified energy economy.

A. Motivation

In the last decade, wind power generation systems have increased their participation with an average annual growth of 15.1%. This is due to the technological improvements, that allow energy production at a more competitive cost as compared with other energy sources. In this order of ideas, the need arises to investigate the impacts caused by wind power generation on electrical power systems. In particular, transient stability studies examine the dynamic behavior when events that modify the topology of electrical networks occur.

B. Literature Review

The authors [1], [2], [3], [4], [5] have discussed the integration of wind power generation into power systems. The impacts of the constant-speed wind turbine model on transient stability are evaluated in [6], [7]. On the other hand, in [8] the maximum rotor speed deviation and the oscillation duration were proposed for the first time as transient stability indicators. In [9] an analysis is presented for different participation percentages of wind energy and the results of the simulations in the time domain for the frequency of the system and the active power of the synchronous generators are exposed. To obtain the results in the above studies, the authors employ commercially available software, which has a large number of components and models with the disadvantage of using a closed code, which makes it impossible to interact with the source code for academic purposes.

In contrast, different authors have developed Matlab-based open-source software for transient stability simulations, and some of them are described below. The Power System Toolbox (PST) performs control studies and dynamic simulation [10]. The Power System Analysis Toolbox (PSAT) has a Simulink interface and the ability to calculate optimal power flows, small-signal stability, and time domain analysis [11]. MatDyn focuses on transient stability analysis but does not include models for wind power generation [12]. In this previous Matlab-based software, each author implements his own numerical integration routines. More recently, in [13] the authors publish a Toolbox for modal analysis in the time domain, and the differential-algebraic equations of the power system are sorted out directly using Matlab solvers.

In [14] an explicit formulation of the differential-algebraic equations is presented, while in [15] a semi-explicit formulation is proposed, distinguishing its numerical advantages. The authors in [16] show a technique that adopts a combination of explicit and implicit methods, seeking to exploit the advantages of each one, considering its efficiency and numerical stability.

C. Contributions

The contributions in this paper encompass:

- Implementation of an open-source in Matlab for transient stability studies that integrates the main components of the electrical system and the type I wind turbine model.
- The solution in the time domain of the differential-algebraic equations using the Matlab solvers, through a completely implicit formulation and a simultaneous approach.
- Review of the transient stability indicators based on the location of the failures and the level of participation of the wind turbines.

D. Paper Organization

In section II the wind power background and modeling are presented with the mathematical formulation for the model type I of the wind turbine. After that, section III describes the maximum rotor speed deviation and the oscillation duration, which are the transient stability indicators selected for this study. Section IV presents the time domain simulation approach and the solution technique in Matlab. Section V exposes the study case and simulation scenarios. Section VI explains the main results and their respective analysis. Finally, the main research conclusions are indicated.

II. WIND POWER

Non-conventional sources of renewable energy have the following characteristics: the ability to regenerate by natural means, reduced dependence on external supplies, few wastes, and low influence on the environment. Particularly, the wind turbine's operation is based on the airflow acting over the rotor blades and transferring the kinetic energy of the air to the rotor shaft where it is converted into mechanical energy. Afterward, the mechanical energy is converted into electricity by the action of the generator.

A. Wind Power Background

Since the beginning of the commercial use of wind turbines in the 1980s, the global wind power installed capacity has increased exponentially as shown in Fig. 1, with an average annual growth of 15.1% in the last decade [17].

