Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Small Disturbance Angle Stability Indication in the Electrical Networks with Variable Speed Wind Turbines

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***Abstract*—The fast growing application of sustainable energy sources imposes major structural changes on the current electric power systems. One of these structural changes is to make use of large variable speed wind turbines within the conventional electrical power networks. The installation of these wind turbines has, indeed, indispensable impacts on the dynamic behavior of the existing electric power systems. Thus, it is important to gain a rather generalized overview on how these wind turbines, which mostly use Doubly Fed Induction Generators (DFIGs), affect the system stability. This paper performs an analytical analysis for the indication of small disturbance rotor angle stability in the power systems equipped with variable speed wind turbines using DFIGs. Also, in order to consider the stochastic characteristic of the sustainable energy sources, the paper applies an iterative-stochastic method to analyze the small disturbance angle stability. The suggested iterative-stochastic methodology is numerically verified, within this paper, by getting applied to an electric power test system.

***Keywords*—Sustainable energy sources, Variable speed wind turbines, Stochastic behavior, Small disturbance angle stability.

I. Introduction

The stability of future power networks in order to avoid the possible imposed incidents must be technically supplied and practically guaranteed. Thus, because of the upcoming structural changes, the concept of system stability requires a fair and complete review to find newer and more efficient methods of indication.

Being large scale and complex are features of modern power systems. Also, because of deregulation, the configuration of interconnected networks is routinely in a state of change. Therefore, an indicator of stability, which covers the vast spectrum of states, is of interest. Such an indicator should be able to reconcile the stochastic behavior of the renewable energy sources and the deterministic approach of stability analysis. This paper intends to perform an analytical analysis for the indication of small disturbance rotor angle stability in the future power systems. It is expected to present a new method of performing a decent coupling between the imposed stochastic effect of wind power and the deterministic small signal stability analysis in the future electrical power networks. To achieve its goal, the paper submits a brief explanation on the small disturbance angle stability and presents a required background on the conventional mathematical tools which are necessary to investigate this type of system stability. Also, characteristics of the future power systems, i.e., the stochastic behavior of renewable energy sources and the dynamic aspects of large variable speed wind turbines are briefly elaborated. Subsequently, the given mathematical descriptions are supported by demonstrating the behavior of a multi-machine power system, in which large variable speed wind turbines play a major role.

Since many of the wind turbines used in the transmission systems are variable speed turbines which use DFIGs, it is important to consider the effects of these machines on the electric power networks, form the angle stability point of view. Thus, another aspect of this paper is to present a mathematical model for analyzing the behavior of wind turbines with DFIGs in the future power systems respecting the small disturbance angle stability. The presented model is expected to enable us to observe the impacts of large and variable speed wind turbines equipped with DFIGs on the small signal stability of the interconnected electric power networks.

Eventually, the paper brings up a possible methodology to analyze the small disturbance angle stability in the prospective power systems by applying an iterative-stochastic approach. By this approach, the uncertain nature of sustainable energy sources is stochastically modeled and subsequently, for each sample of this model an iterative linear analysis is performed. This approach analyzes all possible combinations of loads and sustainable electricity generations. Applying such a method is expected to reveal the most vulnerable operating points of the system.

This paper is organized as follows: Section II describes the small disturbance angle stability analysis in the systems with DFIGs. In section III, the iterative-stochastic method to analyze the small signal stability is discussed. A numerical study and conclusions are presented in section IV and section V, respectively.

II. Small disturbance angle stability in the systems with DFIGs

Small disturbance angle stability is the ability of an electric power system to maintain synchronism when it is subjected to small disturbances [1]. This section summarizes the conventional analysis method of small disturbance angle stability

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978-1-4244-2235-7/09/$25.00

in electric power systems based on the Structure Preserving Model (SPM). Also, the modified equations for analyzing the small signal stability in the power networks, equipped with the locally distributed variable speed wind turbines, are derived within this section.

