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Distributed Generation Impact on Power System Transient Stability: a Stochastic Approach

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Abstract – *This paper proposes a stochastic approach to investigate the impact of increasing distributed generation (DG) penetration levels on power system transient stability. The DG units are considered to be synchronous machines that are connected to the distribution networks. The DG units are customer-owned and can be connected or disconnected from the system by their owners at random, so that the DG units generate power in a stochastic way. The random behavior of the load is taken into account as well and the probability distribution of the aggregated generated power and the load demand of the distribution system are calculated using Monte Carlo Simulation (MCS). The DG penetration level is raised by increasing the number of DG units within the test system in steps, while the load is kept constant. The remaining power production is distributed among the centralized generators, inversely proportional to their fuel efficiency. The most inefficient units are shut down when the power output falls below their minimal generated power. The power system transient stability is examined by applying a permanent fault in one line of the test system. To assess the system stability, the following two indicators are used: the maximum rotor speed deviation and the oscillation duration of the centralized generators.*

Keywords – Distributed generation (DG), Monte Carlo simulation (MCS), power system transient stability.

1. INTRODUCTION

An increasing interest for implementing distributed generation (DG) can be observed in many countries. At a certain point, due to the increasing DG penetration level, the remaining power production is divided among the centralized big power plants, of which some must be shut down because of efficiency considerations.

In [1]-[4] studies to investigate the impact of increasing DG penetration levels on the power system transient stability have been performed by means of a deterministic approach; *i.e.* with deterministic values for the loads and the DG power production. However, in contrast with the large centralized generators within a power system, DG units are in essence non-dispatchable in character [5], [6]. It results from the fact that certain DG units generate power from primary energy sources with inherently stochastic characteristics, such as wind and solar energy, and that DG units can be customer-owned, where the owners decide whether the units are running or not. In both cases the DG units are non-dispatchable and possess stochastic generation characteristics. Therefore a new method is proposed in this paper to investigate the impact of increasing DG penetration levels on the power system transient stability where both the stochastic behavior of DG units and loads are taken into account.

2. RESEARCH APPROACH

2.1 Thirty nine bus New England Test system

The 39-bus New England dynamic test system [7] is used in the studies with some adjustments. Representative values for the parameters of the generators, the exciter, and the governor are taken from [8], [9]. The loads are equally divided in constant impedance, constant power and constant current. Figure 1 shows the test system used throughout the simulations. The 10 centralized generators in this test system are referred to as centralized generation (CG) in this paper.

The power system dynamics simulation package PSS/E 25.4 is used to investigate the dynamic behaviour of the transmission system as well as to run the optimal power flow program used to develop the simulation scenarios. In addition, Matlab® is used for preparing the simulation scenarios and to process the simulation results.

2.2 DG technology

The DG units are synchronous generators, *e.g.* within Combined Heat and Power (CHP) plant, without grid voltage and frequency control, modelled as a standard round rotor generator model with exponential saturation [9].

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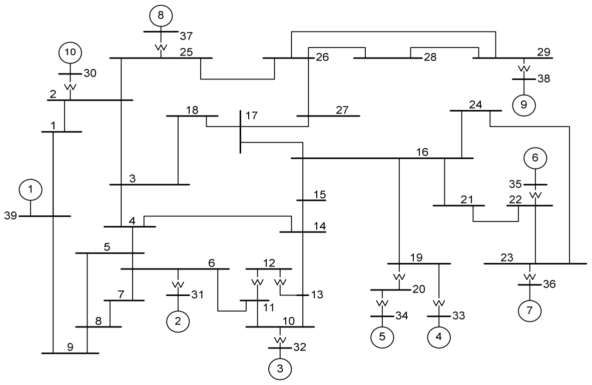

Fig. 1. One-line diagram of the 39-bus New England test system [7].

