A Survey on the Transient Stability of Power Systems with Converter Connected Distributed Generation

Muhamad Reza[1,2]
[1]Electrical Power System Laboratory, Delft University of Technology, Delft, the Netherlands
(The author's affiliation when the work was performed)
[2]ABB Corporate Research, Västerås, Sweden

ABSTRACT

In the classical (vertical) power systems the synchronous operation of every interconnected synchronous machine (with its inherently rotating masses – inertia) is the main requirement for stable operation. As many of the distributed generation technologies are connected to the distribution network via power electronic interfaces, and do not contain inertia, the power system may show different transient stability phenomena. In this paper, the transient stability of power systems with (inertia less) converter connected distributed generation is explored via the Equal Area Criterion method and compared with that of a traditional (vertical) power system. With the existence of a strong external system, it is found that a system with a higher level of penetration of DG exhibits better stability, as measured by improved critical clearing times of the remaining synchronous generator(s).

Keywords: converter connected distributed generation, power systems transient stability

ABSTRAK

Pada sistem tenaga listrik klasik, sinkronisasi di dalam pengoperasian seluruh generator serempak (yang masing memiliki kelembaman/momen inersia) yang terhubung pada sistem adalah persyaratan yang utama untuk kestabilan operasi system tersebut. Dengan banyaknya pembangkit listrik tersebar yang terhubung pada jaringan distribusi listrik melalui perangkat elektronika daya, yang tidak dilengkapi dengan kelembaman/ momen inersia, akan menghasilkan fenomena kestabilan yang berbeda. Di dalam makalah ini, akibat penerapan pembangkit listrik tersebar yang terkoneksi melalu perangkat elektronika data terhadap kestabilan transien dari sebuah sistem tenaga listrik akan diamati dengan menggunakan metoda "Equal Area Criterion". Hasil pengamatan kemudian dibandingkan dengan kestabilan transien sebuah sistem tenaga listrik klasik. Di dalam makalah ini ditemukan bahwa ketika sebuah sistem tenaga listrik masih terkoneksi dengan jaringan listrik eksternal yang rigid, maka penerapan pembangkit listrik tersebar akan meningkatkan kestabilan operasi sistem, yang ditunjukkan dengan peningkatan "critical clearing times" dari generator serempak yang terhubung ke sistem tersebut.

***Kata kunci**: pembangkit listrik tersebar terhubung dengan perangkat elektronika daya, kestabilan transien sistem tenaga listrik*

INTRODUCTION

Driven by the increasing environmental concerns it is expected that many new generation technologies, including renewable generation, will be connected to the electrical power system as distributed generation (DG).

Interfacing DG with Power Electronics

There are a lot of different DG technologies, based on distinct energy sources, such as co-generation, wind turbines, small hydro and fossil-fuelled generators, photovoltaic systems, fuel cells and micro-generation [1]. These DG units, especially the ones whose prime movers are based on renewable energy sources with intermittent characteristics (like wind and solar), are mostly connected to the distribution network via power electronic interfaces, which are primarily used to maximize the energy yield [2].

Note: Discussion is expected before June, 1st 2007. The proper discussion will be published in Electrical Engineering Journal volume 7, number 2, September 2007.

Inertia of Synchronous Generator

The transient stability is defined as the property of a power system to return to a stable operating point after the occurrence of a disturbance [3, 4]. Traditionally, the transient stability problem is to maintain the synchronous operation of the synchronous generators in the system, i.e. to keep the operation speed of the rotors of all synchronous generators constant, which will result in constant angular position between two machines [3, 5].

The fundamental equation that governs the rotational dynamics of the synchronous generator is represented by means of the swing equation [3, 5]:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_a = P_m - P_e \quad \text{[pu]} \qquad (1)$$

Where, H is the stored kinetic energy at synchronous speed per MVAbase, δ is the angular displacement of the rotor in rad, Pm is the shaft power input less rotational losses in pu., Pe is the electrical power crossing the air gap in pu., Pa is the accelerating power in pu., ωs synchronous speed in electrical units in rad/s and t is the time in s.

The more rotational mass the synchronous generator has, the less the generator rotor will respond to an accelerating or decelerating tendency due to a disturbance.

CONVERTER CONNECTED DISTRIBUTED GENERATION

When DG is connected to power systems via a power electronic interface, no inertia is added to the system because:

- The DG itself generates DC power (i.e. f=0), e.g. photovoltaic and fuel cells (figure 1).
- The inertia of the DG whose prime mover involves rotating masses is 'hidden' behind the power electronic interface by decoupling the mechanical rotor speed of the DG with the electrical frequency of the grid (figure 2).