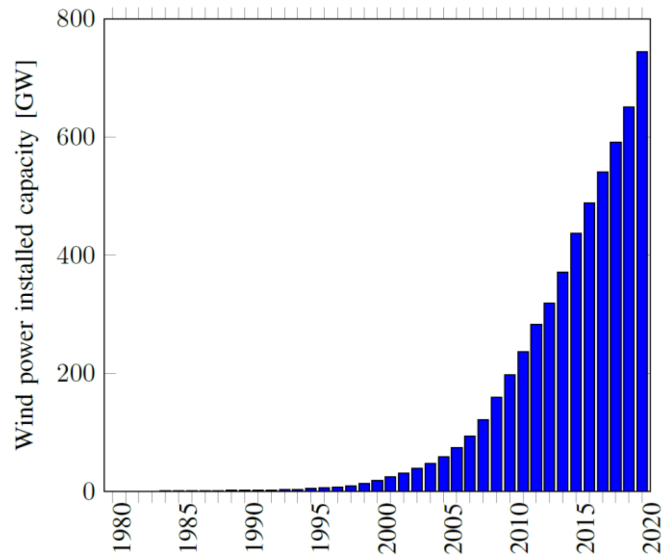


Fig. 1. Wind power global installed capacity [GW] 1980 – 2020 [17].

Under this scenario, the conventional operation of power systems undergoes changes in their dynamic behavior due to the uncertainty in the wind power generation, as a consequence of the fluctuating nature of the wind and the inability of wind turbines to balance the power between generation and demand.

B. Wind Turbine Modeling

The type I wind turbine model is defined in the IEC 61400-27-1 standard as an asynchronous generator connected directly to the network as indicated in Fig. 2. These generators include capacitive compensation, in order to counteract the reactive power that is extracted from the electrical network [18].

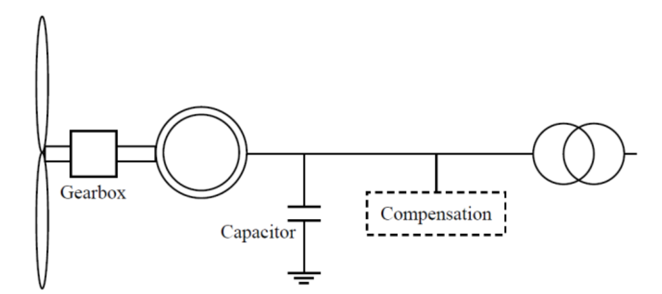


Fig. 2. Type I wind turbine model [19].

This document focuses on the type I wind turbine model, which employs a squirrel cage induction generator illustrated in Fig. 3 [2], [6]. It has fixed rotor resistance and handles simple controls, so that the characteristics of the generator, and the gearbox govern the speed of the rotor. Thus, the rotor speed deviation does not exceed 2% and therefore this generator belongs to the group of constant-speed wind turbines [3], [7].

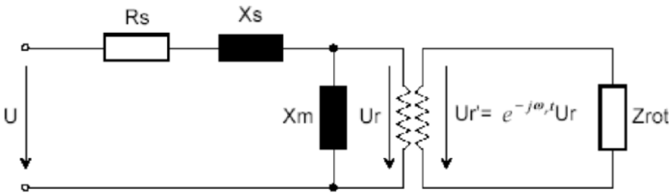


Fig. 3. Squirrel cage induction generator [20].

where R_s is the stator resistance, X_s is the stator reactance, X_m is the magnetizing reactance, Z_{rot} is the impedance of the rotor. The dynamics of the rotor circuits are established by means of slip, which, as well as the speed of the rotor, presents changes according to the power generated. Slip is essential for generating electromagnetic torque in a squirrel cage induction generator, as it induces a current in the rotor when it rotates slower than the stator's magnetic field, creating an opposing magnetic field that produces torque. This slip allows the turbine to adapt to varying wind speeds, adjusting the rotor speed and thereby changing the torque and power generated.

The voltages and currents are expressed in terms of their real (r) and imaginary (m) components. The network bus voltage is related to the machine stator voltages through the set of equations

$$v_r = V\sin(-\theta) \quad (1)$$

$$v_m = V\cos(\theta) \quad (2)$$

where V and θ are the magnitude and angle of the bus voltages, respectively. The active and reactive powers are calculated based on the stator current and voltage components, as follows

$$P = v_r i_r + v_m i_m \quad (3)$$

$$Q = v_m i_r - v_r i_m + b_c(v_r^2 + v_m^2) \quad (4)$$

where i_r and i_m are the real and imaginary components of the stator current, respectively, and b_c is the conductance of the compensation capacitor. The algebraic equations (1) and (2) will be substituted in (3) and (4), which correspond to the network interface in a synchronously rotating reference frame.