A. Conventional Systems Dynamics Based on SPM

Fig. 1 shows a power system with $n+N$ nodes. The first n are internal machine nodes and the remaining N are load buses. $\overline{E}'_k = E'_k \angle \delta_k$ $(k = 1 \dots n)$ is the internal machine voltage phasor behind the transient reactance x'_{dk} including the transformer reactance, if present. E'_k is the magnitude of the internal machine voltage and δ_k is the internal machine angle of the k-th machine. $\overline{V}_k = V_k \angle \theta_k$ $(k = n+1, \dots n+N)$ is the load bus voltage phasor with magnitude V_k and phase angle θ_k.

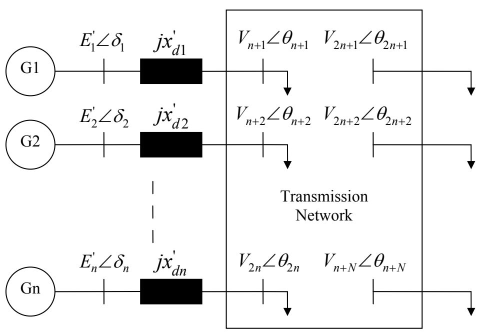

Fig. 1. A multi-machine power system

In order to be able to write such a multi-machine power system dynamics, it is assumed that the mechanical power input is constant and the stator resistance is neglected. The one-axis model is used for the conventional synchronous generators, i.e., the voltage behind the direct transient reactance is no longer constant. It is also assumed that loads are modeled in a static way. A static load is described by:

$$P_L = P_{L0}(\frac{V}{V_0})^{mp} \quad (1)$$

$$Q_L = Q_{L0}(\frac{V}{V_0})^{mq} \quad (2)$$

Where P_{L0} and Q_{L0} are the active and reactive powers at the nominal voltage V_0, respectively. mp and mq are the voltage exponents of the active power and the reactive power. For $mp = mq = 2$ (which is the case in this paper), the active and reactive components of the static load have the constant impedance characteristic.

Before being able to formulize the system dynamics, it should also be noted that the transmission lines are given by an admittance matrix of order (N by N) formed without considering the loads and the d-axis transient reactances x'_d. The kl-th element of the admittance matrix is defined by $\overline{Y}_{kl}$=$G_{kl} + jB_{kl}$, where G_{kl} represents solely the resistances of the respective transmission lines.

Now, the required differential equations to describe the mechanical motion of the k-th synchronous machine ($k = 1 \dots n$) are given by:

$$\dot{\delta}_k = \omega_k \quad (3)$$

$$\dot{\omega}_k = \frac{1}{M_k}[P_{mk} - \frac{E'_{qk}V_{n+k}}{x'_d}\sin(\delta_k - \theta_{n+k})] \quad (4)$$

$$\begin{aligned} \dot{E}'_{qk} &= \frac{1}{T'_{dok}}[E_{fdk} - \frac{x_{dk}}{x'_{dk}}E'_{qk} \\ &+ \frac{x_{dk} - x'_{dk}}{x'_d}V_{n+k}\cos(\delta_k - \theta_{n+k})] \end{aligned} \quad (5)$$

Where ω_k is the rotor speed deviation of the k-th machine with respect to the synchronous speed. x_{dk}, x_{qk} are the d-axis and the q-axis synchronous reactances of the k-th machine. E'_{qk} is the q-axis voltage behind transient reactance of the k-th machine. T'_{dok} is the d-axis transient open circuit time constant of the k-th machine. E_{fdk} is the exciter voltage of the k-th machine. E_{fdk} in this paper is constant (fixed excitation - no Automatic Voltage Regulator, i.e., no AVR) and is given by equaling $\dot{E}'_{qk}$ to zero in the steady state (all time derivatives are equal to zero during the steady state).

As it is known from equations (3)-(5), the described differential equations highly depend on the values of V (magnitude of the voltage) and θ (phase) at the buses of the system. Considering the fact that V and θ are also variables, there is a demand to define other equations to be solved for V and θ. These equations can simply be the non-linear algebraic power balance equations at each node. In other words, one can say that the generated active power at each node is equal to the consumed active power by the load at that node plus the transmitted active power to the connected nodes. This fact is expressed mathematically by:

$$P_k + P_{Lk} = 0 \quad (6)$$

where P_k is the active net production at bus k and P_{Lk} is the consumed active power by the connected load to bus k.