2.3 Increasing DG penetration level

The increasing DG penetration level in the test system is realized in the following way:

- A DG unit is connected to every load bus via a j0.05 pu impedance on the 100 MVA system base.
- Both the nominal real and reactive power of all loads are kept constant.
- The penetration level of DG is raised by increasing the fraction of the total load in the test system that is served by DG. Thus, the DG penetration level in the system is defined as:

$$\%DG_{level}=\frac{P_{DG,Total}}{P_{Load,Total}}\times 100 \tag{1}$$

where PLoad,Total is the total nominal amount of active load within the test system and PDG,Total is the total nominal amount of active power generated by the DG. The DG penetration level is increased in steps of 10% up to 50%.

2.4 Optimal power flow

When DG penetration level is increased, the remaining power is divided among the (dispatchable) CGs by considering the economic operation of the power system. A scheme of the minimum and the maximum loading limits as well as the cost models of the CGs are assumed. An optimal power flow program, whose objective function is to minimize the fuel cost, is run each time that the DG penetration level is raised. The most inefficient CG whose power output falls below its minimum loading limit is shut down and a switched shunt device is implemented in the location of the shut down CG to compensate the former reactive power production. The optimal power flow program is rerun. The following flowchart (Figure 2) illustrates the steps to define the scenarios. The optimal power flow is performed with PSS/OPF, the optimal power flow module of PSS/E 25.4 [9].

2.5 Monte Carlo simulation

The fraction of the total load served by the DG is distributed among the DG units, proportional to the nominal real power consumed by the load at that particular bus (see Table 1). An assumption that there is a driving factor (*e.g.* economically) for DG owner to not only supply their electricity (load) but also to sell their generated power to the grid leads to a scenario that the DG owner would oversize their installed capacity of the DG (CHP) *e.g.* by 20%. During the operation of the DG, stochastic behaviour of the DG owner exist. The DG considered is still less stochastic/intermittent than renewable energy generation likes wind power generation Therefore a Monte Carlo Simulation is considered with the total (aggregated) customer-owned DG stochastically calculated as a binomial distribution where each DG unit within the distribution network is connected to the system with a probability that equals 0.8. Thus, the maximum capacity of DG installed in one load bus can be 125% of the nominal load value. The DG units supply only active power (1MW nominal power each) and no reactive power.

The loads are following a normal distribution, where the mean values are the nominal load (see Table 1), and the standard deviations equal 2.5%. 5,000 samples are generated for the aggregate DG output power and the load at each load bus, in every scenario of an increasing DG penetration level. These 5,000 samples are considered to be sufficient since the MCS has converged after 5, 000 samples.

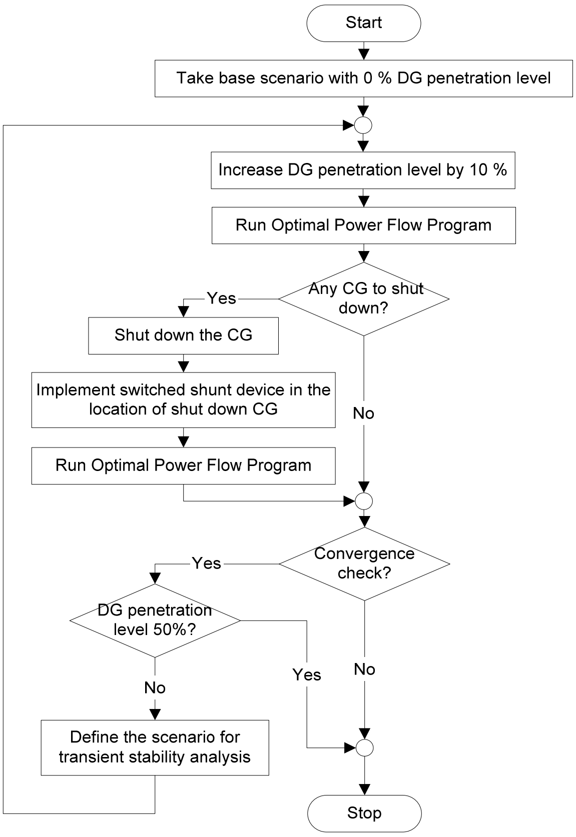

Fig. 2. Flowchart to define the scenarios that represent the system with an increasing DG penetration level.