In addition, the machine electro-magnetic differential equations for the real and imaginary components of the voltage behind the stator resistor are

$$\dot{e}'_r = 2\pi f(1-\omega_m)e'_m - \frac{(e'_r - (x_0 - x')i_m)}{T'_0} \quad (5)$$

$$\dot{e}'_m = -2\pi f(1-\omega_m)e'_r - \frac{(e'_m - (x_0 - x')i_r)}{T'_0} \quad (6)$$

$$x_0 = x_s + x_m \quad (7)$$

$$x' = x_s + \frac{x_R x_m}{x_R + x_m} \quad (8)$$

$$T'_0 = \frac{x_R + x_m}{2\pi f r_R} \quad (9)$$

where r_R is the rotor resistance, x_R is the rotor reactance, x_s is the stator reactance, and x_m is the magnetizing reactance. The variables in (1) to (6), and the stator current components are related by

$$e'_r - v_r = r_s i_r - x' i_m \quad (10)$$

$$e'_m - v_m = r_s i_m - x' i_r \quad (11)$$

where r_s is the stator resistance. The set of differential-algebraic equations (1)-(11) represent the behavior of a wind turbine induction generator and will be solved according with the methodology described in section IV.

III. Transient Stability Indicators

Transient stability refers to the ability of the electrical power system to remain in synchronism when it is subjected to events or disturbances that imply large changes in the topology of the network, introducing transition stages that lead to changes in the state of the system [21]. In order to study the dynamic performance, the maximum rotor speed deviation and the oscillation duration are proposed as transient stability indicators.

A. Maximum rotor speed deviation

The maximum rotor speed deviation, indicated in Fig. 4, is the maximum value that the rotor speed reaches through transient disturbances. This indicator is calculated as [8]

$$Maximum\ rotor\ speed\ deviation = \frac{|\omega_{r,max} - \omega_{r,nom}|}{\omega_{r,nom}} \quad (12)$$

where $\omega_{r,max}$ and $\omega_{r,nom}$ are the maximum and nominal rotor speed, respectively. When the maximum rotor speed deviation is increased as a consequence of longer clearance times, the transient stability margin is reduced and thus the system becomes more susceptible to instability.

B. Oscillation duration

The oscillation duration refers to the time interval from the start of the disturbance to the moment where the rotor speed remains in a band of 10^{-4} pu, for a duration greater than 2.5 s [8]. This indicator is shown in Fig. 4 and can be calculated as

$$Oscillation\ duration = t_{osc} - t_f \quad (13)$$

where t_f is the time when the fault is applied, and

$$t_{osc} = min\{t: |\omega_r(t + n\Delta t) - \omega_r(t)| \leq 10^{-4}; n = 1, \ldots, 2.5/\Delta t\} \quad (14)$$

where $\omega_r(t)$ is the rotor speed at time t and Δt is the simulation step.

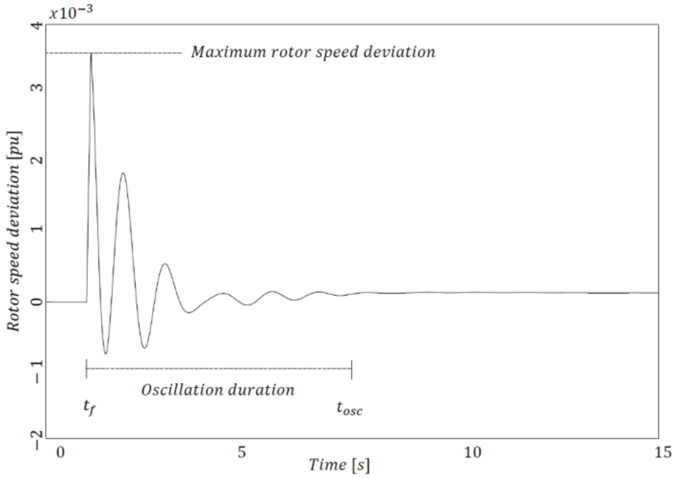


Fig. 4. Transient stability indicators [8].