The same interpretation is valid for reactive power:

$$Q_k + Q_{Lk} = 0 \quad (7)$$

It should be noted that P_k,P_{Lk},Q_k and Q_{Lk} are the functions of V and θ at the systems' buses.

B. Dynamics of the Systems Equipped with DFIGs

For the systems comprising DFIGs, the dynamic parameters of this kind of generators should be considered. This subsection formulizes a one-axis model (a dynamic model with three state variables) for a DFIG. Also, the equations describing the conventional systems dynamics (systems with only synchronous generators) are developed for the systems with both synchronous generators and DFIGs, within this subsection.

The one-axis model (third order model) of DFIGs have been derived in [7], [11], [12]. Assuming that the depicted multi-machine power system in Fig. 1 comprises only DFIGs instead of conventional synchronous generators, and having the derived one-axis model for a DFIG in mind, It is feasible to write the required differential equations to describe the mechanical motion of the k-th DFIG ($k = 1 \ldots n$) as:

$$\begin{aligned}\dot{\delta}_k &= \frac{1}{E'_k T_{0k}}[-T_{0k}(\omega_s - \omega_k)E'_k \\ &- \frac{x_k - x'_k}{x'_k} V_{n+k} \sin(\delta_k - \theta_{n+k}) \\ &+ T_{0k}\omega_s V_r \cos(\delta_k - \theta_{n+k})]\end{aligned} \quad (8)$$

$$\dot{\omega}_k = \frac{1}{M_k}[P_{mk}(\frac{\omega_s}{\omega_k}) - \frac{E'_k V_{n+k}}{x'_k} \sin(\delta_k - \theta_{n+k})] \quad (9)$$

$$\begin{aligned}\dot{E}'_k &= \frac{1}{T'_{ok}}[-\frac{\omega_s}{\omega_k}E'_k + \frac{x_k - x'_k}{x'_k} V_{n+k} \cos(\delta_k - \theta_k) \\ &+ T_{0k}\omega_s V_r \sin(\delta_k - \theta_{r_{n+k}})]\end{aligned} \quad (10)$$

In synchronous generators E' only includes the quadrature component of the electromotive force and generally is referred to E'_q. Since, in DFIGs it is not the same as that for synchronous generators, it is referred to E'. T_0 is the transient open circuit time constant. ω_s is the synchronous speed. ω is the rotor speed. $x = x_s$ is the stator reactance. x' is the transient reactance comes after the voltage E'. $\overline{V}_r$ is the rotor voltage with the magnitude V_r and the phase θ_r.

Now, for a composite system, when it is dealt with the synchronous generators the differential equations (3)-(5) are used to describe the mechanical motion of the generators. While, dealing with the mechanical motion of DFIGs, requires equations (8)-(10). It should be noted that the described algebraic equations (6) and (7) remain intact.

Assume that $nsyn$ synchronous generators are available in the system and the number of DFIGs is $nDFIG$. Also, $nbus$ is the number of buses in the system. Let us introduce

$$\begin{aligned}X \quad &= \quad [\delta_{1syn} \ldots \delta_{nsyn}\ \delta_{1DFIG} \ldots \\ \delta_{nDFIG} \quad &\omega_{1syn} \ldots \omega_{nsyn}\ \omega_{1DFIG} \ldots \\ \omega_{nDFIG} \quad &E'_{q1syn} \ldots \\ E'_{qnsyn} \quad &E'_{1DFIG} \ldots E'_{nDFIG}]^T\end{aligned} \quad (11)$$

and

$$Y = [\theta_1 \ldots \theta_{nbus}\ V_1 \ldots V_{nbus}]^T \quad (12)$$

Thus, considering the differential equations (3)-(5) and (8)-(10) together with the algebraic equations (6)-(7), dynamics of a composite multi-machine power system can be given by:

$$\dot{X} = f(X, Y),\ 0 = g(X, Y) \quad (13)$$

C. Linearization Around Equilibrium Points

The equilibrium of the system given by relation (13) takes place when all time derivatives of the states are zero:

$$\dot{X} = f(X_0, Y_0) = 0 \quad (14)$$

Considering minor deviations from the equilibrium points $(\Delta X, \Delta Y)$, together with the application of the first term of Taylor's expansion [3], the Jacobian matrices A, B, C and D are given such that:

$$\Delta\dot{X} = A\Delta X + B\Delta Y \quad (15)$$

and

$$0 = C\Delta X + D\Delta Y \quad (16)$$

If D has an inverse, it is possible to find ΔY from (16) and replace it into (15). Consequently, the state matrix A_{state} is given by:

$$\Delta\dot{X} = (A - BD^{-1}C)\Delta X = A_{state}\Delta X \quad (17)$$

D. Eigenvalues of the State Matrix

According to the Lyapunov's first method, the small signal stability of a nonlinear dynamic system is given by the roots of the characteristic equation of the system of first approximation [4]. If this method is applied to the system depicted in Fig. 1, then the eigenvalues of the state matrix (A_{state}) can indicate the small signal stability in the following forms:

- The original system is asymptotically stable when the eigenvalues have negative real parts [5].
- The original system is unstable if one eigenvalue has a positive real part [5].

III. Iterative-Stochastic Method

Power systems operate under the limitations derived from the non-storability of electrical energy [6]. The electrical energy produced and consumed throughout the system should be equal permanently. From another viewpoint, production and consumption are not certain quantities. The uncertainty of electricity production increases when the application of renewable energy sources grows. Thus, the stability of power systems is influenced by the stochastic nature of sustainable sources of energy. This section discusses the theory of an iterative-stochastic algorithm to analyze the small disturbance angle stability. Also, a qualitative discussion on this method is presented within this section.

A. Theory and Modeling

The iterative-stochastic method, models the uncertainty of renewable energy sources and the load behavior. Subsequently, for each sample of the load-generation set, a linear analysis, based on the stated SPM, is performed and the relevant eigenvalues are examined.

In this paper, a normal distribution [17] is used for modeling the loads. The consumed active power P_L is sampled based on a normal distribution with the mean value μ and the standard deviation σ, i.e., $P_L \sim N(\mu, \sigma)$. Considering the power factor of the load ($\cos\Phi_L$), the consumed reactive power is given by:

$$Q_L = P_L \tan\Phi_L \quad (18)$$

In order to sample the stochastic power generation, this paper follows the pattern of variable speed wind turbines equipped with DFIGs. The mechanical power given to a DFIG through a variable speed wind turbine can be expressed by [7]:

$$P_m = \frac{1}{2}C_p \rho u^3 A \quad (19)$$

With

$$C_p = \frac{1}{2}(1 + \frac{u_0}{u})[1 - (\frac{u_0}{u})^2] \quad (20)$$

Where P_m denotes the mechanical power, C_p the power coefficient, u_0 the downstream wind velocity at the exit of rotor blades (provided that the upstream wind velocity, u, is between the minimal and the maximal values), ρ the air density and A the swept area of the rotor disc.

For modeling the wind speed, a Weibull distribution [18] is applied. The obtained wind speed samples are inserted into equation (19) to have the samples of the mechanical power.

The dependency of samples on each other in the sampling process influences the iterative-stochastic method. Although the loads follow the normal distribution independently, they still can be correlated due to different reasons such as being in different geographic regions or taking the various load types. A similar reasoning is valid for mechanical power sampling. For a discussion on models of stochastic dependence, one can refer to [6] (Chapter 5). For the sake of simplicity, in this paper, loads are independently sampled, but to be more realistic, the mechanical power samples given to DFIGs, at different nodes, are correlated using the Gaussian copula [8].