2.6 Transient stability indicators

The transient stability of the test system is investigated by applying a permanent fault to the transmission line between buses 15 and 16 carrying 315 MW and 150 MVAr . It is assumed that the fault is cleared by tripping the faulty line after 150 ms. The fault that will disturb the stability of the system is applied to cases with different DG penetration level, taking into account the stochastic behavior of the generation. The impact of the disturbance to each cases will later be compared.

- To assess the transmission system stability, the rotor angle stability of the centralized generators is observed. To quantify the rotor speed oscillation of the centralized generators, two transient stability indicators are applied, namely [1]:
  - The maximum rotor speed deviation.
  - The oscillation duration.

The maximum rotor speed deviation is defined as the maximum rotor speed value achieved during the transient phenomenon. The oscillation duration is defined as the time interval between the application of the fault and the moment after which the rotor speed stays within a bandwidth of 10-4 pu during a time interval longer than 2.5 seconds. Figure 3 shows the two indicators used in this paper.

Table 1. Load data (Nominal).

Bus #	Load		Bus #	Load	
	MW	MVAR		MW	MVAR
3	322	2.4	23	247.5	84.6
4	500	184	24	308.6	-92.2
7	233	84	25	224	47.2
8	522	176	26	139	17
12	7.5	88	27	281	75.5
15	320	153	28	206	27.6
16	329	32.3	29	283.5	26.9
18	158	30	31	9.2	4.6
20	628	103	39	1104	250
21	274	115			

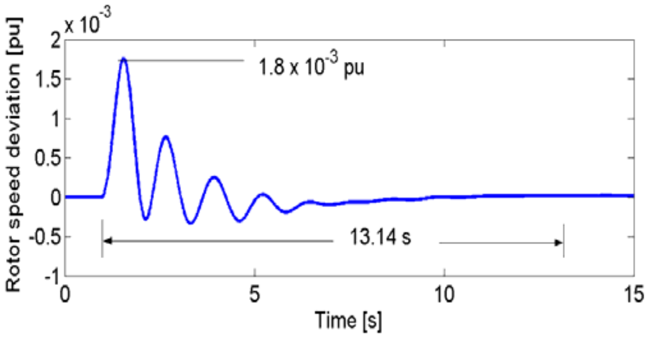

Fig. 3. Transient stability indicators: the maximum rotor speed deviation and the oscillation duration [2].

3. SIMULATION RESULTS

The approach depicted in Figure 2 results in a number of scenarios of a power system with different DG penetration levels. There are five CGs that operate within all scenarios: CG nr. 1-5 (*i.e.* the lowest 5 bars of Figure 4). Therefore, to compare the transient stability performance in the different scenarios, the transient stability indicators are applied on these five CGs.

Figure 5 shows the MCS generated samples representing the active and reactive loads at each load bus. The contours of the histograms of the MCS generated samples representing the DG power generation at each load bus at a 10%, 20%, 30%, 40% and 50% DG penetration level are shown in Figure 6. The MCS generated samples representing the DG power generation at bus nr. 12 and 31 are not shown due to the small values.

Although in this paper the DG units are implemented as synchronous generators, and the rotating mass in the system that 'reduced' due to shutting down the CGs is 'replaced' by the rotating mass of the DG units, the overall rotating mass in the system decreases. The total amount of active power generation in the system remains constant, but the DG units are operated close to unity power factor (since they are mainly intended to deliver active power), which is not the case with the CG units (they also deliver reactive power to maintain the system voltage). Therefore, the total machine rating of the DG units is less than the total machine rating of the shut-down CG units. This makes the system more vulnerable in terms of transient stability (*e.g.* due to disturbance) [12], [13]. Table 2 shows the total stored kinetic energy in the system as a function of the increasing DG penetration level, for both the deterministic and the stochastic approach (average value).

The values of the two stability indicators, *i.e.* the average value in case of the stochastic approach and the deterministic value in the deterministic approach, are shown in Table 3. The expectation that the transient stability of the system reduces with an increasing DG penetration level is confirmed by the two indicators that result from both the stochastic and the deterministic approach. It is interesting to notice that when the DG level increases from 30% to 40%, the oscillation duration significantly decreases in both approaches. This shows that besides the decrease of rotating mass in the system another mechanism plays a role: the power flows in the system. Large power flows have a detrimental effect on the damping of the oscillations [13]: the heavier the lines are loaded, the weaker the connections between the generators and the loads and the larger the rotor angle oscillations of the CGs [3]. The power flows in line 15-16, where the fault is simulated, are displayed in Table 4. From a 30% to a 40% DG penetration level, the effect of the decreased rotating mass is 'compensated' by the relatively small power flows in the system.