IV. Methodology

The assessment of wind power's influence on transient stability is done through the solution of the differential-algebraic equations in the time domain, where the models of the electrical components and the type I wind turbine model are incorporated (set of differential-algebraic equations (1)-(11)). The solution is obtained through an implicit method of numerical integration using a simultaneous approach.

A. Time Domain Power System Analysis

Transient stability studies are usually carried out through time domain simulations, which have the advantage of manipulating complex mathematical models and providing a complete description of the electrical and mechanical variables. This methodology is applied to solve the differential-algebraic equations of the power systems, as shown in [22]

$$\dot{y} = f(y, x) \tag{15}$$

$$0 = g(y, x) \tag{16}$$

where y indicates the vector of dynamic variables, x are the algebraic variables, f are the differential equations, and g are the algebraic equations. Differential equations describe the dynamic behavior of dynamic variables such as the angular position and speed of the rotor [3]. Algebraic equations describe the static components of the power system, such as the electrical network, the loads, and the stator of the generators. Variables that appear in both differential and algebraic equations are known as interface variables [22].

Algebraic equations correspond to the expressions for the current injections $\bar{\iota}$ in the network buses, and the algebraic variables correspond to the vector of complex bus voltages $\bar{v}$ as follows [23]

$$\dot{y} = f(y, \bar{v}) \tag{17}$$

$$0 = \bar{\iota}(y, \bar{v}) - \bar{Y}\bar{v} \tag{18}$$

where $\bar{Y}$ is the bus admittance matrix. The numerical integration of the equations (17) and (18) can be carried out using the partitioned or simultaneous approaches. In the partitioned approach, y and $\bar{v}$ are resolved and updated sequentially; this means that in each integration step, (17) is solved separately for the dynamic variables and (18) for the algebraic variables. In the simultaneous approach, the differential equations f are discretized and transformed into a set of algebraic equations, and they are solved together with the algebraic equations in (18), thereby eliminating the interface errors of the partitioned approach [23]. The simultaneous approach is numerically more stable, has better convergence, and can only be solved using implicit integration methods [23].

B. Solution technique in Matlab

The time domain solution of (17) and (18) is carried out using Matlab numerical integration solvers and the simultaneous approach. These Matlab solvers are designed mainly to deal with ordinary differential equations, but specifically, the *ode15s* and *ode23t* can also solve systems of differential-algebraic equations. This requires the definition of a mass matrix (M), which classifies between differential and algebraic equations, and can be calculated as

$$M = sparse(1{:}nde, 1{:}nde, ones(1{:}nde), nde + nae, nde + nae) \tag{19}$$

where nde indicates the number of differential equations, nae the number of algebraic equations, $sparse$ Matlab command to transform a sparse matrix, removing elements equal to zero, and ones is the Matlab command to create a series of $ones$. For example, when $nde = 2$ and $nae = 3$ the entire matrix M is given by

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{20}$$

Then the mass matrix is multiplied by the implicit form of (17), as follows

$$M\dot{y} = f(y, \bar{v}) \tag{21}$$

V. Study Case and Simulation Scenarios

The nine-bus test system is widely used for dynamic studies in power systems. This system is shown in Fig. 5 and its main characteristics are indicated in Table I. The study is performed by applying a three-phase fault on load buses 5, 6, and 8, with a clearance time of 100 ms.

TABLE I
Characteristics of nine-bus test system.

System characteristics	Values
Buses quantity	9
Generators quantity	3
Loads quantity	3
Transmission lines quantity	9
Total generation	319.64 MW 33.7 MVAR
Total load	315 MW 125.86 MVAR

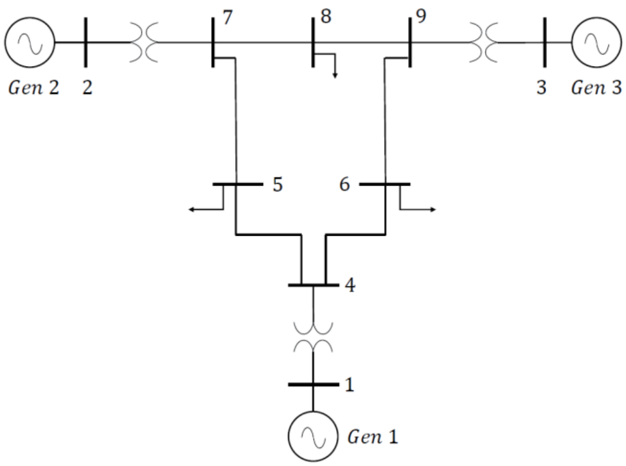


Fig. 5. Nine-bus test system one-line diagram.