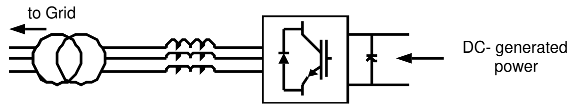

Figure 1. Connecting DG with DC output power to the power system

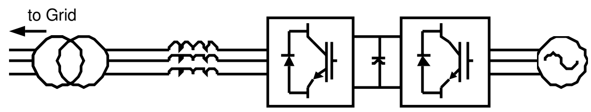

Figure 2. Connecting DG with rotating machines to the power system via a power electronic interface

Thus, in the above-mentioned situations, the DG will not change the acceleration or deceleration of the synchronous generators in the grid, in case of a mismatch between generation and load in the system [4].

Transient Analysis Simulation

In this study, the transient behavior of a power system with converter connected DG is investigated by means of simple test system (shown in figure 3) that consists of 5 buses:

- Bus 2 is an infinite bus (to represent an interconnection with a large external system),
- A plant containing similar and coherent CGs (every CG implemented in this bus is identical and the rotors of all the machine rotate and swing coherently just like all the rotors are mechanically coupled) is connected to bus 1,
- The load that is represented as constant impedance during the transient analysis is connected to bus 5. DG supplying only active power is connected to bus 5 and modelled as negative load.

Figure 4 shows the reactance diagram of the pre-fault test system. Table 1 lists the values of the parameters used in the test system.

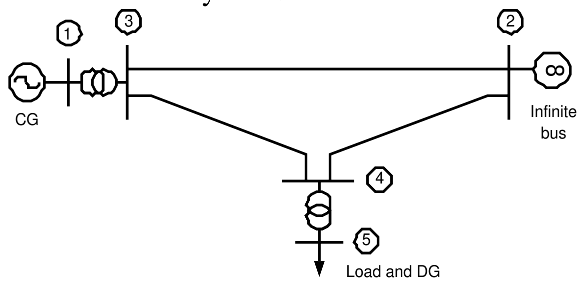

Figure 3. One-line diagram of the test system

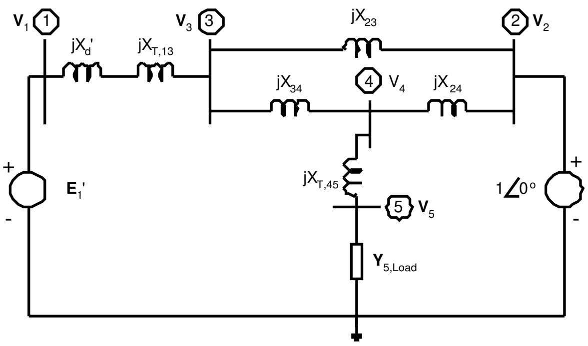

Figure 4. Reactance diagram of the test system in the pre-fault (steady- state) situation

Table 1. Values of the parameters used in the simulation

Parameters	Value	Parameter	Value	Parameters	Value
$MVA_{syst.}$	100 MVA	$X_{T,13}$	0.005 pu	$\|V\|_{inf}$	1.0 pu
$V_{transmission}$	220 kV	$X_{T,45}$	0.005 pu	δ_{inf}	0^o
V_{CG}	20 kV	X_{23}	0.02 pu	V_{Load}	20 kV
		X_{24}	0.02 pu	P_{Load}	2000 MW
		X_{34}	0.01 pu	Q_{Load}	100 MVAR

Ten cases are developed by gradually increasing the amount of converter connected DG. The DG is connected at the same bus as the load (bus 5) and supplies active power only. Therefore, the DG is regarded as negative load in the load bus. In the first case (case 1), no DG is connected in the load bus, and the load is completely supplied by 10 identical CG units in bus 1. By increasing the DG penetration level in steps of 10 % of the active load, one CG unit is shutdown in every case, which results in an altered value of X_d' too (since the CGs are assumed to be in parallel), so that in the last case only one CG remains in the system. The details of the 10 cases developed are listed in Table 2.