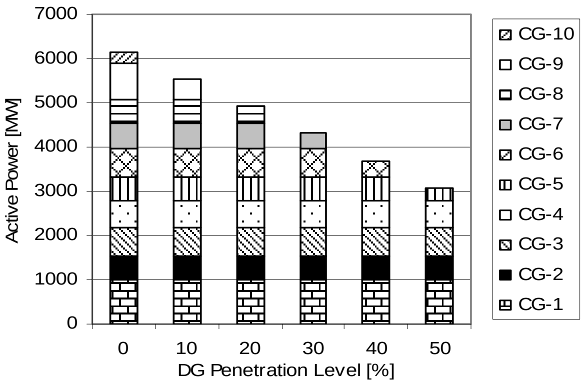

Fig. 4. Dispatched CGs as a function of the DG penetration level.

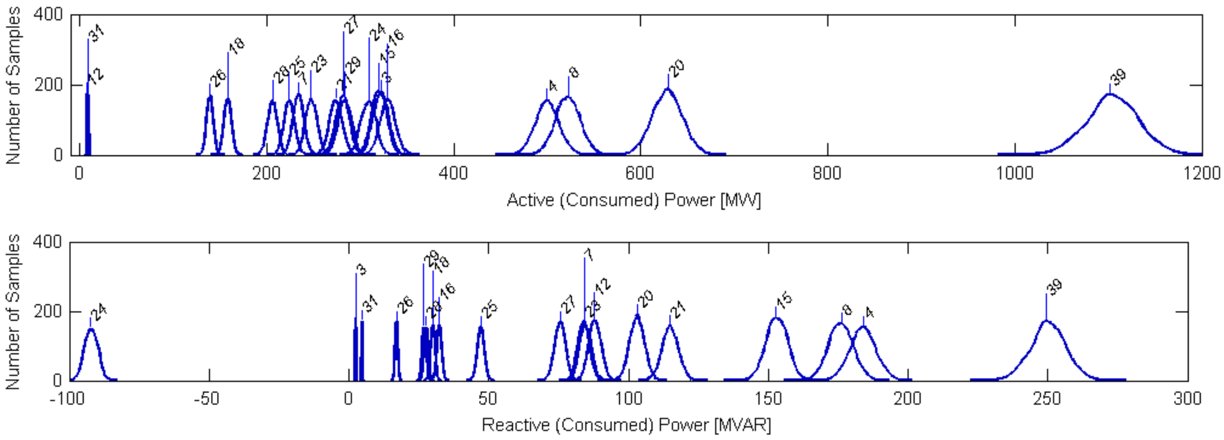

Fig. 5. MCS generated samples representing the active (upper graph) and reactive (lower graph) loads at each load bus.

Table 2. Total stored kinetic energy in the system.

DG level Scenario [%]	Stored kinetic energy of the CG [GJ]	Deterministic approach		Stochastic approach	
		Stored kinetic energy of the DG [GJ]	Total stored kinetic energy [GJ]	Stored kinetic energy of the DG [GJ]	Total stored kinetic energy [GJ]
10	35.212	2.703	37.915	2.707	37.919
20	30.292	5.426	35.718	5.422	35.714
30	27.092	8.121	35.213	8.118	35.210
40	23.772	10.834	34.606	10.837	34.609
50	19.920	13.546	33.466	13.543	33.463

Although the average maximum rotor speed deviations values that result from the stochastic approach (see Table 3) are the same as the results that are obtained by the deterministic approach, significant differences are obtained when the oscillation durations are compared. This gives a signal that the results obtained from the deterministic approach may give either too pessimistic (*e.g.* at the 30% DG penetration level) or too optimistic (*e.g.* at the 40% and 50% DG penetration level) results compared to the results obtained from the stochastic approach.