The simulation scenarios seek to equate the increase in the active power of the load with an equivalent amount of wind power. The wind power penetration level, given in equation 22, is increased in steps of 5% up to 25%; in this way, six sub-scenarios are obtained with wind power penetration levels of 0, 5, 10, 15, 20, and 25%. For the base case, the increase in load is supplied with conventional synchronous generators, which serve as a reference point [8].

$$Penetration\ level = \left(\frac{P_{WP}}{P_{WP} + P_{CG}}\right) 100\% \qquad (22)$$

where P_{WP} andP_{CG} are the total active power generated by wind turbines and conventional synchronous generators, respectively.

VI. Results Analysis

Figs. 6 to 8 present the results of the transient stability simulations for the maximum rotor speed deviation and the oscillation duration when the wind power penetration level increases according to the simulation scenarios.

A. Fault at bus 5

The results for the generators connected to buses 1 and 2 are presented in Fig. 6 when the fault is applied to bus 5. The maximum rotor speed deviation is greater in all scenarios when wind power generation is used. The differences in this indicator are more pronounced for the generator connected in bus 2 compared to the one located in bus 1. Additionally, as the wind power penetration level increases, these absolute differences are attenuated as a consequence of the dynamic response of induction generators.

In the first two simulation scenarios, the oscillation duration is longer when wind turbines are used and for the remaining scenarios, the indicator is lower than the base case employed as a reference. The results obtained for the transient stability indicators are similar to those found in [8], where it is proposed that these indicators can be improved with the implementation of network voltage and frequency control.

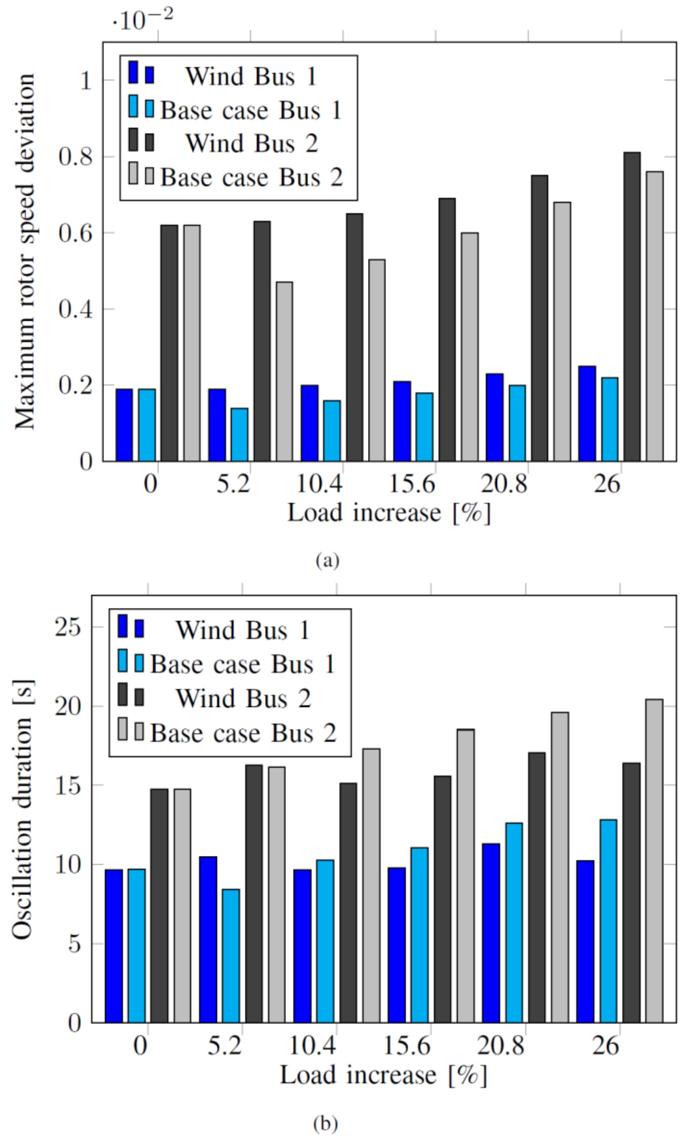
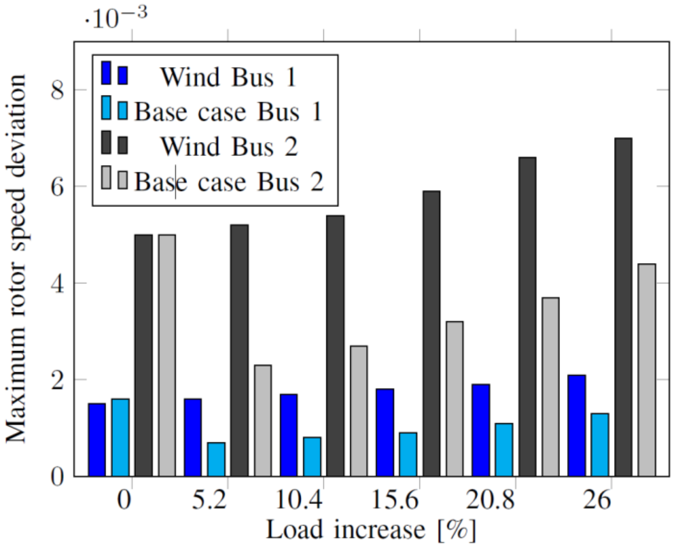