Table 2. Values of the parameters used in the 10 simulation cases

Case [nr.]	CG [# units]	Total CG-Real-Power-Output (P_m) [MW]	Total DG-Real-Power-Output (P_{DG}) [MW]	Total CG H constant [MJ/MVA$_{sys}$]	CG X_d' [pu]
1	10	2000	0	100.0	j0.0100
2	9	1800	200	90.0	j0.0111
3	8	1600	400	80.0	j0.0125
4	7	1400	600	70.0	j0.0143
5	6	1200	800	60.0	j0.0167
6	5	1000	1000	50.0	j0.0200
7	4	800	1200	40.0	j0.0250
8	3	600	1400	30.0	j0.0333
9	2	400	1600	20.0	j0.0500
10	1	200	1800	10.0	j0.1000

The constant load model $\mathbf{Y}_{5,Load}$ (figure 4) is calculated as:

$$\mathbf{Y}_{5,Load} = \frac{\left(P_{Load} - P_{DG}\right) - jQ_{Load}}{\left|\mathbf{V}_5\right|^2} \quad \text{[pu]} \qquad (2)$$

The impact of converter connected DG during the fault (transient situation) is modelled in such that the DGs disconnect during the fault, so that (during the fault) no negative load is implemented (P_{DG} in equation (2) equals to zero). The values of $\mathbf{V}_5$ in equation (2) are obtained by running a load flow program with PSS/E 25.4 on the pre-fault condition of every case. The transient stability of the test system is investigated by applying a temporary three-phase fault to a transmission line in the middle of line 3-4 (See figure 3).

Since the test system can be regarded as a single machine infinite bus (SMIB) system (since all the synchronous machines in bus 1 are coherently operated) the Equal Area Criterion [6] is used to investigate the transient stability phenomena of each case in every scenario. To assess the transient stability performance, one indicator is used, namely the critical clearing time (t_{cr}), which is defined as the maximal time needed to clear the fault present in the system without causing instability.

By deriving the admittance matrix $\mathbf{Y}_{bus}$ (5x5), along with the corresponding reduced admittance matrix $\mathbf{Y}'_{bus}$ (2x2), that explicitly relates bus 1 and bus 2, the values of P_e (thus P_c, P_{max}, and δ), of every case and every (sub-) scenarios (in both pre/post fault and during fault conditions) for equations (3)-(6) [4, 6, 7], are calculated. Subsequently, the critical angles (δ_{cr}) are calculated using the equal area criterion (equation (7)) [3, 5]. Finally, the corresponding critical clearing times (t_{cr}) – the time needed to achieve the critical angles (δ_{cr}) – are computed iteratively using equations (8)-(10) [5].

$$P_e = P_c + P_{max}\sin\left(\delta - \gamma\right) \quad \text{[pu]} \qquad (3)$$

$$P_{max} = \left|\mathbf{E}'_1\right|\left|\mathbf{E}'_2\right|\left|\mathbf{Y}'_{12}\right| \quad \text{[pu]} \qquad (4)$$

$$P_c = \left|\mathbf{E}'_1\right|^2 G'_{11} \quad \text{[pu]} \qquad (5)$$

$$\gamma = \theta'_{12} - \frac{\pi}{2} \quad \text{[rad]} \qquad (6)$$

$$\int_{\delta_0}^{\delta_{cr}} P_m - P_{e,during-fault}\left(\delta\right) = \int_{\delta_{cr}}^{\delta_{max}} P_{e,pre/post-fault}\left(\delta\right) - P_m \qquad (7)$$

$$\delta_n = \delta_{n-1} + \Delta\delta_n \quad \text{[rad]} \qquad (8)$$

$$\Delta\delta_n = \Delta\delta_{n-1} + \left(\frac{\pi f}{H}\right)\left(\Delta t\right)^2\left(P_{a,n-1}\right) \quad \text{[rad]} \qquad (9)$$

$$P_{a,n} = P_m - P_e(\delta_n) \quad \text{[pu]} \qquad (10)$$

Where $\mathbf{E}'_1$ is the transient internal voltage of CG in pu., $\mathbf{E}'_2$ is the transient voltage of the infinite bus, i.e. 1.0 in pu., P_m is the shaft power input less rotational losses in pu., $\mathbf{Y}'_{12}$, θ'_{12}, G'_{11} are respectively the admittance (in pu.), angle (in rad), and susceptance (in pu.) elements of reduced $\mathbf{Y}'_{bus}$ (2x2), $P_{e,during-fault}$, $P_{e,pre/post\,fault}$ are the electrical power crossing the air gap during fault and pre-/post-fault (both in pu.), δ_0, δ_{cr}, δ_{max} are respectively the initial-, critical-, and maximum- rotor angles (all in rad) (See Figure 6), $\Delta\delta_n$, δ_n are respectively the change in angle and the angle in the n-interval iteration (both in rad), f is system frequency in Hz., Δt is the iteration time interval in s, and $P_{a,n}$ is the accelerating power at the middle of the iteration interval in pu.