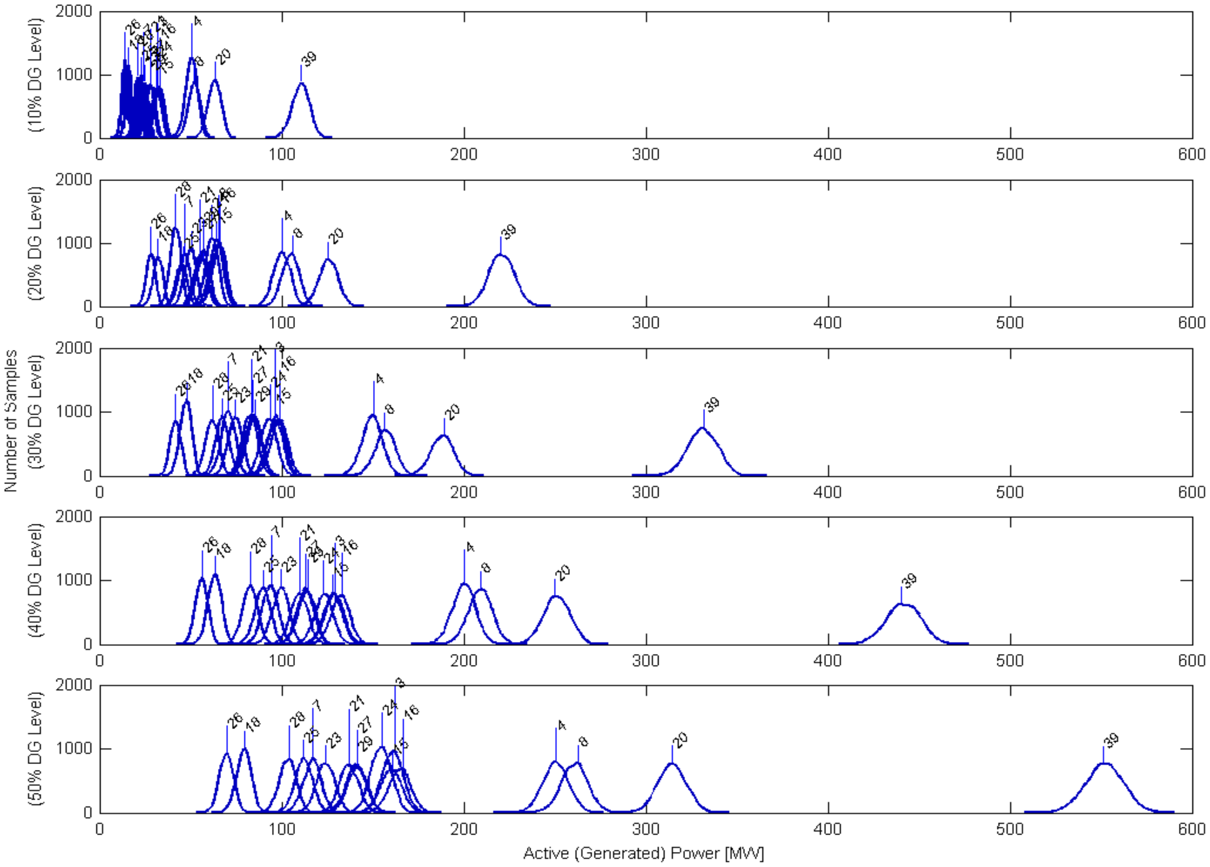

Fig. 6. MCS generated samples representing the DG power generation at each load bus at a 10%, 20%, 30%, 40% and 50 % DG penetration level.

Table 3. The maximum rotor speed deviations and oscillation durations that resulted from the deterministic and the stochastic (average) approaches.

DG penetration level [%]	The maximum. rotor speed deviation [pu]	The oscillation duration [s]	Average of the maximum. rotor speed deviation [pu]	Average of the oscillation duration [s]
10	5.3×10^{-3}	6.31	5.3×10^{-3}	6.32
20	5.5×10^{-3}	7.09	5.5×10^{-3}	7.09
30	5.5×10^{-3}	7.36	5.5×10^{-3}	7.07
40	5.5×10^{-3}	6.31	5.5×10^{-3}	6.86
50	6.3×10^{-3}	6.88	6.3×10^{-3}	7.20

Table 4. The active power flow in line 15-16 (where the fault is applied in the simulation).