It should be recalled that the mechanical dynamic (rotor speed derivation) of a DFIG is described by [5]:

$$\dot{\omega} = \frac{1}{M}[P_m(\frac{\omega_s}{\omega}) - P_e] \tag{21}$$

The steady state electrical speed is usually given in terms of slip (s) defined by:

$$s = \frac{\omega_s - \omega}{\omega_s} \tag{22}$$

Setting the equation (21) to zero, and using the definition of slip, the samples of mechanical power given to a DFIG can be converted to the samples of electrical active power given to the system:

$$P_e = \frac{\omega_s}{\omega} P_m = \frac{1}{1-s} P_m \tag{23}$$

Considering the power factor ($\cos \Phi_G$), the samples of electrical reactive power are given by:

$$Q_e = P_e \tan \Phi_G = \frac{1}{1-s} P_m \tan(\phi_G) \tag{24}$$

B. Qualitative Discussion

The iterative-stochastic algorithm for each couple of (X : $load, Y$: $generation$), performs a linear analysis. If this method is applied to the power system depicted in Fig. 1, then for each couple, $3n$ eigenvalues should be evaluated. Since any eigenvalue with positive real part has to be avoided, it is possible to deal with $max\{Re\{3n\ eigenvalues\}\}$. Considering the fact that at least one eigenvalue will be zero, it is expected that for a stable system, the iterative-stochastic algorithm produces a set of zeros [10].

An important aspect of this method is that the power flow calculation has to be done for each couple of samples. To perform this power flow calculation, one node acts as a slack node. Due to the stochastic generation, direction of power flow may change and as a consequence, PQ nodes may participate in the net production. This affects the conventional PV nodes and/or the slack node. In other words, it is possible that the reactive power consumption, i.e., negative generation, occurs for a synchronous generator (in underexcited mode) [15]. Also, obtaining a negative active power for the slack node may be the case (synchronous motor).It, however, should be noted that a normal DFIG, unlike a synchronous generator, does not have the capability of experiencing the underexcited and overexcited modes. Although this ability can be given to a DFIG by applying power electronic concepts, this paper, for the sake of simplicity does not include them. In other words, the nodes connected to DFIGs are considered PQ nodes (while for synchronous generators, they can be PV nodes) with positive P and Q, i.e., $P, Q > \epsilon$. This is a constraint imposed on the system behavior due to the installation of DFIGs.

Sensitivity to the system parameters is another distinctive feature of the iterative-stochastic method. Elements of the Jacobian matrices A, B, C and D in equation (17) show the parameters which can affect the eigenvalues of the state matrix (A_{state}). The interesting characterisitc of the suggested iterative-stochastic algorithm, based on the stated sensitivity, is to stabilize an unstable system by adjusting the sensitive parameters defined by the elements of A_{state}. For instance, assume that in order to compensate for lack of power somewhere in the system the local renewable sources of energy are applied. Although the lack of power might be solved by this application, the global small disturbance angle stability might be lost if the parameters of the renewable electricity producers (DFIGs, for example) are not selected properly. The iterative-stochastic method makes it possible to derive the appropriate dynamic parameters for the required DFIGs such that the global small disturbance angle stability of the system is preserved.

IV. Numerical Study

In this section, a nine-bus test system is used for demonstrating the iterative-stochastic algorithm. The simulations are performed by using MATLAB and all quantities are in per unit, unless otherwise stated. The conventional system data can be taken from [2] (pp. 38, 39).To highlight the impacts of DFIGs' dynamic parameters, three subsections are defined. The first subsection analyzes the small disturbance angle stability when the renewable energy sources are modeled by a few black boxes. In other words, the dynamic parameters of variable speed wind turbines are intentionally neglected. The second subsection shows how the aforesaid dynamic parameters can jeopardize the global angle stability if they are not selected properly.And the third subsection explains the trend of system stabilizing by selecting the appropriate parameters, for designing a power network with a few variable speed wind turbines, installed locally.

A. Iterative-Stochastic Method - Without DFIGs' Parameters

In order to be able to perform the iterative-stochastic method, the original test system is modified by the installation of three local wind turbines at buses 4, 5 and 6 respectively (see Fig. 2).