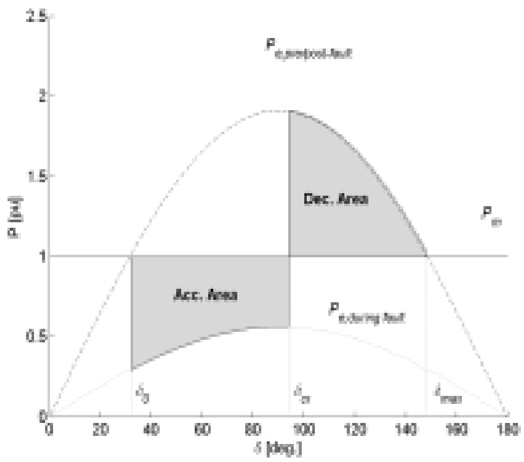

Figure 6. Plot of power-angle curves typically found in every simulation case, showing the initial (δ0), critical (δcr), and maximum (δmax) angles. The accelerating (Acc.) area and decelerating (Dec.) area are equal.

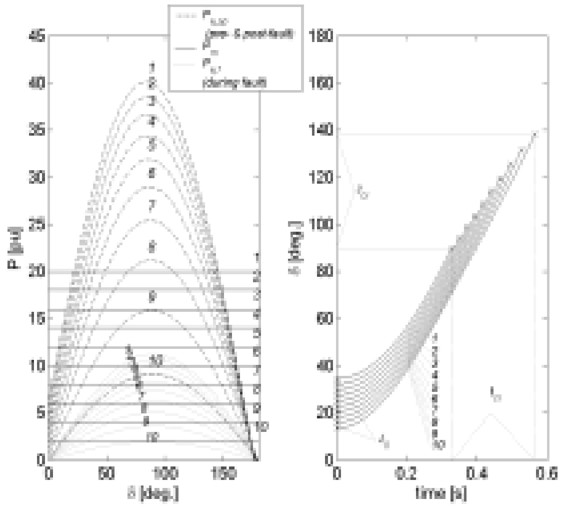

Figure 7. The results when Fault #1 is simulated on either Scenarios I or II (10 cases). Left graph: Plots of the power-angle curves. Right graph: Swing curves plotted until the point where the critical angles (δcr) are reached on the critical times (tcr)

RESULTS

Figure 7 shows the results of Scenario I (10 cases). It is shown in the left graph of figure 7, that when the number of CG units decreases, the plots of P_m, $P_{e,pre/post\text{-}fault}$, and P_e, during fault, and the δ_0 decrease, whereas the δ_{max} increases. Application of the equal area criterion (See Equation (8) and Figure 6) results in rising δ_{cr}-values when the number of CG units connected to the system falls. Although H is decreasing (when the number of CG units decreases, see Table 2) – so that a particular rotor angle would be reached faster if all the other parameters in equations (9) are kept the same – the time needed to reach a particular δ_{cr}, i.e. t_{cr}, is longer (as can be seen in the right graph of figure 7). This is caused by the fact that two opposite effects play a role when the number of CG units is reduced: less H versus a changing network topology (altered value of X_d' since the CGs are assumed to be in parallel). This last effect is the strongest (in this case) and results in lower P_m, $P_{e,pre/post\ fault}$, P_e, during fault curves and δ_0-values. Figure 7: (left graph) shows these situations, whereas higher δ_{max} and δ_{cr}-values are obtained which leads to longer critical clearing times and better stability.

Table 3 shows the critical angles (δ_{cr}) and critical clearing times (t_{cr}) that resulted from the simulation of all the cases.

Table 3. Simulation results

Case [nr.]	δ_0 (deg.)	δ_{max} (deg.)	δ_{cr} (deg.)	t_{cr} (s)
1	34.59	145.41	90.06	0.328
2	32.18	147.82	94.44	0.349
3	29.82	150.18	99.04	0.371
4	27.51	152.49	103.86	0.394
5	25.22	154.78	108.92	0.417
6	22.94	157.06	114.22	0.441
7	20.66	159.34	119.79	0.466
8	18.35	161.65	125.66	0.495
9	15.98	164.02	131.86	0.527
10	13.52	166.49	138.46	0.565

CONCLUSIONS

In this study, a simple 5-bus system is used. The equal area criterion is used to assess the system transient performance, and the critical fault clearing time, which is defined as the maximal time needed to clear the fault applied in the system without causing instability, is used as the system stability indicator.

The results in this paper show with the existence of a strong external system, a better stability is obtained, as measured by longer critical fault clearing times of the remaining synchronous generator(s).

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