DG penetration level [%]	Active power flow in line 15-16 (deterministic approach) [MW]	Average active power flow in line 15-16 (stochastic approach) [MW]
10	279.3	278.7
20	229.8	228.8
30	161.8	160.9
40	14.2	17.4
50	187.2	188.4

Furthermore, with the stochastic approach proposed in this paper, the probability distributions of the stability indicators, shown in Figure 7, are obtained and contain additional information. First of all, the black-and-white statement that the system becomes more unstable when for example the DG penetration level is increased from 10% to 20% can be more nuanced. It can be seen in Figure 7 that the probability distributions of both the maximum. Rotor speed deviations and the oscillation durations overlap in some ranges: the system becomes more unstable with a probability of Pr when the DG penetration level is increased from $\%DG_{level\text{-}i}$ to $\%DG_{level\text{-}(i+1)}$. Figure 8 and Equation 2 illustrate the use of this approach.

Let $g_1(x)$ and $g_2(x)$ be the probability distribution functions of the indicator-x derived from scenario $\%DG_{level\ i}$ (solid line) and $\%DG_{level\ (i+1)}$ (dashed line). Thus, there is a probability that the scenario $\%DG_{level\ i}$ gives a larger indicator value than $\%DG_{level\ (i+1)}$ that can be calculated as follows:

$$\Pr(g_1(x) > g_2(x)) = \int_{x1}^{x2} g_1(x) \left(\int_{x1}^{x} g_2(y) dy \right) dx \qquad (2)$$

Discretizing and applying Equation 2 to the results that we obtained from the stochastic approach, leads to Table 5. As an illustration, in comparison nr. 3, cases with DG penetration level of 30% and 40% are compared. It shows that the maximum. rotor speed deviation of the case with 30% DG can still be higher than the case with 40% DG penetration level with probability of 0.3211.