In order to investigate the effects of wind turbines (as the black box power injectors) and the time-continuous behavior

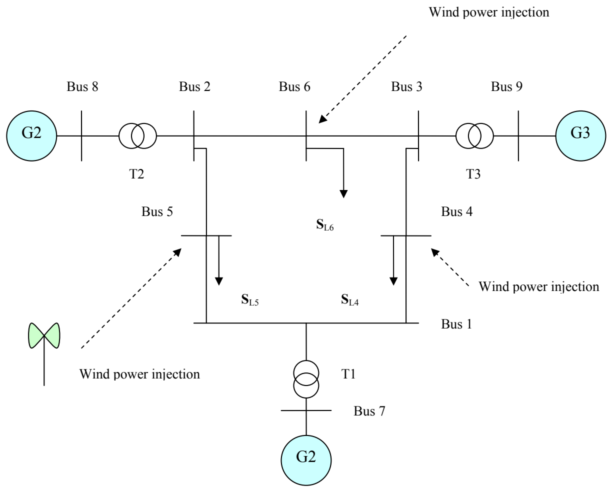

Fig. 2. A 9-bus system with 3 local wind turbines

of the loads some aspects of system data are adjusted in the following way.

- Demanded active power at bus 4: $P_{L4} \sim N(\mu = 1.2, \sigma = 0.3)$. Load power factor at bus 4: $\cos\Phi_{L4} = 0.9$.
- Demanded active power at bus 5: $P_{L5} \sim N(1.27, 0.25)$. Load power factor at bus 5: $\cos\Phi_{L5} = 0.9$.
- Demanded active power at bus 6: $P_{L6} \sim N(1.25, 0.27)$. Load power factor at bus 6: $\cos\Phi_{L6} = 0.9$. It is worth noticing that normally distributed loads may also include negative samples. To have a more accurate analysis, all possible negative samples are converted to zero.
- The stochastic generated active power at buses 4, 5 and 6 is modeled based on the equations (23) and (24). Power factor of generation is set to $\cos\Phi_G = 0.9$. Wind speed follows the Weibull distribution with scaling parameter $A = 13$ and shape parameter $K = 2$ [9]. Wind speed samples, for different buses, are correlated by the correlation matrix $\rho = \begin{pmatrix} 1 & 0.8 & 0.6 \\ 0.8 & 1 & 0.7 \\ 0.6 & 0.7 & 1 \end{pmatrix}$. Also, wind speed at nominal power: $u_N = 15\frac{m}{s}$, nominal power: $P_N = 0.35$, cut in wind speed: $u_{ci} = 5\frac{m}{s}$ and cut out wind speed: $u_{co} = 22\frac{m}{s}$.

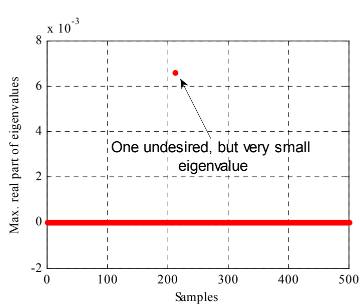

Fig. 3. Instability indicators - Without DFIGs

Fig. 3 shows the distribution of small disturbance angle stability indicators for the above explained test system. According to this figure, the system is at a rather high level of stability for the 500 analyzed samples. It means, without considering the DFIGs' dynamic parameters the system seems to be stable for various operating points.

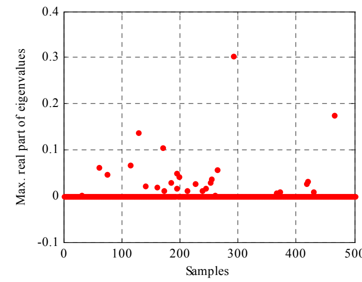

Fig. 4. Instability indicators - Without DFIGs - Sensitivity to P_N

It becomes now possible to check the sensitivity of the system angle stability to some controllable parameters. Fig. 4 shows how the system stability is influenced by the nominal power parameter (P_N) of the wind turbines when this is increased from 0.35 to 0.9. Based on Fig. 4, it can be concluded that the small disturbance angle stability of the system is jeopardized by increasing the parameter P_N for all wind turbines.