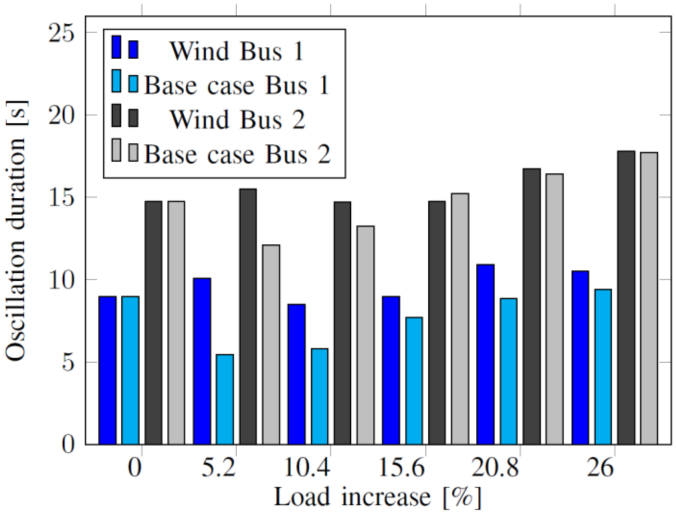
Fig. 6. (a) Maximum rotor speed deviation and (b) oscillation duration when the fault is applied at bus 5 [24].

B. Fault at bus 6

The results for the generators connected to bars 1 and 2 are presented in Fig. 7 when the fault is applied to bus 6. The maximum rotor speed deviation has a greater discrepancy with the increase of the wind power penetration level and the results of the oscillation duration are contrasted with those of Fig. 6 since in general terms the inclusion of wind power implies higher oscillation duration values.