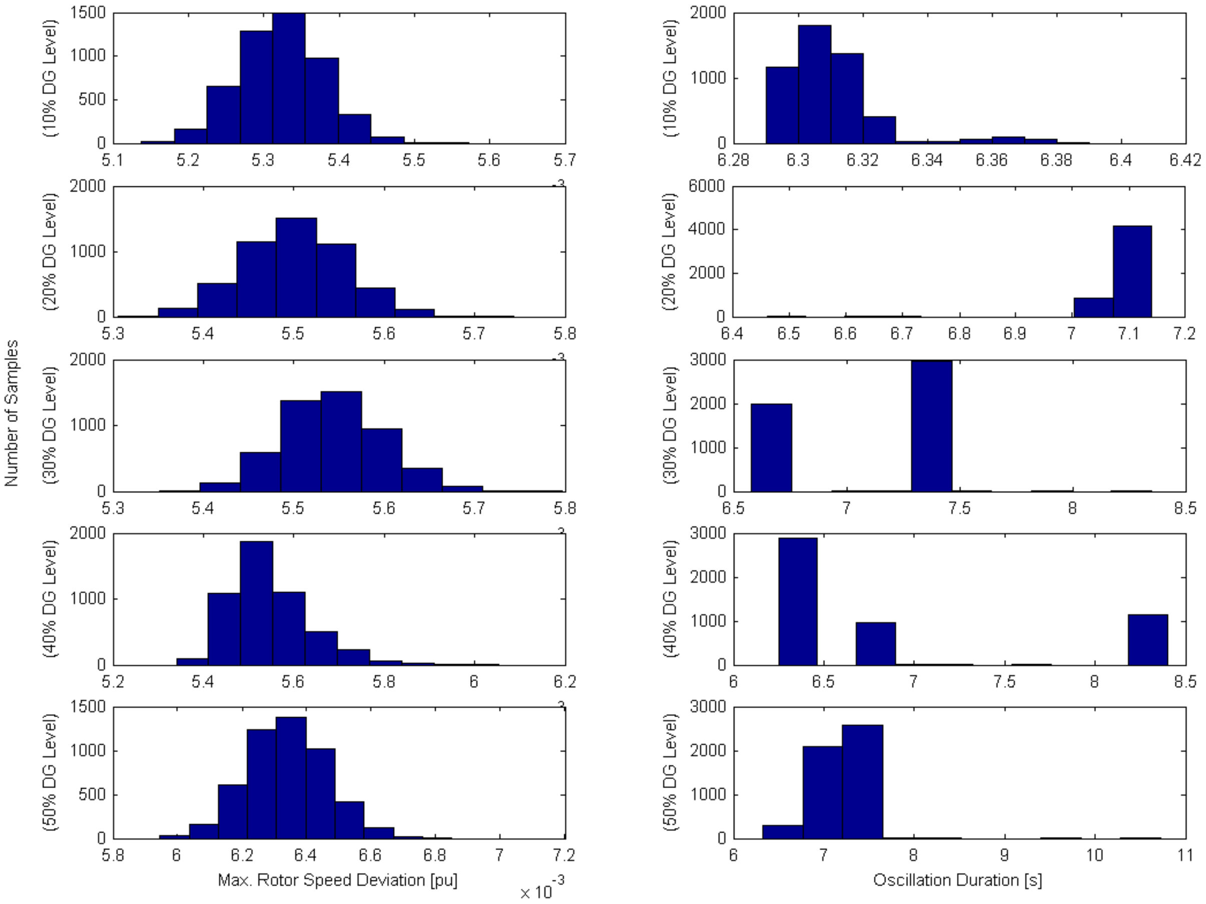

Fig. 7. Histograms of the transient stability indicators: the maximum rotor speed deviations (left graphs) and the oscillation durations (right graphs).

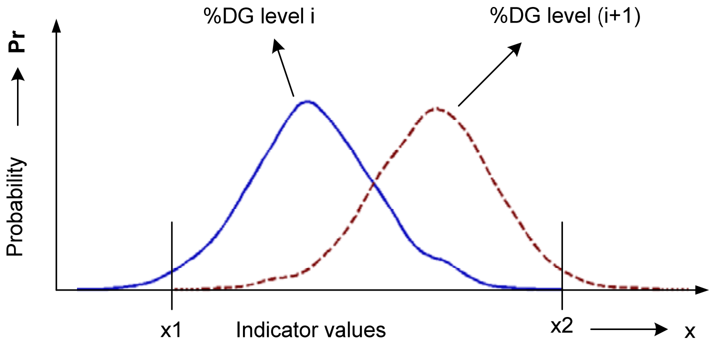

Fig. 8. The probability distributions of the stability indicators overlap.

Table 5. The probability that the indicators resulted from the scenario with lower DG level surpass the indicators resulted from the scenario with the one step-higher DG level.

Comparison nr.	$\%DG_{level}$		$\Pr(g_1(x) > g_2(x))$	
	$g_1(x)$	$g_2(x)$	x = indicator of max. rotor speed deviation	x = indicator of oscillation duration
1	10%	20%	0.0043	0
2	20%	30%	0.1406	0.3984
3	30%	40%	0.3211	0.6942
4	40%	50%	0	0.2413

4. CONCLUSIONS AND SUGGESTIONS

This paper proposes a stochastic approach to investigate the impact of increasing distributed generation (DG) penetration levels on power system transient stability. Both the stochastic behaviour of the DG units and the loads in the system are taken into account.

The computations do not result in a single value of the stability indicators, but in the probability distributions of the stability indicators. In other words: in stead of a black-and-white statement about the system stability a more nuanced result is obtained and additional insight is gained.

The merit of stochastic stability studies is evident even in the case of a relatively simple example as studied in this paper. The results obtained from the deterministic approach vary from the results obtained from the stochastic approach, and therefore, the stochastic approach becomes a necessity when, for example, DG units are used that are based on intermittent renewable energy sources (*e.g.* wind and solar energy), or when the dependence between the renewable DG units, the loads, and between generation and load is taken into account.

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