This section discussed the variation of eigenvalues, as instability indicators, for a specific test system without considering the parameters of DFIGs. Also, the procedure of sensitivity analysis was shown for one system parameter. The next subsection includes the dynamic parameters of the applied DFIGs.

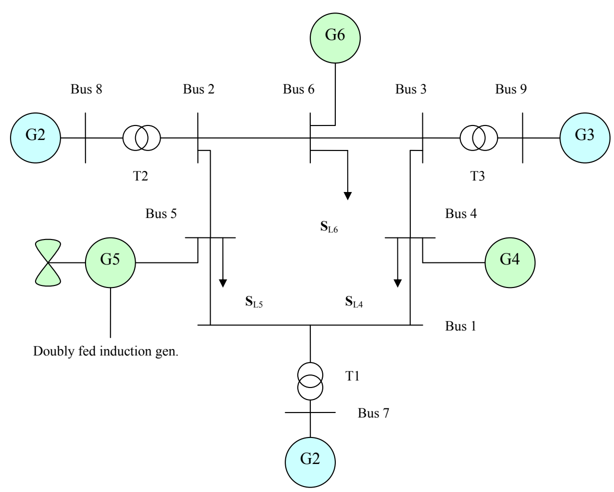

Fig. 5. A system with 3 variable speed wind turbines using DFIG

B. Iterative-Stochastic Method - With DFIGs' Parameters

In this subsection the dynamic parameters of the applied DFIGs are included, i.e., it is dealt with the system depicted in Fig. 5. In order to investigate the impacts of the stated dynamic parameters the following data are added to the modified system data.

- For all DFIGs the parameter x (explained in equations (8)-(10)) is set to 1 (per unit).

- For all DFIGs the parameter x' in equations (8)-(10) is set to 0.1.
- For all DFIGs the parameter T_0 in equations (8)-(10) is set to 0.4.
- For all DFIGs the inertia constant (H) is set to 4.
- For all DFIGs the parameter s in equations (22)-(24) is set to -0.03.
- all parameters relevant to the synchronous generators, load samples and wind speed samples, as compared to the previous subsection, remain intact.

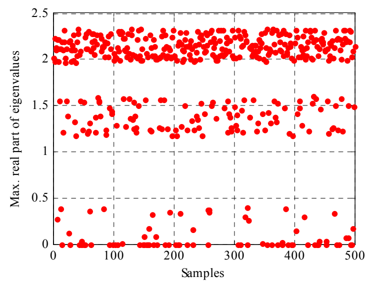

Fig. 6. Instability indicators - With DFIGs

Comparing Fig. 6 to Fig. 3, reveals the impact of DFIGs' dynamic parameters on the global small disturbance rotor angle stability, for the described test system. It, however, is again possible to perform a sensitivity analysis for the described system including DFIGs' parameters. Fig. 7 shows how the system stability is influenced by the nominal power (P_N) of the wind turbines when this is increased from 0.35 to 0.9 for the system including the parameters of DFIGs.

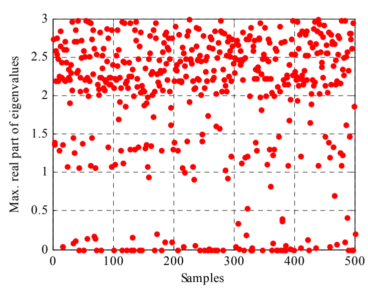

Fig. 7. Instability indicators - With DFIGs - Sensitivity to P_N

C. System Stabilizing

Assume that for the depicted system in Fig. 5 the required locally injected power from each renewable source is 0.35 (per uint).If this power is supplied by the stated variable speed wind turbines using DFIG, most of the maximum real parts of the eigenvalues take positive values (Fig. 6). This implies that the global small disturbance angle stability is significantly influenced in a negative manner. This subsection intends to prove that by applying the iterative-stochastic method, it is possible to improve small signal stability of the system.