(a)



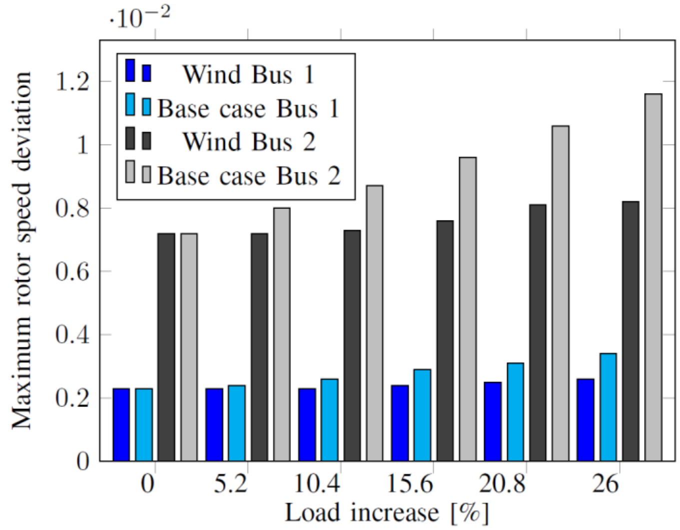
(b)

Fig. 7. (a) Maximum rotor speed deviation and (b) oscillation duration when the fault is applied at bus 6 [24].

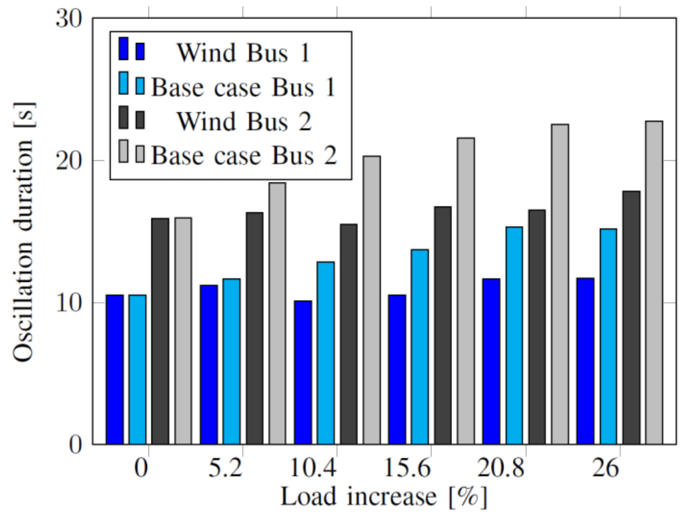
C. C. Fault at bus 8

The results for the generators connected to buses 1 and 2 are presented in Fig. 8 when the fault is applied to bus 8. Figs. 6 to 8 show that the stability indicators in some cases increase and in others decrease, depending on the fault location and the wind power penetration level. Likewise, the results exhibit an increasing trend in terms of the maximum rotor speed deviation and the oscillation duration, which means that the stability margins are reduced.

In order to improve the transient stability indicators, constant-speed wind turbines can be equipped with a pitch control system in such a way that the temporary unbalance



(a)



(b)

Fig. 8. (a) Maximum rotor speed deviation and (b) oscillation duration when the fault is applied at bus 8 [24].

between the input mechanical power and the output electrical power can be minimized. Another option involves modifying some critical parameters of the wind turbine in the manufacturing phase, with the disadvantage of increased complexity and construction costs. Moreover, when wind turbines are considered as distributed generation sources, this increases the strengths of this type of technology, since power consumption at generation points decreases power flows along the lines. The reduction of the power flows in the lines has the consequence of an increase in the damping of the oscillations and makes it possible to improve the stability margins.

VII. CONCLUSIONS

An open-source in Matlab for dynamic studies integrating constant speed wind turbines is developed and a completely implicit formulation with the inclusion of the simultaneous approach has proven to solve the transient stability problem, with the advantage to eliminate interface errors. Transient stability indicators are computed, which showed to be strongly influenced by the location and duration of the faults. There is an increasing trend in the results for the maximum rotor speed deviation and the oscillation duration, which means that the stability margins are reduced with wind power integration. From the results, fault at bus 6 exhibit lower values for the oscillation duration and the maximum rotor speed deviation. On the other hand, the results for faults at buses 5 and 8 manifest similarities which means more susceptibility to lose rotor angle stability. In order to improve the transient stability indicators, constant-speed wind turbines can be equipped with a pitch control system in such a way that the temporary imbalance between the input mechanical power and the output electrical power can be minimized.

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