As it was discussed within the previous subsections, the iterative-stochastic method enables one to perform a sensitivity analysis and to derive the impact of system parameters on the global small signal stability. In other words, it is possible to define how increasing/decreasing the system parameters can improve/exacerbate the system stability. Here, the impacts of a few parameters are listed for brevity and their impacts on the stability indicators, i.e., on Fig. 6 are checked.

By running the sensitivity analysis described in the previous subsections, it is shown that increasing power factor of the loads ($\cos \Phi_L$), power factor of generation ($\cos \Phi_G$), Inertia constant of the conventional synchronous generators (H_{syn}), transient reactance of DFIGs (x'_{DFIG}) and the transient open circuit time constant of DFIGs (T_{0DFIG}) have positive impact on the global small disturbance angle stability. On the contrary, decreasing the resistive effects of the lines (R_{lines}), reactive effects of the lines (X_{lines}), capacitive effects of the lines ($Y_{shunt-lines}$) and the transient reactance of the conventional synchronous generators (x'_{dsyn}) impose positive impacts on the aforesaid type of stability.

Therefore, by selecting the following new parameters, it is tried to stabilize the system of Fig. 5. when the required local power injections at buses 4, 5 and 6 are equal to 0.35 per unit.

- $\cos \Phi_L = 0.97$.
- $\cos \Phi_G = 0.97$.
- $H_{syn,new} = 5H_{syn}$.
- $x'_{DFIG,new} = 5x'_{DFIG}$.
- $T_{0DFIG,new} = 5T_{0DFIG}$.
- $R_{lines,new} = 0.6R_{lines}$.
- $X_{lines,new} = 0.3X_{lines}$.
- $Y_{shunt-lines,new} = 0.3Y_{shunt-lines}$.
- $x'_{dsyn,new} = 0.3x'_{dsyn}$.

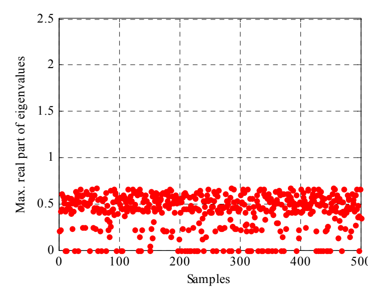

Fig. 8. Instability indicators - Stabilization by selecting the right parameters

Comparing Fig. 8 to Fig. 6 demonstrates how the maximum real parts of the eigenvalues get attenuated by selecting the appropriate parameters for both the conventional synchronous generators and the newly installed variable speed wind turbines using DFIGs.

A more highlighted comparison is given by Fig. 9.

V. Conclusion

It has been shown that although increased supply of renewable energy sources can solve the lack of power, it might impose a negative effect on the small disturbance angle stability of electric power systems.

By introducing an iterative-stochastic algorithm, the uncertain nature of sustainable energy sources was considered in the small signal stability analysis. This method reconciled

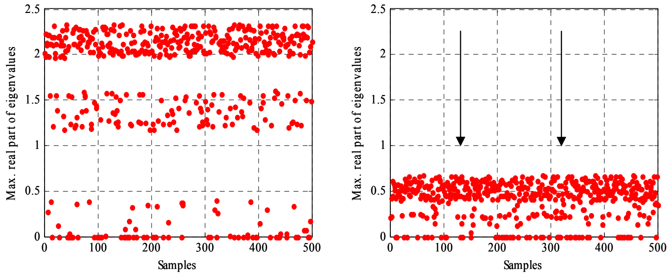

Fig. 9. Instability indicators - Stabilization by selecting the right parameters

the stochastic behavior of renewable energy sources and the deterministic method of stability study.

Also, the trend of change in the indicators of small disturbance angle stability, i.e., the eigenvalues, was investigated and the impacts of DFIGs' dynamic parameters on the eigenvalues were analyzed. Eventually, the sensitivity of small disturbance angle stability to some system parameters was investigated for an electric power test system equipped with a number of renewable energy sources.

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